PROCEEDINGS OF SCIENCE

ENERGETIC FERMI/LAT GRB100414A: ENERGETIC AND CORRELATIONS

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We present multi-wavelength observational results for energetic GRB 100414A with GeV photons. The prompt spectral fitting using *Suzaku*/WAM data yielded the spectral peak energies of $E_{\rm peak}^{\rm src}$ of $1458.7^{+132.6}_{-106.6}$ keV and $E_{\rm iso}$ of $34.5^{+2.0}_{-1.8} \times 10^{52}$ erg with $z = 1.368$. The optical afterglow light curves between 3 and 7 days were well fitted by a simple power law with a temporal index of $\alpha = -2.6 \pm 0.1$. The joint light curve with earlier *Swift*/UVOT observations yields a temporal break at 2.3±0.2 days. This was the first Fermi/LAT detected event that demonstrated the clear temporal break in the optical afterglow. The jet opening angle derived from this temporal break was $\sim 5.8^{\circ}$, consistent with those of other well-observed long GRBs. Our multi-wavelength analyses showed that GRB 100414A follows $E_{\rm peak}^{\rm src} - E_{\rm iso}$ and $E_{\rm peak}^{\rm src} - E_{\gamma}$ correlations. The late afterglow revealed a flatter evolution with the significant excesses at 27.2 days. The most straightforward explanation for the excess is that GRB 100414A was accompanied by a contemporaneous supernova. The model light curve based on other GRB-SNe events is marginally consistent with the observed one.

Gamma-Ray Bursts 2012 Conference -GRB2012,
May 07-11, 2012
Munich, Germany

*This work was supporte by NSC 99-2112-M-001-002-MY3 and NSC 98-2112-M-008-003-MY3

PoS(GRB 2012)077

1. Prompt emission

GRB 100414A triggered the *Suzaku* WAM on 2010 April 14 02:20:22.879(=T0). The WAM [1] is a lateral shield of the Hard X-ray Detector on board the *Suzaku* satellite and can function as a GRB monitor sensitive to the 50−5000 keV gamma-rays (e.g. 2,3). The duration T_{90} was 21.2 ± 0.1 s which places it in the class of long duration events. We performed the spectral analysis using the WAM transient data with 55 energy channels and 1-s time resolution. The WAM2 spectrum was extracted by integrating over T0−1.5 s to T0+24.5 s with the `hxdmkwamspec` in the standard HEADAS 6.9 package provided by NASA/GSFC. The background spectrum was estimated by incorporating the best-fit model of source-free time region on both sides (T0−504.5 to T0−4.5 and T0+37.5 to T0+237.5) of the burst time region. We performed the spectral fitting in Xspec version 12.5 and found that the best-fit model was the GRB Band function ($\chi^2/\mathrm{dof} = 24.4/24$). Two other models we also attempted were a power-law ($\chi^2/\mathrm{dof} = 253.5/26$) and a power-law with an exponential cutoff ($\chi^2/\mathrm{dof} = 35.3/25$). The best-fit parameters for the Band function were α=–0.62(–0.15, +0.17), β=–3.05(–0.28,+0.20), and E_{peak}=616±34 keV. Thus obtained, the fluence in the 100-5000 keV range was $(6.65 \pm 0.21) \times 10^{-5}$ erg cm^{-2}. The corresponding *Fermi*/LAT photon data were downloaded from the Fermi Science Support Center. Based on the likelihood and aperture photometry, we generated the light curve for the $>$ 100 MeV energy range as shown in Figure 1 (left). The highest energy photon from this event was $\sim$ 4.3 GeV at $\sim$40 s after the burst.

