Proceedings of ICRC 2001: 3017 © Copernicus Gesellschaft 2001

ICRC 2001

Recent Yohkoh solar gamma-ray observations

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Abstract.
Yohkoh observed two γ-ray flares in 2000, a X5.7 flare at 10:20 UT on 14 July and a X2.3 flare at 15:08 UT on November 24, with the hard X/γ-ray spectrometers and hard X-ray imager. The two flares emitted several nuclear γ-ray lines and hard X-ray images indicate two sources which are located at both footpoints of the magnetic loop. At the beginning of the peak phase of the July 14 flare, the temporal evolution of the hard X-ray sources suggests that a change in the magnetic loop structure from high-shearing to low-shearing states is associated with magnetic reconnection. Particle accleration is discussed based on the Yohkoh spectroscopic and imaging data.

1 Introduction

Yohkoh has spectroscopic and imaging capabilities for solar flares and provides hard X-ray spectral/ imaging and γ-ray spectral data. The hard X- and γ-ray spectral observations are important for a study of high-energy particle acceleration and transport at flare sites, while the hard X-ray image data provide crucial information on magnetic reconnection and particle acceleration at flare sites. Simulataneous observations with the spectroscopic and imaging instruments enable us to discuss high-energy phenomena on the Sun in detail. Yohkoh measured two γ-ray flares in 2000: a X5.7/3B flare on July 14 (Share et al., 2001; Klein et al., 2001) and a X2.3/2B flare on November 24. Both flares emitted significant electron bremsstrahlung continuum and γ-ray lines which is due to nuclear deexcitation, neutron-capture and positron annihilation. The hard X-ray sources of the July 14 flare exhibited characteristic motions suggesting occurrence of magnetic reconnection (Masuda et al., 2001). The November 24 flare produced more intense γ-ray flux than the July 14 flare and shows a typical two hard X-ray sources. In the present paper we present Yohkoh γ-ray spectral and hard X-ray image data of the two X-class flares and discussed high-energy particle production in the flares.

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2 Observations

A γ-ray spectrometer on board Yohkoh observed a large flare at 10:20 UT on July 14, 2000. Its GOES class is X5.7, optical importance 3B and location N22 W07 AR9077. The count-rate time profiles at 0.04-0.82, 1-2, 2.22 and 4-7 MeV in Fig. 1. We see small and main peaks of high-energy photon emission at 10:22 and 10:27 UT, respectively. The time profile of 2.22 MeV line has a longer decay time compared with the others. The background level at high energies gradually decreases with time. The flare started at 10:13 UT but Yohkoh misses the rising phase of the flare before 10:20 UT. The HXRS experiment (Farnik, 2000) covered hard X-ray data between 10:05 and 10:15 UT. It exhibited a small peak of X-ray emission at 10:12-10:15 UT. We plot the background-subtracted hard X- and γ-ray count spectra (flare-averaged) (Share et al., 2001) in Fig. 2. Here the hard-X-ray spectrum is preliminary because the deadtime correction has not yet completed. The γ- ray spectrum exhibits nuclear deexcitation lines of Ne at 1.64 MeV, C at 4.44MeV and O at 6.13 MeV and neutron- capture line at 2.22 MeV.

The Yohkoh hard X-ray image at 33-53 keV are analyzed by Masuda et al. (2001). They found that two hard X-ray sources characteristically move as the flare pregresses. The temporal variation in the hard X-ray image at 33-53 keV are shown in Fig. 3. A simplified magnetic neutral line is indicated in each panel. Initially (10:24:23-10:24:37 UT) the two sources are located near the magnetic neutral line but gradually separate from the neutral line (10:26:41-10:27:03 UT). The motions are thought to provide important diagnostics for magnetic reconnection.

