

# Optical Behavior of GRB 061121 around its X-Ray Shallow Decay Phase

T. Uehara<sup>1</sup>, M. Uemura<sup>2</sup>, A. Arai<sup>3</sup>, R. Yamazaki<sup>4</sup>, K. S. Kawabata<sup>2</sup>, M. Ohno<sup>5</sup>, Y. Fukazawa<sup>1</sup>, T. Ohsugi<sup>2</sup>, M. Yoshida<sup>2</sup>, S. Sato<sup>6</sup>, and M. Kino<sup>6</sup>

(Affiliations can be found after the references)

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## ABSTRACT

**Aims.** We report on a detailed study of the optical afterglow of GRB 061121 with our original time-series photometric data. In conjunction with X-ray observations, we discuss the origin of its optical and X-ray afterglows.

**Methods.** We observed the optical afterglow of *Swift* burst GRB 061121 with the Kanata 1.5-m telescope at Higashi-Hiroshima Observatory. Our observation covers a period just after an X-ray plateau phase. We also performed deep imaging with the Subaru telescope in 2010 in order to estimate the contamination of the host galaxy.

**Results.** In the light curve, we find that the optical afterglow also exhibited a break as in the X-ray afterglow. However, our observation suggests a possible hump structure or a flattening period before the optical break in the light curve. There is no sign of such a hump in the X-ray light curve.

**Conclusions.** This implies that the emitting region of optical was distinct from that of X-rays. The hump in the optical light curve was possibly caused by the passage of the typical frequency of synchrotron emission from another forward shock distinct from the early afterglow. The observed decay and spectral indices are inconsistent with the standard synchrotron-shock model. Hence, the observation requires a change in microphysical parameters in the shock region or a prior activity of the central engine. Alternatively, the emission during the shallow decay phase may be a composition of two forward shock emissions, as indicated by the hump structure in the light curve.

**Key words.** gamma rays: bursts

## 1. Introduction

Gamma-ray bursts (GRBs) and their afterglows are widely believed to be emission from relativistically expanding shells (e.g., Zhang & Mészáros 2004; Mészáros 2006). GRBs, or prompt emissions are considered to arise from internal shocks caused by collisions between the shells. After the collisions, the shell keeps expanding and generates an external shock colliding with the interstellar medium. As a result, synchrotron emission from the shocked region is observed as afterglows. This synchrotron-shock model successfully reproduces the observed temporal evolution of spectral energy distributions (SEDs) of late afterglows. According to this model, the flux of the synchrotron emission from afterglows is described with a power-law form, that is,  $f_i(t) \propto t^{-\alpha} \nu^{-\beta}$ , where  $\alpha$  and  $\beta$  are a decay index and a spectral slope, respectively (Sari et al., 1998). A jet geometry was suggested by an achromatic break observed in light curves of afterglows (e.g., Rhoads, 1997; Sari et al., 1999). This has recently been called into question because chromatic breaks were detected at the time when the jet scenario predicts achromatic ones (Willingale et al., 2007).

Owing to quick identifications and notifications of GRBs by the *Swift* satellite, the number of observations of early afterglows has been increasing in all wavelengths (Gehrels et al., 2004). X-ray light curves of early afterglows, in particular, turned out to have more complicate profiles than those previously expected from the standard synchrotron-shock model. Although a simple power-law decay was expected in the standard model, the early X-ray light curves actually consist of three stages with different decay indices; the initial steep decay ( $\alpha \sim 3 - 5$ ), the shallow decay ( $\alpha \sim 0.5 - 1.0$ ), and the normal decay phases ( $\alpha \sim 1$ ) (Nousek et al. 2006; O’Brien et al. 2006). While the steep decay

phase is likely a high-latitude emission of the prompt emission (Kumar, Panaitescu 2000; Yamazaki et al. 2006; Liang et al. 2006; Zhang et al. 2006), the origin of the shallow decay phase is currently unknown. Several models have been proposed for this phase, for example, the late energy injection into the shocked region, the time-dependent microphysics in the shock, or prior outflow emission (Sari, Meszaros 2000; Nousek et al. 2006; Zhang, Mészáros 2001; Panaitescu et al. 2006; Toma et al. 2006; Ioka et al. 2006; Dado et al. 2006; Yamazaki 2009).

Each of those models predicts distinct behaviors of SED variations in early afterglows. Simultaneous multiwavelengths observations are required to provide crucial clues on the nature of the early afterglow phase. Panaitescu et al. (2006) reported that the early break after the shallow decay phase is chromatic on the basis of 6 afterglows. Yost et al. (2007) additionally reported that GRB 051109A also exhibited a clear chromatic break. Panaitescu et al. (2006) proposed that the observed light curves require the temporal evolution of microphysical parameters in the emitting region of early and late afterglows. On the other hand, some afterglows apparently exhibited achromatic breaks after the X-ray shallow decay phase. Krühler et al. (2009) reported on optical—IR and X-ray light curves of GRB 080710, in which an achromatic break was observed. Blustin et al. (2006) reported another example of a possible achromatic break in GRB 050525A, while X-ray flares make difficult to accurately determine a break time (also see, Klotz et al. 2005). In some of past cases, optical observations were too sparse to determine break times and to catch the detailed behavior on either side of the breaks. We definitely need new observations in which break times can be determined accurately both in X-ray and optical light curves.

GRB 061121 was detected by the *Swift* Burst Alert Telescope (BAT) at 15:22:29 (UT) 21 November 2006 (Page et al. 2006). *Swift* also reported the discovery of a bright optical afterglow with Ultraviolet/Optical Telescope (UVOT), which was soon confirmed at 14.9 mag<sup>1</sup> by ground-based telescopes (Yost et al. 2006). Its redshift was estimated to be  $z = 1.314$  by spectroscopic observations of the optical afterglow (Bloom et al. 2006). This bright burst is a typical GRB following a well-known empirical relationship between  $E_p$  and  $E_{iso}$  (Amati et al. 2006). The early X-ray light curve has several breaks as other systems observed in the *Swift* era (Nousek et al. 2006). Prompt onsets of multiwavelength observations for GRB 061121 provided a unique opportunity to study the temporal evolution of X-ray and optical afterglows (Yost et al. 2006; Melandri et al. 2006; Uemura et al. 2006). Page et al. (2007) reported on multiwavelength data during the prompt and afterglow phase of this GRB. According to them, both X-ray and optical flux monotonically decayed, which can be described with an early exponential rise followed by a power-law decay phase.