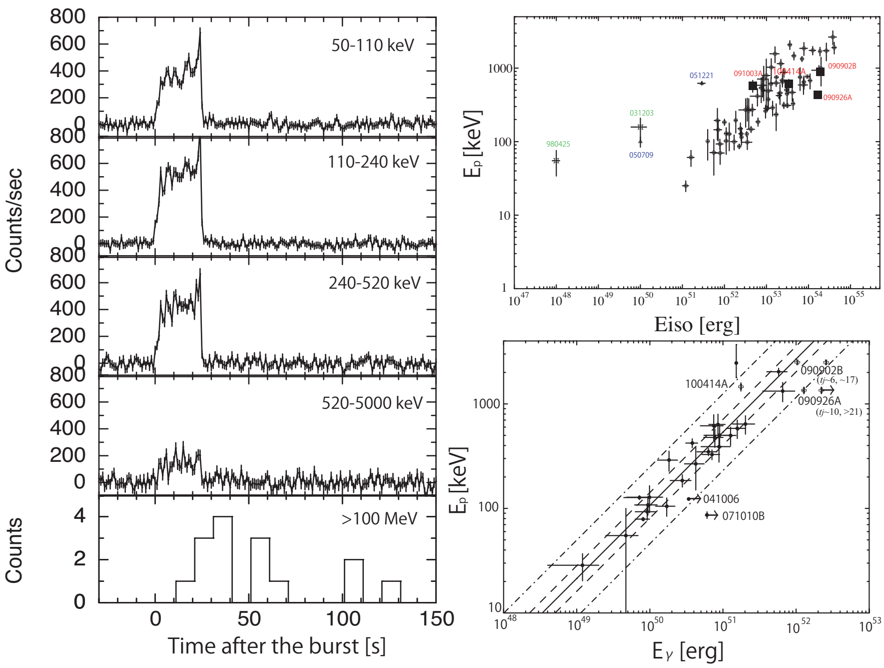

Figure 1: Left: Prompt X-ray and gamma-ray light curves of GRB100414A, as observed using *Suzaku*/WAM and *Fermi*/LAT. Top right: The $E_{\mathrm{peak}}^{\mathrm{src}} - E_{\mathrm{iso}}$ relation combined with the data points of GRBs 100414A, 091003A, 090926A and 090902B (filled square). Bottom right: The $E_{\mathrm{peak}}^{\mathrm{src}} - E_{\gamma}$ relation including the data for GRBs 100414A, 090926A and 090902B corrected for a homogeneous circumburst medium. For GRBs 090926A and 090902B, there are two points for their possible jet break summarized in Table 1. The dashed and dash-dotted lines indicate the 1σ and 3σ scatter of the correlation, respectively.

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Table 1: *Suzaku*/WAM observations of *Fermi*/LAT events with redshift.

GRB	z	T_{90} [s]	E_{peak} [keV]	t_{jet} [d]	E_{iso} [10^{52} erg]	E_γ [10^{50} erg]	Eh [GeV]
100414A	1.368	21	616^{+56}_{-45}	2.3±0.2	$34.5^{+2.0}_{-1.8}$	17.6	4.3 (40s)
091003	0.8969	23	576^{+106}_{-72}	—	$4.7^{+0.6}_{-0.4}$	—	—
090926A	2.1062	13	434^{+32}_{-30}	$\sim$10 or $>$ 21	$167.3^{+11.9}_{-8.4}$	128 or $>$ 222	19.6 (25s)
090902B	1.822	19	885^{+39}_{-38}	$\sim$6 or $\sim$17	$193.3^{+5.9}_{-3.2}$	104 or 257	33.4 (82s)
090510	0.903	0.33	—	—	—	—	30.5 (0.829s)