A X2.3/2B flare (N22 W07, AR9236) was observed at 15:08 UT on November 24 and its duration. The count-rate time profiles at 0.48-0.54, 2.22, 4-7 and 7-17 MeV are shown

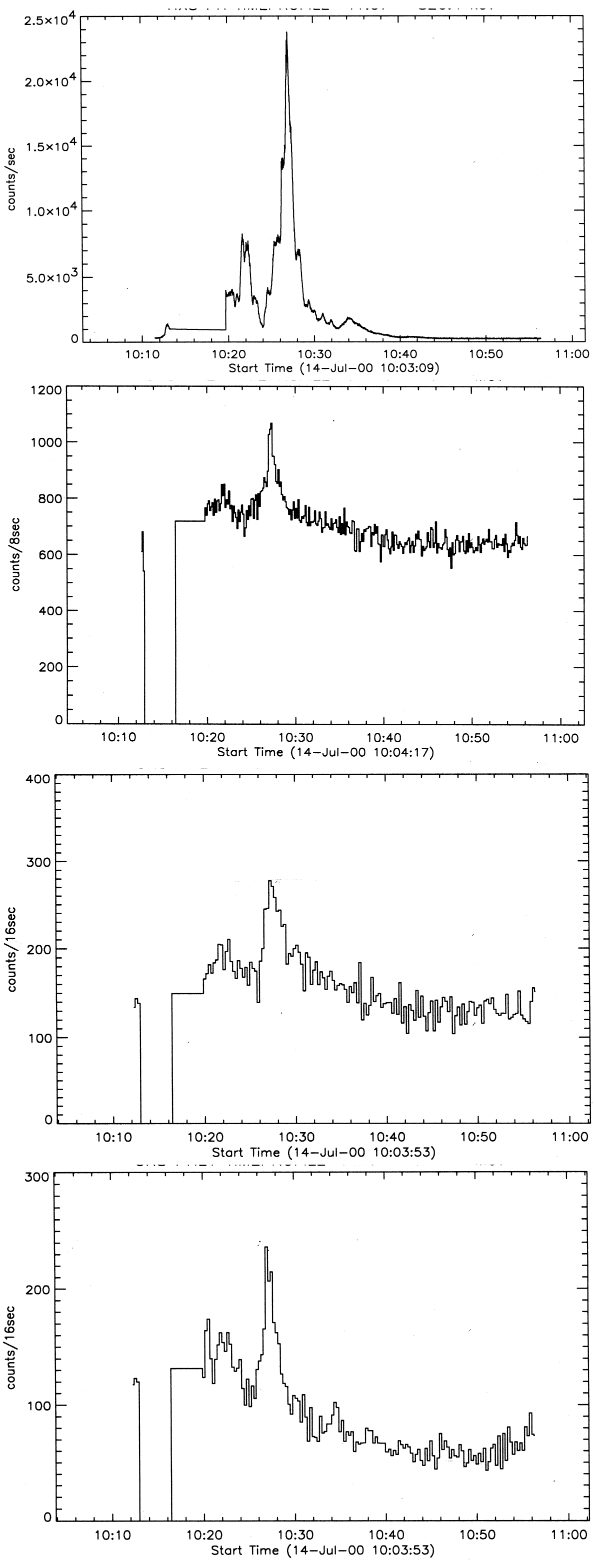

Fig. 1. Count rate time profiles at 0.04-0.82 (top panel), 1-2 (second), 2.22 (third) and 4-7 MeV (bottom) of the July 14 flare.

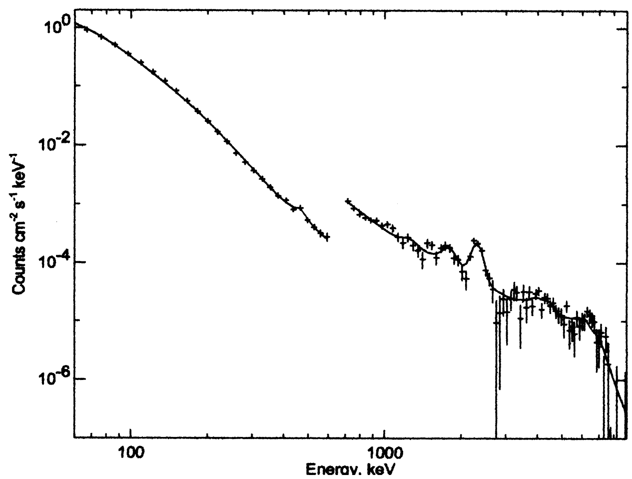

Fig. 2. Flare-averaged hard X- and γ-ray spectra of the July 14 flare (Share et al., 2001).