Here we report on our optical and infrared observations using the Kanata 1.5-m telescope. Our continuous time-series observations enabled us to reveal the optical behavior near the X-ray shallow decay phase. We describe the details of our observations in section 2. Combined with other published data, we report the temporal evolution of the optical and X-ray afterglows in section 3. In section 4, we discuss the nature of the variations in the light curves using the synchrotron-shock model. Finally, we summarize our results in section 5.

## 2. Observation and Data Analysis

### 2.1. Optical observations

Our observation started at 16:37 (UT) 21 November 2006,  $4.6 \times 10^3$  s after the GRB trigger time, and ended at 19:57 (UT). The observation was performed with TRISPEC attached to the Kanata 1.5-m telescope at Higashi-Hiroshima Observatory of Hiroshima University. TRISPEC is a simultaneous imager and spectrograph with polarimetry covering both optical and near-infrared wavelengths (Watanabe et al. 2005). We used the imaging mode for the observation of GRB 061121 and obtained 77 sets of  $R_c$ ,  $J$ , and  $K_s$  band images. The exposure time of a  $R_c$ -band image was 123 s. During the 123 s exposure, short exposures of a few seconds were taken for NIR arrays, and yielded net exposures of 120 and 96 s for each  $J$ - and  $K_s$ -band image, respectively.

The central wavelength of the TRISPEC's  $R_c$  system is  $\sim 620$  nm, slightly shifted from the standard one ( $= 645$  nm). The difference in magnitude between these systems is expected to be 0.008 mag when a power law spectrum with a spectral index of 1.0 is assumed. In the following discussion, we neglect this small difference.

We show an example of the obtained images in the right panel of figure 1. We also show the same field in the Second Palomar Sky Survey (POSS2) in the left panel for comparison. The afterglow is the object marked with the black bars. After making dark-subtracted and flat-fielded images, we obtained magnitudes of the afterglow and comparison stars using a Java-based PSF photometry package. For a comparison star, we used USNO-B1.0 0768-0239968 (R.A. =  $9^h48^m54^s.78$ , Dec. =  $-13^\circ1'17''.9$ ;  $R_c = 18.02$ ). The comparison star was constant within 0.02 mag during our observation, checked

**Table 1.** Results of our photometric observation.

| Time (s) <sup>*</sup> | $R_c^{**}$ mag. | $R_c'$ mag <sup>†</sup> . | error | N <sup>‡</sup> |
|-----------------------|-----------------|---------------------------|-------|----------------|
| 4699                  | 18.16           | 18.17                     | 0.03  | 3              |
| 5283                  | 18.23           | 18.24                     | 0.15  | 4              |
| 6261                  | 18.40           | 18.42                     | 0.08  | 2              |
| 6675                  | 18.53           | 18.55                     | 0.09  | 5              |
| 7501                  | 18.63           | 18.66                     | 0.09  | 6              |
| 8427                  | 18.74           | 18.76                     | 0.18  | 7              |
| 9466                  | 18.77           | 18.80                     | 0.10  | 8              |
| 10632                 | 18.92           | 18.95                     | 0.10  | 9              |
| 11941                 | 19.18           | 19.22                     | 0.09  | 10             |
| 13409                 | 19.49           | 19.55                     | 0.23  | 11             |
| 15056                 | 19.10           | 19.14                     | 0.21  | 12             |

\* Time since the GRB trigger.

\*\* Raw  $R_c$  magnitude.

†  $R_c$  magnitude (host corrected).

‡ Number of images in each bin

by USNO-B1.0 0767-0229365 (R.A. =  $09^h49^m05^s.080$ , Dec. =  $-13^\circ13'22''.21$ ). Using neighbor USNO stars, we checked systematic errors of magnitudes depending on comparison stars, and found that it is smaller than 0.2 mag. The comparison star is the same as that used in Halpern et al. (2006a), Halpern and Armstrong (2006a), and Halpern and Armstrong (2006b) which present observations in a late stage of the afterglow. In the following section, we performed an analysis of our light curve in conjunction with those late-time observations.

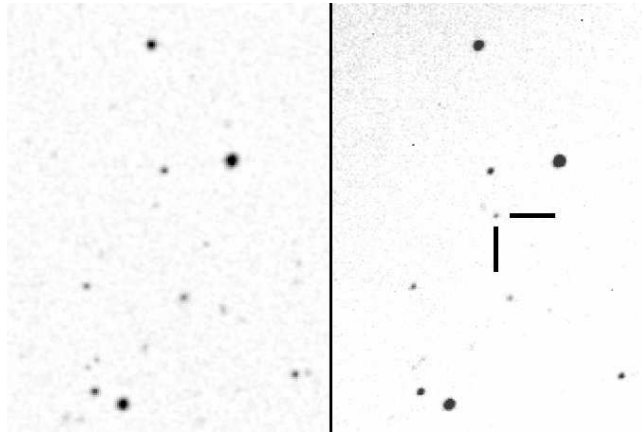
Additionally, table 1 contains  $R_c$ -magnitudes obtained by our optical observations. In this table, the magnitudes are averages in equally spaced bins in the logarithmic scale of the time. While we obtained  $J$  and  $K_s$  band images using TRISPEC, IR afterglows were not significantly detected. Typical 3-sigma upper limits of each frame are 16.0 and 13.7 mag in  $J$  and  $K_s$  bands, respectively.

For deep photometry of the host galaxy component, we obtained  $R_c$ -band images with the 8.2-m Subaru Telescope and the Faint Object Camera and Spectrograph (FOCAS; Kashikawa et al. 2002) on 2010 May 7 (UT). The total exposure time was 240 s. We can easily recognize the host galaxy as a point source at the GRB afterglow position in the obtained image. Using the same comparison star as mentioned above, we derived the magnitude of the host galaxy to be  $R_c = 22.99 \pm 0.03$ .

