MAXI Observation of Blazars

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Abstract

Longterm X-ray observation is reported of the high-energy peaked BL Lac object Mrk 421 with MAXI, in order to demonstrate the power of MAXI for the study of blazars. One of the most important properties of blazars is their rapid intensity variation, which is a useful probe for the high energy phenomena related to their jets, including the particle acceleration. The unprecedentedly high sensitivity of MAXI as an all-sky X-ray monitor makes it the ideal observatory for studies of the longterm variation of blazars. Actually, MAXI has successfully detected several strong X-ray flares from Mrk 421, with the X-ray flux at highest level among those ever recorded from the object. The physical quantities associated with the flares were evaluated, from the close examination on the MAXI lightcurve.

Key words: galaxies: active — galaxies: BL Lacertae objects: individual (Mrk 421) — X-rays: galaxies — radiation mechanisms: non-thermal

1. Introduction

Blazars, including BL Lac objects, are a class of active galactic nuclei which host a jet emanating close to our line of sight. In addition to their non-thermal radiation ranging from the radio to gamma-ray frequencies and strong polarization at radio and optical frequencies, they are characterized by their rapid and high-amplitude intensity variations or flares. From close examination on the variability of blazars, we can probe the dynamics of their jet, as well as to particle acceleration and cooling processes operating there. In the last two decades, X-ray observations with Ginga, ASCA and RXTE (e.g., Takahashi et al. 2000, Kataoka et al., 2001 Tanihata et al. 2001) have been one of the most powerful tools for such purpose. Moreover, recent monitoring X-ray observations with Swift successively detected flares from a number of blazars (e.g., Tramacere et al. 2009).

Thanks to its high sensitivity as an all sky X-ray monitor, in combination with its high sky coverage ($\sim 95\%$ per day; Sugizaki et al. 2011), it is of no doubt that MAXI (Matsuoka et al. 2009) is an ideal observatory to investigate the longterm X-ray variation of blazars. Therefore, the MAXI lightcurve of more than 20 blazars are currently made public from the MAXI web site[1]. Actually, we have succeeded in making prompt alerts of two strong X-ray flares from the famous blazar Mrk 421 with MAXI (Isobe et al. 2010a, 2010b). In the present paper, we demonstrate the potential of MAXI for the study of the blazar variability, by discussing the X-ray features of Mrk 421 during these flares, together with their physical implication, referring to Isobe et al. (2011).

*1 `http://maxi.riken.jp/top/index.php`

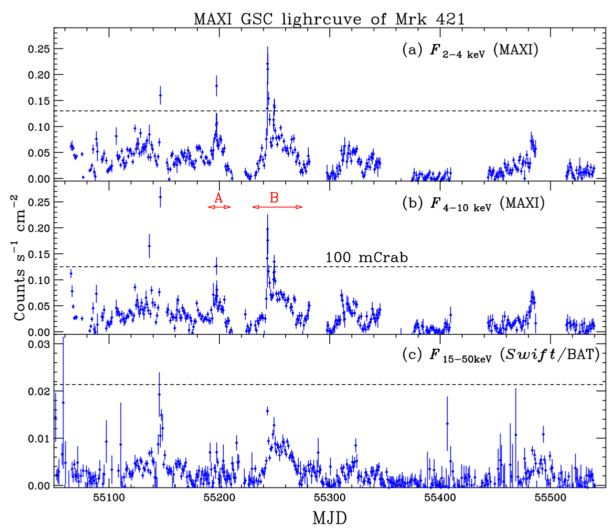

Fig. 1. Daily MAXI lightcurce of Mrk 421 in 2 – 4 keV (panel a) and 4 – 10 keV (panel b), F_{2-4}, and F_{4-10} respectively, from 2009 September 23 to 2010 December 9, in comparison with the hard X-ray light curve with the Swift BAT in 15 – 50 keV F_{15-50} (panel c). The data corresponding to the two arrows, denoted as A and B, are expanded to figure 2. The dotted lines indicate the intensity of the 100 mCrab source in the individual energy range.