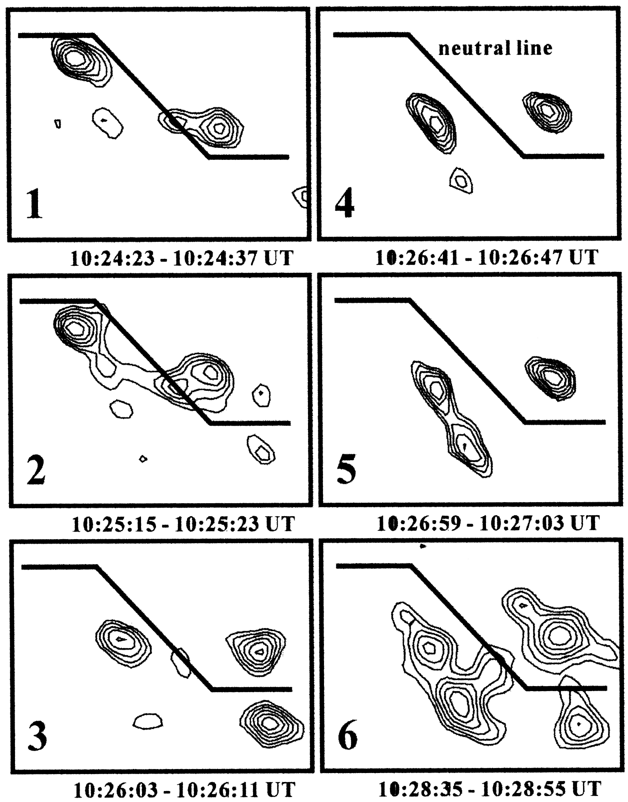

Fig. 3. Hard X-ray images at 33-53 keV in 10:24-10:29 UT of the July 14 flare. A simplified magnetic neutral line is indicated in each panel.

in Fig. 4. The γ-ray flux is much higher than that of the July 14 flare. The background-subtracted γ-ray count spectrum is shown in Fig. 5 (Courtesy of Share). This spectrum is