### 2.2. Data analysis of the *Swift* data

We analyzed public data of GRB 061121 observed with X-Ray Telescope (XRT) and UVOT on *Swift*. We processed the XRT all orbits of data, adopting the standard screening with the XRT pipeline *FTOOL xrtpipeline* (Version: 0.10.3). We extracted light curve and spectra with a rectangular  $40 \times 20$ -pixel region for the Windowed Timing (WT) mode, and 40-pixel radius region for the Photon Counting (PC) mode from the source position, respectively. The background was also extracted from  $40 \times 20$ -pixel region for the WT mode, and 40-pixel radius region for the PC mode, far from the source, respectively. While beginning of GRB for WT mode data and PC mode data, we found that the count rate is high enough to cause the pile-up effect, and we adopted the standard pile-up correction as described by Romano et al. (2006) and Vaughan et al. (2006).

<sup>1</sup> Mag show Vega magnitude in this paper.



**Fig. 1.** Optical images of the field of GRB 061121 in POSS2 (left panel) and observed with the Kanata 1.5-m telescope (right panel). The field of view is  $4' \times 3'$  and the top is north. The afterglow is an object marked with the black bars in the right panel.

In the following section, the unit of time is set to be seconds from the GRB trigger. Optical and X-ray parameters are indicated by subscripts of “O” and “X”, respectively.

### 3. Results

#### 3.1. Optical and X-ray light curves

We show the X-ray and optical light curves of GRB 061121 in figure 2. Our optical observations and X-ray observations by XRT are indicated by the filled circles and crosses, respectively. The open circles and squares are optical observations with  $R_c$ ,  $V$  (“White light” (UVOT) bands reported to GCN, respectively (Page et al. 2007; Yost et al. 2006; Melandri et al. 2006; Sonoda et al. 2006; Marshall et al. 2006; Golenetskii et al. 2006; Halpern et al. 2006b; Cenko 2006; Halpern et al. 2006a; Efimov et al. 2006a; Halpern and Armstrong 2006a,b; Efimov et al. 2006b). About the optical flux, the contribution of the host galaxy is subtracted. The flux density of the host galaxy is  $2.14 \mu Jy$  in  $R_c$ , which was estimated based on our Subaru observation as described in section 2. The flux density was corrected for the Galactic extinction of  $E(B - V) = 0.04$  (Schlegel et al. 1998). The absolute magnitude of the host galaxy is  $-21.86$  mag in  $R_c$ .

According to Page et al. (2007), the X-ray light curve of GRB 061121 is divided into 4 phases depending on their decay indices. In this paper, we follow their definition of the phases for the X-ray light curves, that is, an initial flare, a plateau ( $\alpha_{X1} = 0.38 \pm 0.06$ ), a shallow decay ( $\alpha_{X2} = 1.07 \pm 0.05$ ), and a normal decay phases ( $\alpha_{X3} = 1.53 \pm 0.03$ ). The errors of these parameters, as well as other parameters given in this paper, represent  $1-\sigma$ .

In the optical light curve, we can see a possible flare in a very early phase at  $t = 76$  s. This implies that the optical flux may be associated with the prompt emission in X-rays and  $\gamma$ -rays in this phase (Page et al., 2007). In the X-ray plateau phase, the optical light curve can be described with a simple power-law decay. Using  $V$ -band observations by UVOT from 240 to 2000 s, we calculated the power-law decay index to be  $\alpha_{O1} = 0.72 \pm 0.08$ .

During the subsequent shallow decay phase, our observation revealed a monotonic fading of the optical afterglow. The light curve can be described with a simple power-law having a decay index of  $\alpha_{O2} = 0.96 \pm 0.06$ . Page et al. (2007) reported a  $V$ -band decay index of  $0.66 \pm 0.04$  from the onset of the fading to a break at  $\sim 2.5 \times 10^4$  s. This decay index was estimated based on

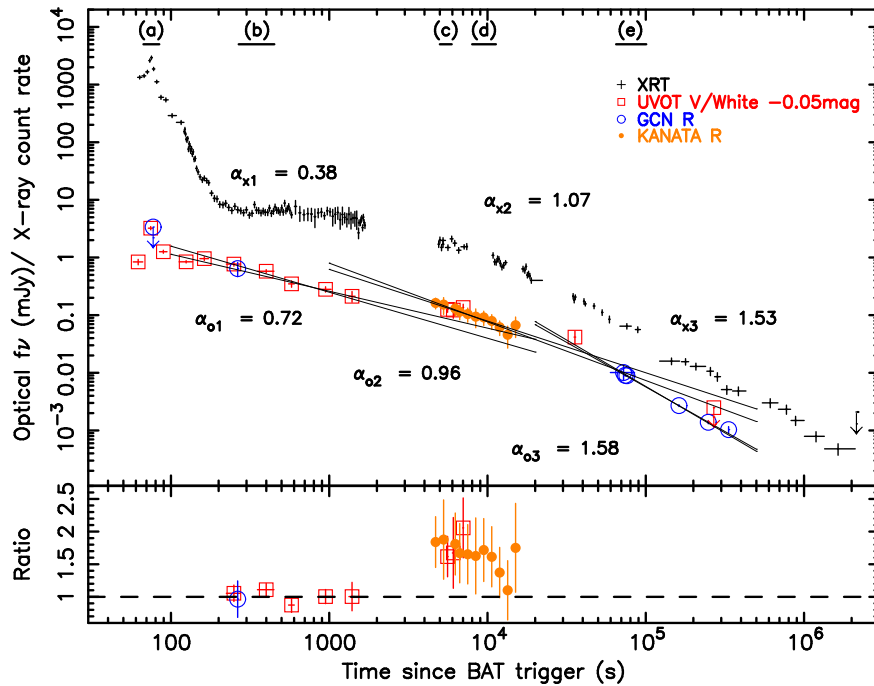
the exponential-to-power-law model, which assumes a monotonic fading during the fading stage of the afterglow. The  $\alpha_{O2}$  estimated from our time-series photometry is, however, significantly larger than that reported in Page et al. (2007). We tried to fit a simple power-law model to the optical light curve from 240 s to 16 ks including our data. For the fitting, our  $V$ -band data was shifted to corresponding  $R_c$ -band magnitude. The  $V - R_c$  of the afterglow was estimated from two almost simultaneous  $V$ - and  $R_c$ -band observations, that is,  $t \sim 280$  and  $\sim 6300$  s. The average color of the afterglow is calculated to be  $V - R_c = 0.05$ . The best-fitted parameters yield a chi-square/d.o.f of 76.3/15. This value is too high to conclude that the afterglow decayed with a simple power-law form from 240 s to 16 ks, and rather suggests that there is a sub-structure around the termination of the X-ray plateau phase.