2. Longterm MAXI observation of Mrk 421

The high-energy peaked BL Lac object Mrk 421, located at a redshift of $z = 0.031$, is one of the brightest blazars in the X-ray band. In 1990s, it was recognized

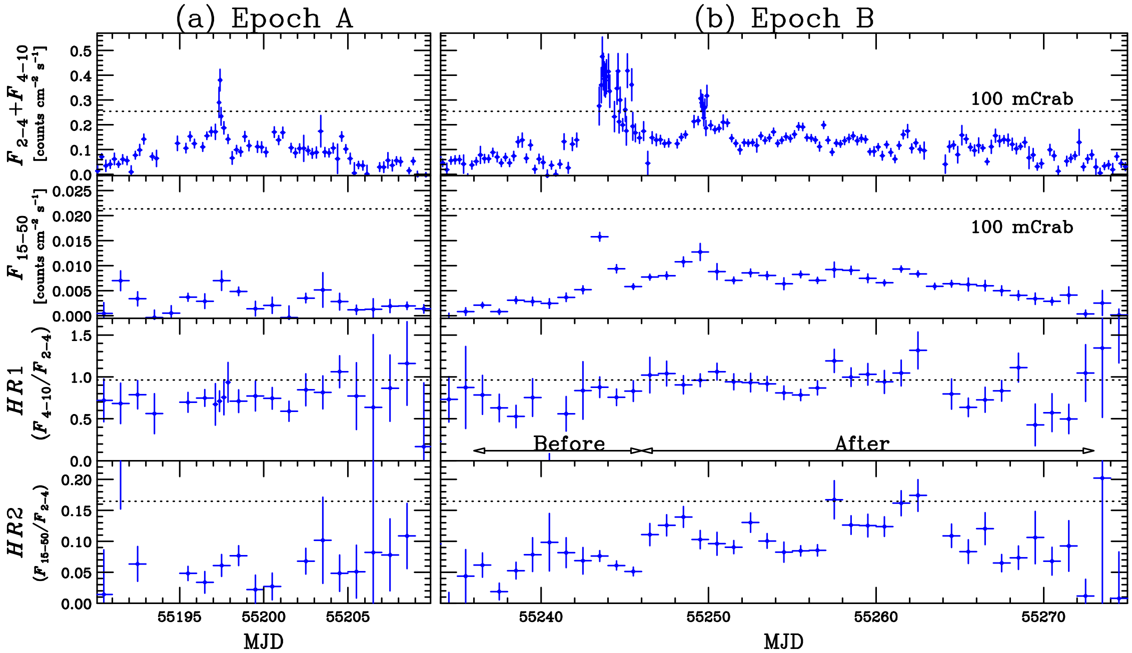

Fig. 2. Lightcurves of Mrk 421 during Epochs A and B defined in figure 1 are plotted in panels (a) and (b), respectively. The first row shows the 2 – 10 keV MAXI data, $F_{2-4} + F_{4-10}$, in a time resolution of 6 hours, while the second row displays the daily Swift BAT data, F_{15-50}. The third and forth rows show the daily averaged hardness ratios, $HR1$ and $HR2$ respectively. The dotted lines in the first and second rows indicate the count rate for a 100 mCrab source, while those in the third and forth panels show the hardness for the Crab-like spectrum.

as the brightest extragalactic source in the very high energy (VHE) γ-ray range above $\sim$ 100 GeV (Punch et al. 1992). The multi-wavelength spectral energy distribution of the object is basically well-understood in the framework of a simple one-zone synchrotron-self-Compton (SSC) model. In the case of Mrk 421, the peaks of the synchrotron and inverse Compton spectral components are located around the X-ray and VHE γ-ray frequencies. These makes the source one of the most interesting target for the longterm monitoring observation with MAXI.

