COLOR INDICES OF OPTICAL AFTERGLOWS OF LONG GRBS IN THE *SWIFT* ERA

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Abstract. We show the power of the method of the color indices that uses the commonly available multiband photometry of optical afterglows (OAs) of long GRBs detected by *Swift*. Our study shows that for most OAs, in the observer frame, these colors, corrected for the Galactic reddening, display prominent clustering in the color-color diagrams. The color indices enable us to distinguish OAs from other types of objects even without available gamma-ray emission. The color-color diagrams can be used to assess the extinction inside the host galaxy. Our approach is also generally important for investigating the numerous faint OAs for which obtaining spectra with good S/N ratio is often impossible.

1 Introduction, data analysis, and results

Color indices of optical afterglows (OAs) of GRBs are a powerful and innovative approach to the study of such events. They help us to:

- (1) search for the common properties of the afterglows, especially in order to investigate the spectral energy distribution and its changes, even by using photometric filters with small or moderate telescopes,
- (2) constrain the properties of the interstellar medium in the host galaxy of GRB,
- (3) distinguish among the individual radiation mechanisms (*e.g.* synchrotron radiation *versus* supernova, which is important also for an investigation of the GRB-supernova relation),
- (4) find out whether an optical event is related to a GRB even if no gamma-ray monitor detected the GRB (*e.g.* if no gamma-ray monitor was observing at the time of the GRB),
- (5) search for orphan afterglows (GRBs with the jet not pointing directly towards the observer; gamma-ray emission is not detected, but the optical one may be

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Fig. 1. Color-color diagrams of the OAs of *Swift* GRBs in the observer frame ($t - T_0 < 10$ d in the observer frame). The colors are corrected for the Galactic reddening using the maps of Schlegel *et al.* (1998). The large cross represents the mean colors (centroid) of the ensemble having $z < 3.5$. The OA of GRB 060218 is not included in calculating the centroid. The arrows denote the representative reddening outside our Galaxy: $E_{B-V} = 0.5$ mag.

observed; also gamma-ray emission too faint even when the jet is pointing towards the observer is possible). See Rhoads (1997) and Huang *et al.* (2002) for more.

Here, we compare the color indices of 21 *Swift* GRBs (from GRB 050128 to GRB 080810) with those used in our previous analysis (Šimon *et al.* 2001). Because of space limitations, the reader is referred to J. Greiner's Web page <http://www.mpe.mpg.de/~jcg/grbgen.html> for full references on each OA.

We show that a given color index of the ensemble of OAs with redshift $z < 3.5$ forms a very narrow belt with time. Namely, $(B - V)_0 = 0.46 \pm 0.28$ for $t - T_0$ from 0.0025 to 1.72 d; $(V - R)_0 = 0.38 \pm 0.13$ for $t - T_0$ from 0.0018 to 3.23 d; $(R - I)_0 = 0.46 \pm 0.11$ for $t - T_0$ from 0.0011 to 2.84 d. We note that OAs of the *Swift* GRBs are mapped in much earlier phases than before, which extends the belts to very small $t - T_0$. These belts in the time evolution of the color indices are valid even when the OA undergoes extreme changes of its brightness (the OA of GRB 080319B: a decrease by 7.9 mag during $t - T_0 < 4.6$ h). It is therefore possible to combine the data of the individual OAs obtained in different $t - T_0$.

The prominent concentration of colors of the OAs in Figure 1 is caused by the fact that most of the available measurements map part of the spectrum of the OAs with a very similar slope. This clustering enables us to identify the important properties of OAs at $t - T_0$ less than about 3.2 d. The spectral shape of OA is very smooth, with no bumps or strong lines, between the B to I bands in the observer frame. However, a real spectral break (not caused by the Lyman break) of some OAs is observed, as suggested by the tail in the $(B - V)_0$ vs. $(V - R)_0$ diagram (Fig. 1). These features display only negligible time evolution.

The color indices of the individual members of the ensemble were compared with the absolute magnitudes M_R corrected using our approach described in Šimon *et al.* (2001). These M_R , measured in the initial phase (the early decay), at the rest-frame $(t - T_0)_{\text{rest}} = 0.1$ d spanned over a very broad range between $M_R \approx -20$ and -27 . Spectra of most OAs in this spectral region are mutually quite similar while their luminosity in a given $t - T_0$ largely differs: the spectral shape in the fireball model (Sari *et al.* 1998) does not depend on the input energy, while the luminosity of the OA at a particular epoch depends on it.

The characterization of spectra of OAs by spectral index of the power-law function is valid only for a limited part of the real spectrum. The color indices are thus an important method for a study of the spectral properties of OAs, especially when a spectral break is present in some OAs.

The color indices of the OAs give us the possibility to separate the contributions of synchrotron radiation and supernova using the commonly available photometry (see Šimon *et al.* 2004, 2010). This is important mainly for analysis of faint OAs. Color indices are thus a much better tool to resolve the evolution of supernova in the profile of an OA than the light curves themselves.

Our present study confirms our previous findings that the color indices of the OAs are very specific. This also gives us hope to search whether an optical event is related to a GRB even without available gamma-ray detection.

As already stated in Section 1, the colors of OAs provide us with direct information about the environment of GRB. Several important consequences for the reddening inside the host can be made. The strong concentration of most colors of OAs suggests that the reddening inside their host galaxies must be quite similar and relatively small. *Swift* data show no variations of reddening even in the very early phase of the OA. Several possibilities exist: (a) GRBs with detected OAs are on the earth watching side of a star-forming region; (b) very low dust abundance in the host galaxy; (c) the density and dust abundance of the local interstellar medium (*e.g.* dust from the progenitor) is reduced by intense radiation of GRB (model by Waxman & Draine 2000).

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