MAXI Monitoring of Crab Pulsar during the GeV Gamma-ray Flare on September 2010

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Abstract.
We report on the MAXI GSC X-ray monitoring of the Crab nebula and pulsar during the GeV gamma-ray flare on 2010 September detected by AGILE and Fermi-LAT. There were no significant variations on the pulse-phase-averaged and pulsed fluxes during the gamma-ray flare. The pulse profile also showed no significant change during the period. The upper limits on the variation of the pulse-phase-averaged and pulsed fluxes on MJD 55457.5−55462.5 in the 4-10 keV band are 1% and 19% at the 90% confidence limit of the statistical uncertainty, respectively. Here, the measured fluxes include a 2% systematic uncertainty at the 1-σ limit due to the error on the instrument calibration. The lack of variations in the pulsed component in multi-wavelength range (radio, soft X-ray, hard X-ray, and gamma-ray) supports the nebula origin for the gamma-ray flare.

1. Introduction
The Crab nebula is a remnant of the supernova on 1054. There is a neutron star (pulsar) with a spin period of 33 ms at the center of the nebula. The Crab nebula has been the standard candle of X-ray and gamma-ray astronomy, because the flux and spectrum have been expected to be steady for a long time scale of years. Surprisingly, AGILE and Fermi-LAT reported a gamma-ray flare on 2010 September 18−23 in more than 100 MeV energy range [1, 2]. RXTE-ASM, Swift-BAT, INTEGRAL did not detect variation for the pulse-phase-averaged flux [3]. Radio observation showed no evidence for a glitch, and no changes of pulsed flux and pulse profile shape [4]. Swift-XRT and RXTE-PCA follow-up observations did not detect any changes of flux, spectrum and pulse profile [5, 6]. Chandra and HST follow-up observations found some activated region around the nebula [7]. Recently, two more GeV flare episodes, happened on October 2007 and February 2009, were reported by AGILE and Fermi, respectively [2, 7]. Swift, Super-AGILE and Fermi have not seen significant variations in the pulsed emission in hard X-ray to gamma-ray during the three flaring periods.
2. Observation
MAXI (Monitor of All-sky X-ray Image) is an all-sky X-ray monitor, mounted on the Japanese Experiment Module - Exposed Facility (JEM-EF or Kibo-EF) on the International Space Station (ISS) [8]. It carries two types of X-ray cameras: the Gas Slit Camera (GSC; [9, 10]) for 2−30 keV band and Solid-state Slit Camera (SSC; [11, 12]) for 0.5−12 keV band, using gas proportional counters and X-ray CCDs, respectively. GSC scans almost all sky every 92 minutes with the field of view (FoV) with width of 1.5 degree (FWHM). MAXI GSC scans almost all sky every 92 mins by a transit duration about 1 min. The time resolution of GSC is 50 µs. The absolute time assignment is confirmed to be accurate within the stability of the time (1σ = 0.2 ms) [10].
MAXI has been monitoring the Crab nebula since the start of the operation on August 15, 2009 (UT), including the whole duration of the gamma-ray flare on September 2010. Here, we report on the MAXI monitoring of the Crab nebula during the GeV gamma-ray flare. The details will be shown in Morii et al. (2011) [13] in the near future.

3. Light curve and pulse profile
To measure the pulse-phase-averaged flux, we extracted the circular region on the sky coordinate and subtracted the background counts from the near-by region as done in the usual photometry method. Figure 1 (top) shows the light curves of the pulse-phase-averaged flux in 4−10 keV band. On the other hand, to measure the pulsed flux, we proceeded the following steps. At first, the times of events were corrected to the solar system barycenter. The time sequence was folded in the pulse period of Crab pulsar provided at the web site of the Jodrell Bank radio observatory [14]. In this folding, the time variation of effective area and exposure times were corrected [15, 16]. We fitted the pulse profiles with a model of \( a \times T + b \), where \( T \) was a template pulse profile made from the data from December 13, 2009 to January 11, 2010, and the baseline offset of un-pulsed component was subtracted from the all phase bins. From this fit, we obtained the pulsed flux by \( F_{\text{pulse}} = a \sum T_i / N \). Figure 1 (bottom) shows the light curve of pulsed fluxes in 4−10 keV band. There is no significant flux change on the gamma-ray flare period. The 90% confidence level upper limits on the variation of the pulse-phase-averaged and pulsed fluxes on the flare period (MJD 55457.5−55462.5) were 1% and 19% in the 4−10 keV band. The pulse profile during the flare period is shown in Figure 2. There is no significant change from the template pulse profile.

4. Summary
We report on the MAXI GSC observation of the Crab pulsar during the gamma-ray flare. It is the only report showing the pulse profile and pulsed flux of the Crab pulsar on the whole duration of the gamma-ray flare in the X-ray band. The lack of the changes on the pulsed component in the gamma-ray energy range (> 100 MeV) suggests the nebula origin for the gamma-ray flare. The same result obtained in our MAXI observation as well as that obtained in radio and hard X-ray energy ranges support this scenario.

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Figure 1. GSC light curves of the pulse-phase-averaged flux (top panel) and pulsed flux (bottom panel) of Crab nebula in the energy range of 4–10 keV in 2.5-day time bin. The horizontal and vertical axes are shown in units of MJD (modified Julian day) minus 55000 (2009 June 18) and photons cm$^{-2}$ s$^{-1}$, respectively. The vertical error bars correspond to 1 $\sigma$ statistical errors. The time center (MJD 55460.0) of the GeV gamma-ray flare period (MJD 55457.5–55462.5) is denoted by a vertical dotted line.

Figure 2. Top panel: Pulse profile of Crab pulsar in the 4–10 keV during the gamma-ray flare on MJD 55457.5–55462.5 obtained by GSC. The vertical axis is the flux shown in an unit of counts cm$^{-2}$ s$^{-1}$. The solid histogram is the template pulse profile with the best fit. The bottom panel is the residual of the data from the best fitting model. In both panels, the vertical error bars correspond to 1 $\sigma$ statistical errors.

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