The optical light curve, then, exhibit another break around  $3 \times 10^4$  s, which is followed by the normal decay phase described with  $\alpha_{O3} = 1.58 \pm 0.03$ . By fitting a broken power-law model, we calculated a break time of  $4.6_{-2.3}^{+4.5} \times 10^4$  s. About the last break from the shallow decay to the normal decay phase, no significant time lag is detected between the X-ray and optical breaks, while the errors of break times are quite large;  $3.2_{-0.6}^{+2.1} \times 10^4$  s and  $4.6_{-2.3}^{+4.5} \times 10^4$  s for the X-ray and optical break times, respectively. It is noteworthy that the optical decay index is almost same as the X-ray one after this break. According to the standard synchrotron shock model, this strongly indicates the passage of the cooling frequency of the synchrotron emission within the optical band at the break time.

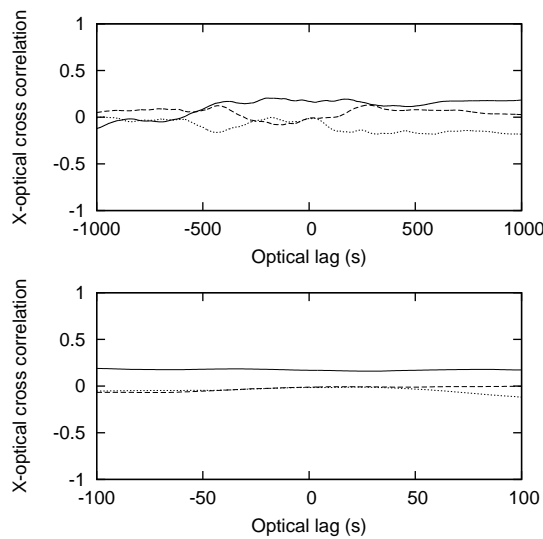
We searched possible correlations between X-ray and optical short-term variations. We calculated cross-correlations using 3 segments in which simultaneous optical and X-ray data are available. The optical data was divided into the following parts; i)  $4.8 \times 10^3$  s  $< t < 7.5 \times 10^3$  s, ii)  $1.0 \times 10^4$  s  $< t < 1.4 \times 10^4$  s, and iii)  $1.6 \times 10^4$  s  $< t < 1.9 \times 10^4$  s. The resultant cross-correlations are shown in figure 3. The correlation functions are flat and show no prominent feature. We cannot detect any significant correlations between optical and X-ray short-term variations.

#### 3.2. Spectral energy distribution

Figure 4 shows infrared–X-ray SEDs. The figure contains 5 panels in which simultaneous optical and X-ray observations are shown for the 5 phases. We fitted a power-law model with a single absorption component for the X-ray spectra. All 5 spectra



**Fig. 2.** Optical and X-ray light curves of GRB 061121 afterglows. The abscissa denote the time since the GRB trigger in seconds. In the top panel, the ordinate denote the flux density in mJy for optical data and the count rate for X-ray data observed with XRT. Our observations and X-ray observations by XRT are indicated by the filled circles and crosses, respectively. Open circles and squares are optical observations with  $R_c$  and V/White light (UVOT) bands reported to GCN or taken by UVOT, respectively. The solid lines are 95 % confidence regions of the best fitted power-law models for optical light curves. The labels, (a), (b), (c), (d), and (e), represent the time intervals for the SED analysis (see section 3.2). In the bottom panel, the ordinate denote the ratio of the observed flux density to the best-fitted model of the plateau phase. V band points are shifted by  $-0.05$  to match the  $R_c$  band points.



**Fig. 3.** X-ray/optical cross correlations for short-term variations. The solid, dashed, and dotted lines were calculated from the data of  $4.8 \times 10^3 \text{ s} < t < 7.5 \times 10^3 \text{ s}$ ,  $1.0 \times 10^4 \text{ s} < t < 1.4 \times 10^4 \text{ s}$ , and  $1.6 \times 10^4 \text{ s} < t < 1.9 \times 10^4 \text{ s}$ , respectively. The upper and lower panels show correlation functions in long and short time scales, respectively. No significant correlation can be seen.

in figure 4 can be described with absorption models with a hydrogen column density of  $N_H = 2.2 \pm 0.15 \times 10^{21} \text{ cm}^{-2}$  in the observer’s frame, which corresponds to  $N_H = 9.2 \times 10^{21} \text{ cm}^{-2}$  in the rest-frame. The solid lines in the figure indicate the best fitted unabsorbed power-law component of X-ray spectra. As can be seen from the figure, spectral slopes  $\beta$  ( $f_\nu \propto \nu^{-\beta}$ ) were slightly larger in the plateau phase (panel b) and a phase just after the op-

tical break (panel c) than those in later phases. Table 2 contains results of our best fitted parameters in each period.

In the figure, the optical flux was corrected for the galactic and extragalactic extinctions. The correction for the extragalactic extinction was performed with the relationship between the visual extinction  $A_V$  and the hydrogen column density  $N_H$  for the “Q2” model in Maiolino et al. (2001) ( $N_H/A_V = 3.3 \times 10^{21} \text{ cm}^{-2}$ ). We estimated the  $N_H$  from the best-fitted model of

**Table 2.** Best fit parameters for X-ray spectra

| Time interval (s)                       | $\beta$         | $\chi^2/\text{d.o.f}$ |
|---|-----------------|-----------------------|
| $6.7 \times 10^1 < t < 8.7 \times 10^1$ | $0.09 \pm 0.01$ | 267/195               |
| $4.3 \times 10^2 < t < 5.4 \times 10^2$ | $1.39 \pm 0.04$ | 19/17                 |
| $5.0 \times 10^3 < t < 6.0 \times 10^3$ | $1.34 \pm 0.05$ | 14/12                 |
| $8.0 \times 10^3 < t < 1.2 \times 10^4$ | $1.16 \pm 0.04$ | 10/9                  |
| $6.5 \times 10^4 < t < 1.0 \times 10^5$ | $1.12 \pm 0.09$ | 10/9                  |

X-ray spectra, and set to  $N_H = 9.2 \times 10^{21} \text{ cm}^{-2}$  as mentioned above. The conversion from  $A_V$  to those in other bands was performed following the equations in Cardelli et al. (1989).