Figure 1 shows the longterm MAXI lightcurves of Mrk 421 in the 2 – 4 keV and 4 – 10 keV ranges, F_{2-4} and F_{4-10} respectively, in comparison with the 15 – 50 keV hard X-ray lightcurve, F_{15-50}, obtained with the Swift BAT, which is publicly available from the web page of the Swift BAT transient monitor results. These lightcurves visualize that the source is highly variable in all the X-ray energy ranges. At least four significant X-ray flares with an X-ray flux of $\gtrsim$ 100 mCrab in the 2 – 4 and/or 4 – 10 keV range were detected with MAXI, although the first and second ones were unfortunately observed in a relatively worse instrumental condition. We, then, investigate the X-ray behavior of Mrk 421 during the third and forth flares, detected with MAXI on 2010 January 1 (MJD = 55197; Isobe et al. 2010a) and February 16 (MJD = 55243; Isobe et al. 2010b), respectively. For this purpose, the MAXI data during Epochs A and B, defined in figure 1 panel (b), were extensively examined.

Figure 2 shows the 2 – 10 keV MAXI lightchrve of Mrk 421, $F_{2-4} + F_{4-10}$, and the 15 - 50 keV Swift BAT lightcurve, F_{15-50}, during Epochs A and B, together with the hardness ratios defined as $HR1 = F_{4-10}/F_{2-4}$ and $HR1 = F_{15-50}/F_{2-4}$. We measured the maximum X-ray flux during Epoch A as 120 ± 10 mCrab in 2 – 10 keV at MJD = 55197.4, although the timing of the flare peak was not covered with the Swift BAT. During Epoch B, the source continued to be in an active state with a 2 – 10 keV flux of $\sim$ 50 mCrab for nearly one month, and there are multiple flares in its lightcurve. The lightcurve of the source peaks at MJD = 55243.6, with an X-ray flux of 164 ± 17 mCrab in 2 – 10 keV. Probably concurrent with this flare, a strong activity in the VHE γ-rays are reported on MJD = 55244 with the maximum VHE flux exceeding 10 times the Crab level (Ong et al. 2010). The source exhibited the second flare, and its peak flux was derived as 108 ± 7 mCrab at MJD = 55249.6.

Recent progress in the X-ray monitoring observations successively revealed strong X-ray flares from Mrk 421; these include the flare in 2006 June with the 2 – 10 keV flux of $\sim$ 85 mCrab (Tramacere et al.2009) the flare in 2008 June with $\sim$ 130 mCrab (Donnarumma et al.2009) and the flare in 2009 December with $\sim$ 100 mCrab (D'Ammando et al.2009). Here, we emphasize

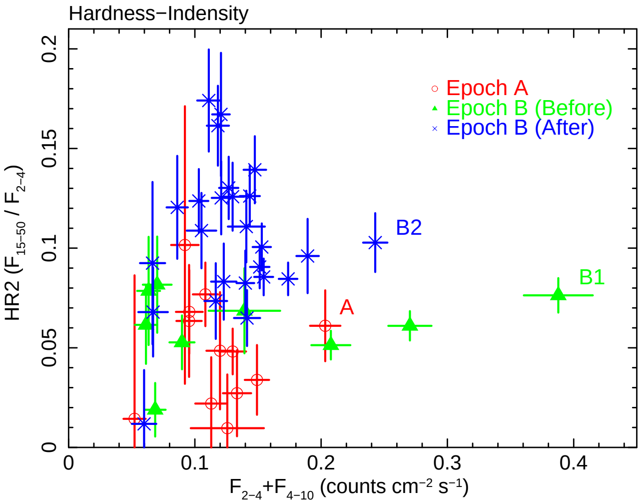

Fig. 3. Hardness ratio $HR2 = F_{15-50}/F_{2-4}$, plotted against the source intensity $F_{2-4} + F_{4-10}$. The definition of "Before" and "After" the first peak of Epoch B is shown in figure 2. The data points corresponding to the peak of Epoch A, first and second ones of Epoch B is indicated as A, B1 and B2, respectively.

