Structure in the early afterglow lightcurve of the \(\gamma\)-ray burst of 29 March 2003

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Gamma-ray bursts (GRBs) are energetic explosions that for 0.01–100 s are the brightest \(\gamma\)-ray sources in the sky.\(^\text{1,2}\) Observations of the early evolution of afterglows we expected to provide clues about the nature of the bursts, but their rapid fading has hampered such studies; some recent rapid localizations\(^\text{3-5}\) of bursts have improved the situation. Here we report on an early detection of the very bright afterglow of the burst of 29 March 2003 (GRB030329). Our data show that, even early in the afterglow phase, the light curve shows unexpectedly complicated structures superimposed on the fading background.

GRB030329 was detected by the HETE-2 satellite on 29 March 2003 at 11:37:14.67 UT.\(^\text{6}\) A prompt identification of its burst position, which was notified 0.051 d after the burst, enabled observers to make observations during an early phase of the afterglow of the GRB. A new very bright optical source of magnitude 12 was discovered within the error circle of the GRB position, and then continuously monitored by a number of observers.\(^\text{7}\)
Optical spectroscopic observations determined its redshift to be $z = 0.168$, and using this, its isotropic released energy was calculated to be $E_{\text{iso}} = 8 \times 10^{51}$ erg s$^{-1}$ (30–400 keV). In the 30-years of studying GRBs, this GRB afterglow is the closest except for the suspected supernova associated with GRB980425.[12]

We initiated time-series CCD photometric observations on 29 March 2003 at 12:53:41 UT, about 0.053 days after the burst, at Kyoto University, with 25- and 30-cm telescopes. After the observation at Kyoto, observations at Saitama, the Dynic Astronomical Observatory, and the Bronberg Observatory started with 20-cm, 60-cm, and 30-cm telescopes, respectively. Follow-up observations were performed on 30 March 30, 3, 5, and 6 April at Kyoto, on 30 March at Hida, and on 30 and 31 March at Bronberg. A dark-current image was subtracted from obtained CCD images, and then flat-fielding was performed. We calculated the magnitudes of the afterglow with neighbour comparison stars (GSC1434.239, GSC1434.129, and GCS1434.192), whose constancy was better than 0.04 mag during our observation. Our unfiltered CCD observation yields a magnitude system near that of the $R_c$-system, since the sensitivity peak of the camera is near to the peak of the $R_c$-system, and the spectra of early afterglows have a smooth continuum without strong emission lines or absorption edges in the optical range. The difference between our unfiltered CCD and the $R_c$-system is less than 0.02 mag when the spectrum is described with a simple power law ($f(\nu) \propto \nu^p$) with index, $-2.0 < p < 0.3$, as expected in GRB optical afterglows.[13]

Our obtained light curve is shown in Fig. 1. In Fig. 1a, the abscissa and the ordinate denote the time from the burst in days and the $R_c$-magnitude, respectively. To date, the light curve of afterglows, in particular during the early phase of $\lesssim 0.1$ days, has been sampled only sparsely, which has been insufficient to observationally verify theoretical models. As can be seen in this figure, we succeeded in obtaining a completely continuous light curve from 0.053 to 0.500 days, or for 11 hours in GRB030329, which reveals the presence of unambiguous detailed structures in the light curve of early afterglows.

The light curve of the GRB030329 afterglow exhibits clear, and repeating deviations from a canonical power-law model. The dotted line in Fig. 1a is the best fitted power-law model using our light curve and the GRB Coordinates Network data between 0.5 and 10 days. The average decay index, $\alpha$ ($f \propto t^\alpha$) is calculated to be $-1.115 \pm 0.006$. This is
a standard value for early afterglows of GRBs. As can be seen in the figure, the fading of the afterglow cannot be described only by this simple model. The residual from the single power-law model is shown in Fig. 1b. During the first day, the light curve can be described with four segments, that is, two sets of ascending and descending branches of bumps. Their transitions were not smooth, but occurred in short timespans. A relatively rapid fading presumably follows these bumps. At the end of the first day, the afterglow ceased fading, and then, experienced a rebrightening. While they were sampled only partially, the light curve shows that the bumps after 1 d had a rising time-scale of 0.1 day. It is interesting to note that an early bump around 0.4 day in Fig. 1 had a timescale of the same order as the later bumps. This similarity might imply that these large (amplitude \( \sim 0.4–0.5 \text{ mag} \)) bumps were of the same nature.

The afterglow of GRBs is now widely believed to be synchrotron emission from a forward shock region in an expanding jet colliding with ambient medium, whereas the GRB itself is from an internal shock region between shells.\(^\text{12, 14}\) In a number of afterglows, it is well known that light curves show a sudden increase of the fading rate due to the jet geometry, typically a few days after the burst.\(^\text{15, 16}\) In the case of GRB030329, this jet break is expected to appear later than 60 days from its isotropic energy and redshift.\(^\text{17, 18}\) This indicates that the jet break is expected not to appear in Fig. 1, and hence, it is difficult to explain the variation in Fig. 1 with the jet break. As well as the jet break, another well-known phenomenon, the supernova bump is evidently difficult to explain the multiple modulations.\(^\text{19}\) In GRB030329, the feature of a supernova spectrum appeared 7 days after the burst.\(^\text{20}\) The optical flux before 7 days was hence dominated by the afterglow emission itself.

In some GRB afterglows, similar deviations from a general fading component have been reported.\(^\text{21, 22, 23}\) The recent object, GRB021004 is the first object exhibiting multiple fluctuations 1 day after the burst.\(^\text{24}\) In GRB030329, we found that the large amplitude bumps appeared even in the first day after the burst. The mechanism of these bumps has not been established yet, but the continuous light curve of the bumps of GRB030329 should help us to understand them.
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Figure 1. Light curves of the optical afterglow of GRB030329. The abscissa denotes the time from the burst (29 March 2003, 11:37:14.67 UT in days, shown in logarithmic scale. The ordinate denotes the $R_c$-magnitude in a and the residual magnitude from a power-law decay in b. The dotted line in a is the best-fitted power-law model, which was used to calculate the residual magnitude in b. Our observations are indicated with filled circles with error bars, indicating standard errors. The exposure times of each frame were 30, 40, 60, 30-60 and 45 s for Kyoto, Saitama, the Dynic Astronomical Observatory, the Hida Observatory and the Bronberg observations, respectively. The points in the figure are binned points of the observations with $\Delta \log t_{\text{day}} = 0.002$. Using a smoothly broken power-law model $f(t) = (f_1(t)^{-n} + f_2(t)^{-n})^{-1/n}$ with $f_i(t) = k_i t^{-\alpha_i}$ we determined decay indices $\alpha_i$ to be $0.74 \pm 0.02$ ($0.053 < t < 0.085$), $0.95 \pm 0.01$ ($0.085 < t < 0.163$), $0.65 \pm 0.04$ ($0.163 < t < 0.227$), and $1.16 \pm 0.01$ ($0.227 < t < 0.492$). The break times
are 0.085 ± 0.028, 0.163 ± 0.060, and 0.227 ± 0.043. Note that the 0.16-day break time was calculated with a broken power-law model without the smoothness parameter. The smoothness parameters, \( n \), are 94±51 for the earlier break and 69±89 for the later break, indicating rapid state transitions.