For the correction of the extragalactic extinction, we used the “Q2” model because it provides the most plausible optical–IR SEDs, as shown below. According to the synchrotron-shock model, the spectral slope at the optical region should be  $\beta_O = \beta_X - 0.5$  in the case of  $\nu_m < \nu_O < \nu_c < \nu_X$ , where  $\nu_m$  and  $\nu_c$  are typical and cooling frequencies of the synchrotron emission from a forward shock (Sari et al. 1998). In figure 4, we show the expected spectral slope of  $\beta_O = \beta_X - 0.5$  with  $\nu_c = 10^{18} \text{ Hz}$ , indicated by the dotted lines. The optical flux is required to be over this dotted lines in order to satisfy the condition expected by the synchrotron-shock model. In addition to the “Q2” model, the figure also contains optical–IR points corrected with the Milky Way model ( $N_H/A_V = 1.6 \times 10^{21} \text{ cm}^{-2}$ ; open triangles) and with the “Q1” model ( $N_H/A_V = 6.7 \times 10^{21} \text{ cm}^{-2}$ ; open squares)(Maiolino et al. 2001). As can be seen in panel (c), a high  $A_V$  provided by the Milky Way model yields an unnaturally sharp break between  $R_c$  and  $J$ -bands. Corrected by the “Q1” model, the optical flux is too low to be interpreted by the synchrotron-shock model with  $\beta_O = \beta_X - 0.5$ . The models for SMC ( $N_H/A_V = 1.5 \times 10^{22} \text{ cm}^{-2}$ ) and LMC ( $N_H/A_V = 7.6 \times 10^{21} \text{ cm}^{-2}$ ) also yield further lower optical flux. Thus, the “Q2” model provides the best correction among those models.

Near the peak of the prompt emission, as can be seen in panel (a) of figure 4, the optical flux is much above the power-law component of X-rays. This indicates that the emission mechanism or source of the optical emission is distinct from those of the prompt X-ray and  $\gamma$ -ray emission.

In panel (c) of figure 4, there is a difference between the optical flux and the spectrum extrapolated from the X-ray data (the solid line in the figure). The SED, hence, requires a spectral break between the optical and X-ray bands. This is consistent with the situation for the case of  $\nu_m < \nu_O < \nu_c < \nu_X$ . In the standard model,  $\nu_c$  evolves with time, decreasing in case of constant density medium, increasing in case of wind medium. Since our findings privilege a constant density medium as discussed in subsection 4.2, we expect at one point that  $\nu_c$ , decreasing with time, will cross the optical band. At that time, the optical and X-ray decay will become identical, and the SED will be compatible with a simple power law. This is the case in panel (e), suggesting that  $\nu_c$  crossed the optical band around  $t = 5 \times 10^4 \text{ s}$ .

## 4. Discussion

### 4.1. A possible hump structure in the optical light curve

Here, we discuss the substructure in the optical light curve around 5 ks. The behavior of the optical and X-ray light curves is unclear in the transition phase from the plateau to the shallow decay phases ( $1.5 \times 10^3 \text{ s} \lesssim t \lesssim 4.6 \times 10^3 \text{ s}$ ). In figure 2, the

solid lines denote 95 % confidence regions of the power-law decay model for each phase of the optical afterglow. As indicated by these lines, our observation suggests that the plateau phase is terminated by a flattening phase or a hump in the optical afterglow.

We checked the significance of this hump with a correction of colors, because the best-fitted models were calculated with data taken with different bands; the  $V$ - and  $R_c$ -band observations in the plateau and shallow decay phases, respectively. The lower panel of figure 2 shows the ratio of the observations to the best-fitted model of the plateau phase. We converted  $V$ -band observations to our  $R_c$ -band ones, by adding  $V - R_c = 0.05$  to the  $V$ -magnitudes. The hump appears over a 2.2-sigma level even with the color correction.

By contrast, there is no sign of such a hump in the X-ray light curve between those two phases. In addition, there is a large difference in the optical and X-ray decay indices in the plateau phase, compared with those in the subsequent shallow and normal decay phases. The X-ray and optical light curves apparently exhibit different behaviors during the X-ray plateau phase and the transition phase to the shallow decay phase.

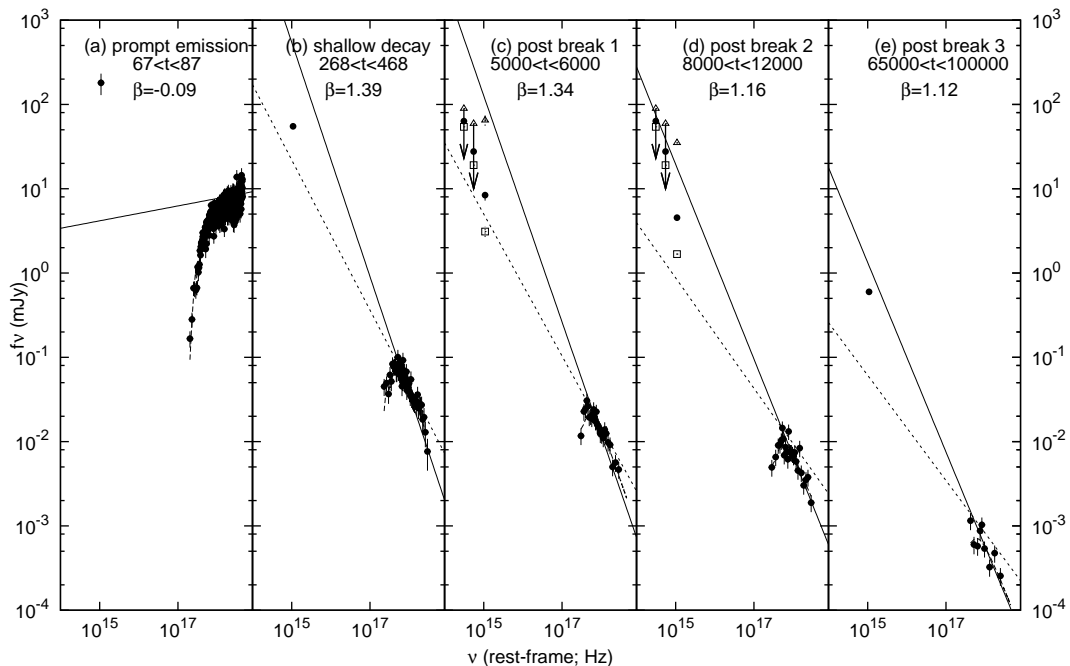
### 4.2. Implication to the synchrotron-shock model

In this subsection, we discuss the behavior of the afterglow of GRB 061121 based on the synchrotron-shock model. In the case of  $\nu_m < \nu_O < \nu_c < \nu_X$ , Urata et al. (2007) proposed a relation between the decay indices of the X-ray and optical bands described as  $\alpha_X - \alpha_O = 1/4$ . In the plateau and shallow decay phases of GRB 061121, the  $\alpha_X - \alpha_O$  is  $0.34 \pm 0.10$  and  $0.11 \pm 0.08$ , respectively. The classical synchrotron-shock model, hence, fails to reproduce the observed light curves of GRB 061121 in the shallow decay phase. It can only marginally reproduce the light curve in the plateau phase.