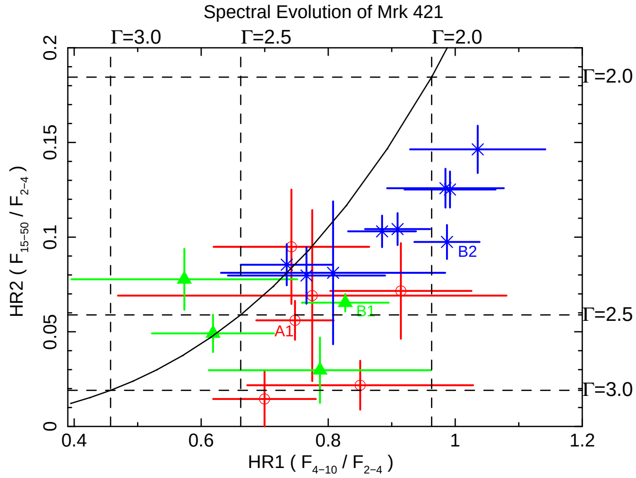

Fig. 4. The relation between $HR1$ and $HR2$, averaged over 3 days. The data points during the flare of Epoch A, the first and second ones of Epoch B is indicated as A, B1, and B2, respectively. The hardness ratios for some representative photon index are shown by the dashed lines. A simple strait power-law spectrum in the whole MAXI-Swift BAT energy range corresponds to the solid curve.

that the maximum X-ray flux in the first flare in Epoch B, measured with the MAXI, is higher than any other previous results. Therefore, the X-ray flare, detected with MAXI on MJD = 55243, is concluded to be the strongest one among those ever recorded from Mrk 421.

3. Spectral evolution

Since the hardness ratios, $HR1$ and $HR2$, shown in figure 2 indicate the spectral variation of Mrk 421 associated with these flares, we examined the intensity-related hardness change in figure 3. Throughout Epoch A, no statistically significant hardness change was found. The hardness before the decay of the first flare in Epoch B is similar to that in Epoch A, even though a factor of 4 intensity variation was observed. In contrast, after the decay of this flare, the source exhibited a spectral hardening. Especially, the source spectrum is found to become hardest, when the source flux (~ 40 mCrab) was about one forth of the maximum at the peak of the flare. Toward the end of Epoch B, the hardness of the source appears to return to the value similar to those during Epoch A.

In order to roughly evaluate the spectral shape of Mrk 421, we plot the relation between $HR1$ and $HR2$ in figure 4. Assuming a simple power-law model, a photon index of $\Gamma = 2 - 2.5$ is suggested from the diagram, in $2 - 10$ keV. In addition, the figure indicates a convex X-ray spectrum in the MAXI-Swift BAT energy range, where the X-ray spectral slope in $15 - 50$ keV is stepper than that in $2 - 10$ keV. These spectral shape is consistent with the previous results, in which the synchrotron spectral peak energy was determined to be $E_{\rm p} = 0.3 - 5$ keV (e.g., Tanihata et al. 2004).

In the previous observations, a positive correlation between $E_{\rm p}$ and the synchrotron peak luminosity $L_{\rm p}$ was widely reported (e.g., Tanihata et al. 2004, Tramacere et al. 2007). Such correlation is thought to be quite natural within the simple framework of a one-zone SSC model, since the synchrotron peak energy and luminosity, respectively, scale as $E_{\rm p} \propto B\gamma_{\rm p}^2\delta$ and $L_{\rm p} \propto B^2\gamma_{\rm p}^{2(2-\Gamma_{\rm p})}\delta^{2+\Gamma_p}N_{\rm e}V$, where $\gamma_{\rm p}$, $\Gamma_{\rm p}(<2)$, $N_{\rm p}$ and V is the maximum Lorentz factor of the radiating electrons, the synchrotron photon index below $E_{\rm p}$ (assuming a simple PL spectrum), the normalization of the electron number density spectrum, and the volume of the emission region, respectively. However, the hardness-intensity plot in figure 4, which is regarded as equivalent to $E_{\rm p}$-$L_{\rm p}$ relation, suggests an opposite tendency as discussed above, especially during Epoch B. The one-zone SSC model requires fine tuning of the physical parameters like a combination of the increase in B, $\gamma_{\rm p}$ or δ and the decrease in $N_{\rm e}$ or V, for explanation of such an unusual spectral change. We regard that these results may prefer a multiple-zone/component SSC model (e.g., Ushio et al. 2009).