2. Optical Afterglow and Jet Break

We performed the optical afterglow observations using the Canada France Hawaii Telescope (CFHT)/MegaCam within the framework of the EAFON (e.g. 4,5,6,7). The r'-band monitoring observations covered the duration from 5.2 days to 57.6 days after the burst. Additional g'- and i'-band images were taken on the night of 2010 April 20 (6.2 days after the burst). Because of the bright moon phase, there was no optical observation between 7 and 26 days. The standard CFHT's data pipeline reduced all of the data. The light curves demonstrated the steep decay occurring between 3 and 7 days after the burst. The temporal indices were -2.3, -2.6 ± 0.1 and -2.7 in g'-, r'-, and i'-bands, respectively. The spectral energy distribution (SED) of optical afterglow during the steep decay phase (at $\sim$6.2 days) could be satisfactorily expressed according to a simple power law with the spectral index $\beta = 1.2 \pm 0.2$. Despite the paucity of observations for the optical afterglow, the joint light curve using *Swift*/UVOT strongly suggested a temporal break. The decay indices before and after the break were ~ 1 and ~ 2, respectively, fully consistent with typical well-observed long GRB optical afterglows. To examine whether the jet model is applicable to present afterglow, we utilized the relations (e.g [8]) and calculated p and α based on the observed β. The observed values were in agreement with the calculated value of $\alpha = 2.4 \pm 0.4$, assuming that we were observing a jet expansion phase in the frequency range above the synchrotron cooling. In addition, although the X-ray afterglow observation was also poor, the decay index $\alpha_X = 2.3 \pm 0.4$ between 2.0 and 7.4 days was also consistent with the jet model. The case of wind density profile with $\nu_m < \nu_{opt} < \nu_X < \nu_c$ also satisfied the closure relation. However, it is unlikely for the late (6.2 days) afterglow. We also attempted to fit the g'-band light curve including the UVOT data using the broken power-law model by fixing the temporal decay indices of former and post jet break at -1.3 and -2.6, respectively. The UVOT data were calibrated according to the SDSS field stars that have similar colors to the GRB afterglow, and were converted to g' band magnitudes. We successfully fitted the light curve and obtained the jet break time as $t = 2.3 \pm 0.2$ days. The jet opening angle derived from this temporal break was $\sim 5^\circ.8$, consistent with those of other well-observed long GRBs (e.g. 9 and references therein).

3. Energetic and Correlation

The abundance of the multi-wavelength data for estimating the jet break time makes GRB 100414A one of the most favorable targets for evaluating the $E^{src}_{peak} - E_{iso}$ and $E^{src}_{peak} - E_\gamma$ relations of studies that had stagnated because of a lack of data on the $E^{\rm src}_{\rm peak}$ estimation and long-term optical monitoring. In particular, the current event was the first *Fermi* /LAT detected event exhibiting the clear jet break features. To examine the correlations with the least systematics errors, we collected five LAT-detected events observed using the *Suzaku*/WAM, as summarized in Table 1. The spectral analysis of the WAM data was performed in the same manner as described in Section 2.1. The estimated $E_{\rm iso}$ of GRB 090902B in the 1 keV to 10 MeV range using *Suzaku*/WAM are consistent with the value derived from the *Fermi* /GBM observation[10]. In the case of GRB 090926A, the value is slightly smaller than that of the estimation (2.3×10^{54} erg) using *Fermi* /GBM [11]. The most likely reason for this inconsistency is that the energy range of *Suzaku*/WAM is insufficient in detecting the underlying power-law component in the *Fermi* /LAT-GBM spectrum[12]. GRB 090510 was the short event, and the spectral parameters were not effectively constrained, we excluded this event for the evaluation of correlation. The marginal optical temporal break time $t_{\rm jet}$ of GRB 090926A and GRB 090902B was reported [10,11,13,14]. As summarized in Table 1, the values vary widely according to the estimation methods. We also excluded the GRB 091003 for the evaluation of the $E^{\rm src}_{\rm peak}-E_\gamma$ relation because of a lack of the $t_{\rm jet}$ estimation. Interestingly, the three selected events (GRB 090926A, GRB 090902B and the current one) shared commonality in the delayed highest energy photons from their main burst (GRB 090926A, GRB 090902B).

Figure 1 (Right) shows the $E^{\rm src}_{\rm peak}-E_{\rm iso}$ and $E^{\rm src}_{\rm peak}-E_\gamma$ relations with *Suzaku*/WAM observed LAT-detected events. We found that all four events were highly consistent with previous studies of the $E^{\rm src}_{\rm peak}-E_{\rm iso}$. As shown in Figure 1, the measured values of current event ($E^{\rm src}_{\rm peak}=1458.7^{+132.6}_{-106.6}$ keV and $E_{\rm iso}=34.5^{+2.0}_{-1.8}\times10^{52}$ erg) adhered closely to the $E^{\rm src}_{\rm peak}-E_{\rm iso}$ relation. Although the background GRB physic of this correlation is not yet completely understood, the characteristics of different sub-classes of GRBs become apparent [15] . To compare other categories of the events (e.g., short duration GRBs and sub-energetic events), we plotted them in Figure 1. These features were clearly different from those of the current event. The present event and GRB 090902B were also consistent with $E^{\rm src}_{\rm peak}-E_\gamma$ correlation (Figure 1). In the case of GRB 090926A, E_γ thoroughly depends on the jet break time estimation.

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