Panaitescu et al. (2006) generalized the formulae of the synchrotron-shock model by including the variations of the energy ( $E$ ) in the blast wave, the energy ratio for electrons and the magnetic field ( $\varepsilon_i$  and  $\varepsilon_B$ ), and the ambient medium ( $n$ ) in the following form;  $E(> \Gamma) \propto \Gamma^{-e}$ ,  $\varepsilon_B \propto \Gamma^{-b}$ ,  $\varepsilon_i \propto \Gamma^{-i}$ , and  $n(r) \propto r^{-s}$ . The decay indices of optical and X-ray light curves are calculated as in equations (9) and (10) in Panaitescu et al. (2006). Using those formulae, we evaluate the presence of the energy injection ( $e > 0$ ) or the time variations of microphysical parameters ( $b \neq 0$  or  $i \neq 0$ ) for GRB 061121.

We first assume  $s = 0$ , namely the uniform distribution of the interstellar medium. In the following examination, we calculate  $p$  from  $\beta$  in each time-interval shown in table 2. For the plateau phase, assuming  $b = 0$  and  $i = 0$ , we find that the optical and X-ray light curves yield inconsistent  $e$ , that is,  $e = 1.32 \pm 0.24$  and  $4.05 \pm 0.37$  calculated from  $\alpha_{O1}$  and  $\alpha_{X1}$ , respectively. This inconsistency can be reconciled only when  $s$  takes a narrow range of  $s = 1.22 \pm 0.01$  and  $e$  takes an unnaturally large value ( $e \sim 7$ ). In the other case of  $s > 0$ , the inconsistency in  $e$  becomes more extreme. These results indicate that the observed light curves during the plateau phase cannot be reproduced only with the energy injection scenario. Temporal variations of the microphysical parameters are, hence, required. Assuming  $e = 0$  and  $s = 0$ , we obtain  $b = -2.10 \pm 0.36$  and  $i = 2.04 \pm 0.12$ . The positive  $i$  implies a low efficiency of the energy for accelerating electrons in highly relativistic shocks.

During the shallow decay phase after the optical hump, the decay indices changed to  $\alpha_{O2} = 0.96$  and  $\alpha_{X2} = 1.07$ . Even in this phase, the condition of  $b = 0$  and  $i = 0$  yields different  $e$  values calculated from  $\alpha_{O2}$  (yielding  $e = 0.64 \pm 0.20$ ) and  $\alpha_{X2}$



**Fig. 4.** Spectral energy distributions derived for the time intervals of (a)  $6.7 \times 10^1 \text{ s} < t < 8.7 \times 10^1 \text{ s}$ , (b)  $4.3 \times 10^2 \text{ s} < t < 5.4 \times 10^2 \text{ s}$ , (c)  $5.0 \times 10^3 \text{ s} < t < 6.0 \times 10^3 \text{ s}$ , (d)  $8.0 \times 10^3 \text{ s} < t < 1.2 \times 10^4 \text{ s}$ , and (e)  $6.5 \times 10^4 \text{ s} < t < 1.0 \times 10^5 \text{ s}$ . The time intervals of the SEDs for each panel are indicated in figure 2. The abscissa and ordinate denote the rest-frame frequency in Hz and the flux density in mJy, respectively. The filled circles are X-ray observations by XRT, optical observations reported to GCN, and our optical—IR observations. The IR observations just provide upper limits of the flux. For the extragalactic extinction, the optical and IR data were corrected with the “Q2” model (Maiolino et al. 2001). The open triangles and squares are data in which their corrections for the extinctions were performed with the Milky Way model and the “Q1” model, respectively (Guidorzi et al. 2007). We omit arrows indicating upper limits of the IR points of the open triangles and squares. The solid lines represent the best fitted power-law model for the X-ray spectra. The dotted lines are expected spectral slopes from the synchrotron-shock model.

( $e = 1.19 \pm 0.25$ ). Assuming  $e = 0$ , we obtain  $b = -0.50 \pm 0.27$  and  $i = 0.75 \pm 0.12$  for this phase. It is interesting to note that the absolute values of both  $b$  and  $i$  decreases from the plateau to shallow decay phases. From the early to late stages, the condition of the blast wave may resemble the classical picture in which no temporal variation in the microphysical parameters is required. Thus, the model proposed by Panaitescu et al. (2006) can explain the light curves in both the plateau and shallow decay phases by changing the microphysical parameters.

An alternative model was proposed by Ioka et al. (2006), which consider prior activities before the main prompt emission. According to their model, the shallow decay of X-ray afterglows appears because a blast wave obtains additional energy by colliding with prior ejecta without significant decelerating of shells. This model is possibly preferable for GRB 061121, since it has a precursor  $\sim 75 \text{ s}$  before the peak of the main prompt emission (Page et al. 2007). The precursor may be a sign of the existence of the prior activity.

Ioka et al. (2006) define the the prior ejected mass as a power-law form of  $\gamma$ , that is,  $M(< \gamma) \propto \gamma^a$ . The decay indices of X-ray and optical afterglows are given with  $\alpha_X = (a - 3)/2 + (a - 11)(p - 2)/8$  and  $\alpha_O = (7a - 25)/8 + (a - 11)(p - 2)/8$  in the case of  $v_m < v_O < v_c < v_X$ , respectively. For the plateau phase of GRB 061121, the X-ray and optical decay indices provide a consistent  $a$  within errors for possible values of  $p$  ( $2.2 \gtrsim p \gtrsim 2.8$ ). In the case of  $p = 2.78$ , for example, we obtained  $a = 4.94 \pm 0.48$  from  $\alpha_{X1}$  and  $a = 5.05 \pm 0.10$  from  $\alpha_{O1}$ . For the shallow decay phase, assuming  $p = 2.68$ , for example, we calculated  $a = 5.99 \pm 0.44$  from  $\alpha_{X2}$  and  $a = 5.23 \pm 0.10$  from  $\alpha_{O2}$ . Thus,

the decay indices of the plateau and shallow decay phases can be reproduced with the prior activity model proposed by Ioka et al. (2006), while a temporal variation of  $a$  would be needed.