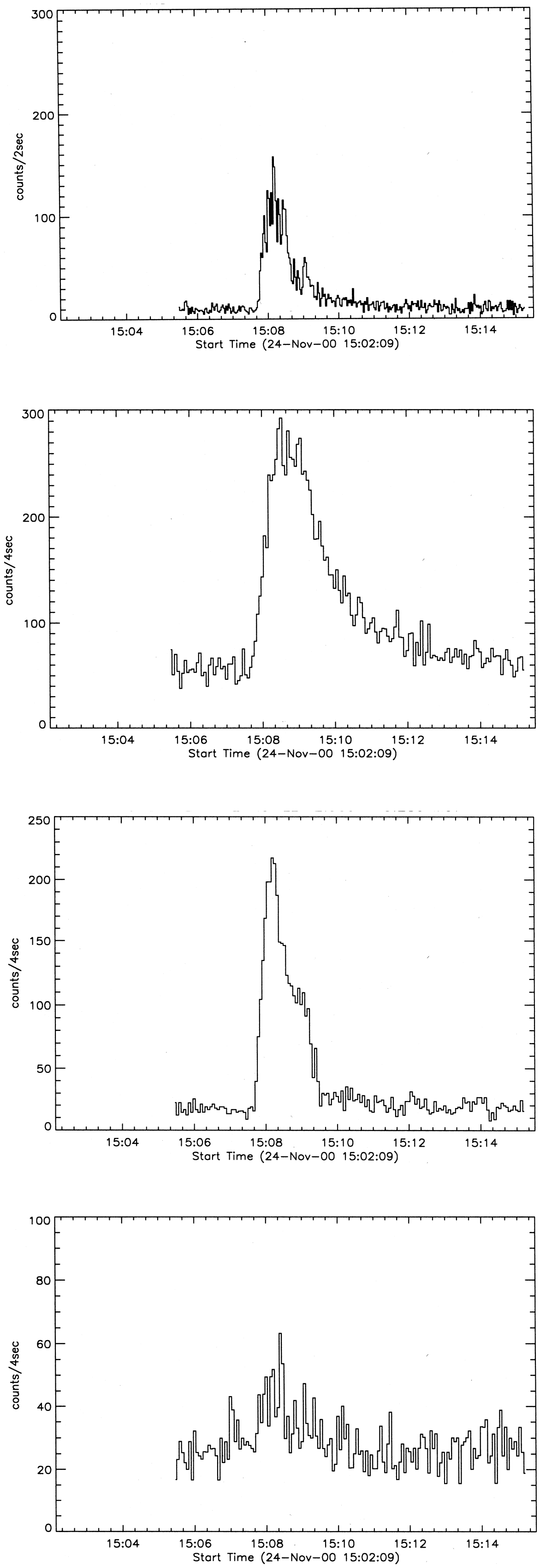

Fig. 4. Count rate time profiles at 0.48-0.54 (top panel), 2.22 (second), 4-7 (third) and 7-17 MeV (bottom) of the November 24 flare.

preliminary. We see the 2.22 MeV line, C and O nuclear deexcition lines and a complex of a few weak lines at 1-2 MeV. The hard X-ray (53-93 keV) images observed at 15:07:50 and 15:09:02 UT is shown in Fig. 6. There are clear two hard X-ray sources which are located at both footpoints of the magnetic loop. We found the small motions of the hard X-ray sources from detailed analysis of the temporal evolution. The distance between two sources slightly varies with time.

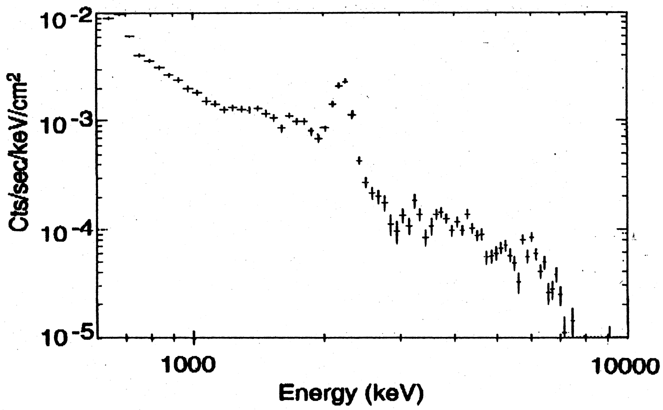

Fig. 5. Backbround-subtracted γ-ray spectrum of the November 24 flare.

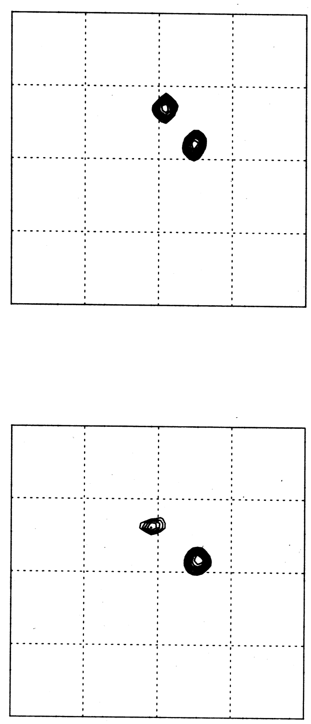

Fig. 6. Hard X-ray images at 53-93 keV at 15:07:50 (top panel) and 15:09:02 UT (bottom panel) of the November 24 flare.