4. Physical parameters associated with the flares

By closely examining the timescale of the flares, we evaluated the physical parameters within the jet of Mrk 421. The decay time of the flare in Epoch A is estimated as $t_{\rm d} \sim 2.5 \times 10^4$ s. Here, we simply assume that the decay of the flare is controlled by the cooling process of electron inside the jet. In the case of high-energy peaked BL Lac object, including Mrk 421, the synchrotron radiation is usually the most dominant cooling process, and its cooling timescale is described as $\tau_{\rm cool} \sim 1.5 \times 10^3 B^{-3/2} E_{\rm keV}^{-1/2} \delta^{-1/2}$ s seen from the observer's frame, with B, $E_{\rm keV}$, and δ being the magnetic field in G, the synchrotron photon energy in keV, and the beaming factor of the jet, respectively. The relation of $t_{\rm d} \sim \tau_{\rm cool}$ gives a time-averaged magnetic field of $B \sim 4.5 \times 10^{-2} (\delta/10)^{-1/3}$ G in the flare of Epoch A. This is found to be within the typical value for Mrk 421, determined from the one-zone SSC modeling to the multi-wavelength spectrum ($B = 0.036 - 0.44$ G; Kino et al. 2002).

The rise time of the Epoch A flare is suggested to be shorter than $t_{\rm d}$ as $t_{\rm r} \lesssim 2 \times 10^4$ s. Since the shortest timescale of the lightcurce associated with the flare should be longer than the light crossing timescale of the emission region, we can put the upper limit on the size of the emission region as $R \leq c t_{\rm d} \delta/(1+z) \sim 6 \times 10^{15}$ cm, where c is the speed of light. This upper limit is regarded to be reasonable in comparison with that in the previous strong X-ray flares (e.g., Donnarumma et al. 2009).

We applied the similar method to the strongest X-ray flare from Mrk 421, taking place during Epoch B. The data gap before this flare (see figure 2) only a loose upper limit is put on the rise time as $t_{\rm r} < 1.3 \times 10^5$ s, corresponding to a region size of $R \lesssim 4 \times 10^{16}$ cm. In contrast, the decay time of $t_{\rm d} \sim 1.4 \times 10^5$ s, which is a factor of ~ 6 longer than that in the Epoch A flare, corresponds to a weaker magnetic field strength of $B \sim 1.5 \times 10^{-2} (\delta/10)^{-1/3}$ G. This is found to be slightly outside the range of the previous results (Kino et al. 2002). Based on close examination on X-ray lightcurve of several high-energy peaked BL Lac objects, obtained in the long-look ASCA and RXTE observation with a duration of $\gtrsim 1$ week, a possibility was discussed that day-scale flares of high-energy peaked BL Lac objects are composed of short events with a timescale of $\sim 10^4$ s (Tanihata et al. 2001). Then, we propose that this strongest X-ray flare detected with MAXI is a superposition of several flares with a shorter timescale.

5. Summary

By making the best use of the MAXI data, we have successfully detected several bright X-ray flares from the BL Lac object Mrk 421, with an X-ray flux of the ~ 100 mCrab level in $2 - 10$ keV. The high quality continuous lightcurve derived with MAXI enabled us to evaluated the physical parameters in the jet of the source during the strong flares. As a results, we obtained several new insight, related to the jet physics. These clearly shows that the longterm MAXI observation is useful for the study of blazars. However, in order to strengthen the results, simultaneous multi-wavelength spectra and its longterm variation is necessary. Therefore, we strongly encourage multi-wavelength observations of blazars, in cooperation with MAXI.

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