Both models in Panaitescu et al. (2006) and Ioka et al. (2006) can explain the observed light curves of GRB 061121, only when time variations in  $b$ ,  $i$ , or  $a$  are allowed. The situation is further confusing when we consider the presence of the optical hump between the plateau and shallow decay phases. The discontinuity around the hump indicates a variation of the optical decay index, which means a further variation in  $b$ ,  $i$ , or  $a$  during the hump.

The hump in the optical light curve between the plateau and shallow decay phases is apparently not seen in the X-ray light curve. This implies that the dominant emitting regions are different in X-ray and optical afterglows around the hump. The hump structure reminds us of the two-component jet model; the hump may be explained with a scenario that the emission from a narrow jet may dominate in the plateau phase, while that from a wide jet became dominant after the hump (Sheth et al. 2003; Peng et al. 2005). In this case, the hump structure may appear when  $v_m$  of the synchrotron emission from the wide jet passes the optical band. The classical synchrotron-shock model failed to reproduce the light curves possibly because of the composition of the two components in the plateau and shallow decay phases.

In the standard synchrotron-shock model, an increase of the density of the shock region would produce a hump in the optical light curve which is not seen in X-rays if  $v_c$  lies between the optical and X-ray bands (Panaitescu and Kumar 2000). Hence,

the optical hump of GRB 061121 may also be reproduced if the external shock passed through a high density region in the inter-stellar medium at  $t = 2\text{--}6$  ks.

We finally note that there are several sources which exhibit optical light curves analogous to GRB 061121, that is, GRB 021004 (Uemura et al. 2002), GRB 050525A (Klotz et al. 2005; Blustin et al. 2006), GRB 060117 (Jelínek et al. 2006), GRB 060526 (Dai et al. 2007), and GRB 061007 (Mundell et al. 2007). For all of them, an early decay phase was terminated by a flattening or a hump at  $10^{2-4}$  s, which was followed by a steeper decay phase. An important point is that the decay indices before and after the flattening phase are different each other. This characteristic feature may commonly be observed in a group of GRB afterglows. If the emission during the early decay phase has a different nature from that during the later decay phase, the relationship of those two components possibly causes the diversity in light curves of optical afterglows and the correlation between early X-ray and optical light curves.

## 5. Summary

We performed time-series photometry of the optical afterglow of GRB 061121 with the 1.5-m Kanata telescope, and reported on a detailed study of the afterglow with published X-ray and optical data. The decay index of the optical light curve was significantly different between the plateau and shallow decay phases. The optical light curve possibly has a hump structure between the plateau and shallow decay phases, while no sign of such a hump is seen in the X-ray light curve. The different behavior in the optical and X-ray light curves indicates that they have distinct emitting sources. The hump structure in the optical light curve may imply a passage of the typical frequency of the synchrotron emission from another forward shock distinct from the early afterglow. The optical decay index became same as the X-ray one in the late phase after the final break at  $\sim 4.6 \times 10^4$  s. In conjunction with the temporal evolution of SEDs, we propose that this break is caused by the passage of the cooling frequency at the optical band. In both the plateau and shallow decay phases, the observed decay and spectral indices are inconsistent with the standard synchrotron-shock model. They require the variation of microphysical parameters in the shock region or the prior activity of the central engine. It is also possible that they are due to the composition of two forward shock components if the hump structure in the light curve was caused by another forward shock.