3 Discussion

The rising phase of the July 14 flare was not measured with Yohkoh. The HXRS observed hard X-rays between 10:05 and 10:15 UT and exhibited a small peak of X-ray emission at 10:12-10:15 UT. It is not clear whether there is a strong X- and γ-ray peak between 10:15 and 10:20 UT. Since the γ-ray spectrometer consists of a BGO scintillation detector, its line resolution is not high (the energy rsolution FWHM is about 15 % at 662 keV). The flare-averaged γ-ray spectrum exhibits the neutron-capture line and nuclear deexcitation lines of Ne at 1.64 MeV and C and O in the 4-7 MeV band. Further, we see a small peak of Ne line at 1.64 MeV. Share et al. (2001) derived the proton spectrum from a ratio of the 2.22 MeV to 4-7 MeV fluences. The spectral index of the proton power-law spectrum is 3.12 ± 0.15 and a number of protons is 1.1x10^{32} protons per MeV at 10 MeV. The hard X-ray spectrum shows the weak 511 keV line resulting from positron annihilation. The count-rate time profiles are similar at hard X- and γ-ray energies, implying that electrons and ions were simulataneously accelerated to high energies.

The hard X-ray images demonstrates the important temporal evolution during the main peak, as shown in Fig. 3. We see two clear hard X-ray sources which are thought to be located at both footpoints of the magnetic loop. The two hard X-ray sources are located near the magnetic neutral line at 10:24:23-10:24:37 UT, indicating that magnetic loop is strongly sheared (high shear state). Later the two hard X-ray sources start to move along the neutral line and simulatneously separate from the magnetic neutral line at 10:26:03-10:27:03 UT. As a consequent, the magnetic field becomes weakly sheared (low shear state). Masuda et al. (2001) proposed that magnetic reconnection causes the change in the magnetic field configuration from the high-shearing state to the low-shearing state. The magnetic energy storaged within the strongly sheared magnetic field is released by the magnetic reconnection. The magnetic reconnection generates fast shock waves which could accelerate electrons and ions to high energies (Tsuneta and Naito, 1998). The acclerated particles precipitate to the chromosphere and produce hard X-rays and γ-rays.

Surprisingly intense and long-duration solar energetic particles (SEPs) were observed from the July 14 event (Reames, et al., 2001). A strong CME event was measured associated with this event. The intense SEPs are thought to be accelerated by CME-driven shock in the higher corona. A total number of the CME-associated SEPs is much higher than that of γ-ray producing protons.

The November 24 flare emitted much intense hard X- and γ-rays compared with the July 14 flare. The γ-ray fluence of the November 24 flare is about one order of magnitude as large as that of the July 14 flare, though the SEP flux of the November 24 event is two orders of magnitude smaller than that of the July 14 event. It suggests the possibility that a fluence ratio of the γ-ray producing protons to the CME-associated protons in the November 24 event is much higher than that of the July 14 event. It indicates that there is not a correlation between the γ-ray producing proton and SEP fluxes (Reames, 1999). The same γ-ray lines were detected from the two flares. Concerning the timeprofile of the neutron-capture line at 2.22 MeV, both flares exhibit the long decay time compared with those of electron bremsstrahlung and nuclear deexcitation lines. It is because of the time required for neutrons to slow down and be captured. We can estimate a ratio of the ^3He to H abundances in the photosphere from the decay time of the 2.22 MeV line (Price et al., 1983; Murphy et al., 1997). Assuming that the photospheric hydrogen density is 1.3x$10^{17} cm^{-3}$, we obtain the ratio of (2-4)x10^{-5} for the two flares. This is consistent with the previous results (Yoshimori et al., 1999).

The hard X-ray image at 53-93 keV shows a typical two sources during the flare. Their locations correspond to both footpoints of the magnetic loop, indicating that accelerated electrons streamed down to the chromosphere and produce hard X-rays through bremsstrahlung. The hard X-ray image is independent on X-ray energy at 23-93 keV and there is little temporal variation in the hard X-ray source positions. Further, the 4-channel X-ray data of the hard X-ray telescope exhibit an extremly hard spectrum (power law index of about 2.0 below 100 keV) during the peak phase (15:07:40-15:09:00 UT), suggesting that there was a powerful electron acceleration mechanism at the flare site.

Acknowledgements. We would like to acknowledge G.H. Share and R.J. Murphy for their analyzing the Yohkoh γ-ray spectra and discussing the particle accleration and transportation. We thank F. Farnik for his sending the HXRS time profiles. We wish Dr. T. Kohmura for his support of completing the manuscript. This work has been supported by Grant-in-Aid for Scientific Research of Ministry of Education, Science and Culture C-1640290.

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