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## References

- Amati, L., Frontera, F., Guidorzi, C., & Montanari, E. 2006, GRB Coordinates Network, 5848, 1
- Bloom, J. S., Perley, D. A., & Chen, H. W. 2006, GRB Coordinates Network, 5826, 1
- Blustin, A. J., Band, D., Barthelmy, S., Boyd, P., Capalbi, M., Holland, S. T., Marshall, F. E., Mason, K. O., et al. 2006, ApJ, 637, 901
- Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
- Cenko, S. B. 2006, GRB Coordinates Network, 5844, 1
- Dado, S., Dar, A., & De Rújula, A. 2006, ApJ, 646, L21
- Dai, X., Halpern, J., Morgan, N., Armstrong, E., Mirabal, N., Haislip, J., Reichart, D., & Stanek, K. 2007, ApJ 658, 509
- Efimov, Y., Rumyantsev, V., & Pozanenko, A. 2006a, GRB Coordinates Network, 5850, 1
- Efimov, Y., Rumyantsev, V., & Pozanenko, A. 2006b, GRB Coordinates Network, 5870, 1
- Gehrels, N., Chincarini, G., Giommi, P., Mason, K. O., Nousek, J. A., Wells, A. A., White, N. E., Barthelmy, S. D., et al. 2004, ApJ, 611, 1005
- Golenetskii, S., Aptekar, R., Mazets, E., Pal'shin, V., Frederiks, D., & Cline, T. 2006, GRB Coordinates Network, 5837, 1
- Guidorzi, C., Gomboc, A., Kobayashi, S., Mundell, C. G., Rol, E., Bode, M. F., Carter, D., La Parola, V., et al. 2007, A&A, 463, 539
- Halpern, J. P., Mirabal, N., & Armstrong, E. 2006b, GRB Coordinates Network, 5840, 1
- Halpern, J. P., Mirabal, N., & Armstrong, E. 2006a, GRB Coordinates Network, 5847, 1
- Halpern, J. P. & Armstrong, E. 2006a, GRB Coordinates Network, 5851, 1
- Halpern, J. P. & Armstrong, E. 2006b, GRB Coordinates Network, 5853, 1
- Ioka, K., Toma, K., Yamazaki, R., & Nakamura, T. 2006, A&A, 458, 7
- Jelínek, M., Prouza, M., Kubánek, P., Hudec, R., Nekola, M., Řídký, J., Grygar, J., Boháčová, M., et al. 2006, A&A, 454, L119
- Kashikawa, N. et al. 2002, PASJ, 819, 54
- Klotz, A., Boer, M., Atteia, J. L., Stratta, G., Behrend, R., Malacrino, F., & Damerjji, Y. 2005, A&A, 439, L35
- Krühler, T., Greiner, J. & Afonso, P. 2009, A&A, 508, 593
- Kumar, P. & Panaitescu, A. 2000, ApJ, 541, L51
- Liang, E. W., Zhang, B., O'Brien, P. T., Willingale, R., Angelini, L., Burrows, D. N., Campana, S., Chincarini, G., et al. 2006, ApJ, 646, 351
- Maiolino, R., Marconi, A., & Oliva, E. 2001, A&A, 365, 37
- Marshall, F. E., Holland, S. T., & Page, K. L. 2006, GRB Coordinates Network, 5833, 1
- Melandri, A., Guidorzi, C., Mundell, C. G., Steele, I. A., Smith, R. J., Monfardini, A., Carter, D., Kobayashi, S., et al. 2006, GRB Coordinates Network, 5827, 1
- Mészáros, P. 2006, Reports on Progress in Physics, 69, 2259
- Mundell, C. G., Melandri, A., Guidorzi, C., Kobayashi, S., Steele, I. A., Malesani, D., Amati, L., D'Avanzo, P., et al. 2007, ApJ, 660, 489
- Nousek, J. A., Kouveliotou, C., Grupe, D., Page, K. L., Granot, J., Ramirez-Ruiz, E., Patel, S. K., Burrows, D. N., et al. 2006, ApJ, 642, 389
- O'Brien, P. T., Willingale, R., Osborne, J., Goad, M. R., Page, K. L., Vaughan, S., Rol, E., Beardmore, A., et al. 2006, ApJ, 647, 1213
- Page, K. L., Sakamoto, T., Marshall, F. E., Barthelmy, S. D., Burrows, D. N., Roming, P., & Gehrels, N. 2006, GCN Report, 15.1
- Page, K. L., Willingale, R., Osborne, J. P., Zhang, B., Godet, O., Marshall, F. E., Melandri, A., Norris, J. P., et al. 2007, ApJ, 663, 1125
- Panaitescu, A. and Kumar, P. 2000, ApJ, 543, 66
- Panaitescu, A., Meszaros, P., Burrows, D., Nousek, J., Gehrels, N., O'Brien, P., & Willingale, R. 2006, MNRAS, 369, 2059
- Peng, F., Konigel, A., & Granot, J. 2005, ApJ, 626, 966
- Piran, T. 1999, Phys. Rep., 314, 575
- Rhoads, J. E. 1997, ApJ, 487, L1
- Romano, P., Campana, S., Chincarini, G., Cummings, J., Cusumano, G., Holland, S. T., Mangano, V., Mineo, T., et al. 2006, A&A, 456, 917
- Rykoff, E. S., Mangano, V., Yost, S. A., Sari, R., Aharonian, F., Akerlof, C. W., Ashley, M. C. B., Barthelmy, S. D., et al. 2006, ApJ, 638, L5
- Sari, R. & Meszaros, P. 2000, ApJ, 535, L33
- Sari, R. & Piran, T. 1999, ApJ, 517, L109
- Sari, R., Piran, T., & Halpern, J. P. 1999, ApJ, 519, L17
- Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
- Sheth, K. Frail, D. A., White, S., Das, M., Bertoldi, F., Walter, F., Kulkarni, S., & Berger, E. 2003, ApJ, 595, L33
- Sonoda, E., Maeno, S., Hara, T., Matsumura, T., Tanaka, K., Tanaka, H., & Yamauchi, M. 2006, GRB Coordinates Network, 5830, 1
- Toma, K., Ioka, K., Yamazaki, R., & Nakamura, T. 2006, ApJ, 640, L139
- Uemura, M., Arai, A., & Uehara, T. 2006, GRB Coordinates Network, 5828, 1
- Uemura, M., Kato, T., Ishioka, R., & Yamaoka, H. 2002, PASJ, 55, L31
- Urata, Y., Yamazaki, R., Sakamoto T., & Huang, K. 2007, ApJ, 668, L95
- Vaughan, S., Goad, M. R., Beardmore, A. P., O'Brien, P. T., Osborne, J. P., Page, K. L., Barthelmy, S. D., Burrows, D. N., et al. 2006, ApJ, 638, 920
- Watanabe, M., Nakaya, H., Yamamuro, Y., Zenno, T., Ishii, M., Okada, M., Yamazaki, A., Yamanaka, Y., et al. 2005, PASP, 117, 870
- Willingale, R., et al. 2007, ApJ, 662, 1093
- Yamazaki, R., Toma, K., Ioka, K., & Nakamura, T. 2006, MNRAS, 369, 311
- Yamazaki, R. 2009, ApJ, 690, L118
- Yost, S. A., Schaefer, B. E., & Yuan, F. 2006, GRB Coordinates Network, 5284, 1
- Yost, S. A., Swan, H. F., Rykoff, E. S., Aharonian, F., Akerlof, C. W., Alday, A., Ashley, M. C. B., Barthelmy, S., et al. 2007, ApJ, 657, 925

- Zhang, B., Fan, Y. Z., Dyks, J., Kobayashi, S., Mészáros, P., Burrows, D. N., Nousek, J. A., & Gehrels, N. 2006, *ApJ*, 642, 354  
Zhang, B. & Mészáros, P. 2001, *ApJ*, 552, L35  
Zhang, B. & Mészáros, P. 2004, *International Journal of Modern Physics A*, 19, 2385
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<sup>1</sup> Department of Physical Science, Hiroshima University, 1-3-1 Kagamiyama, Higashi-Hiroshima 739-8526, Japan  
e-mail: uehara@hep01.hepl.hiroshima-u.ac.jp

<sup>2</sup> Hiroshima Astrophysical Science Center, Hiroshima University, 1-3-1 Kagamiyama, Higashi-Hiroshima 739-8526, Japan

<sup>3</sup> Faculty of Science, Kyoto Sangyo University, Motoyama, Kamigamo, Kita-Ku, Kyoto-City 603-8555, Japan

<sup>4</sup> Department of Physics and Mathematics, Aoyama Gakuin University, 5-10-1 Fuchinobe, Sagamihara 252-5258, Japan

<sup>5</sup> Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku Sagamihara, Kanagawa 252-5120, Japan

<sup>6</sup> Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8602, Japan