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Analysis of the late phase of three optical afterglows of GRBs using color indices(*)

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Summary. — We find that although the absolute magnitude of the optical afterglow (OA) of GRB011121 in the late phase ($t - T_0 > 10$ days) is approximately consistent with that of the SN 1998bw-type supernova SN 2001ke, previously found by Garnavich P. M. *et al.* (*ApJ*, **582** (2003) 924), a good match of their colors occurs only for $t - T_0 = 13$–23 days in the observer frame of GRB011121. We are able to constrain the possible SN in the OA of GRB010222 to be of the peculiar SN 1998bw or SN 2002ap type, but not of SNe classified as Type Ic in the database of Poznanski D. *et al.* (*PASP*, **114** (2002) 833). Neither colors nor absolute magnitude of the OA of GRB970508 in the late phase are consistent with those of any of the above-mentioned (sub)types of SN. These results imply that the bumps in the late phase of the OAs can be caused by several mechanisms. Color indices thus appear to be a powerful tool in the analysis of these phenomena, even for archival data of OAs.

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PACS 95.30.Gv – Radiation mechanisms; polarization.
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1. – Introduction

The method of the color indices of optical afterglows (OAs) of GRBs is a powerful and straightforward approach to the study of such events. Although it has been applied to other phenomena in astrophysics for many decades, it is only very rarely used in the analysis of the OAs [12,13]. The main advantage of using color indices is that they enable to resolve small variations of the profile of the spectra of the OAs from the measurements in the commonly used $UBVRIJ$ filters. In addition, they enable us to resolve between

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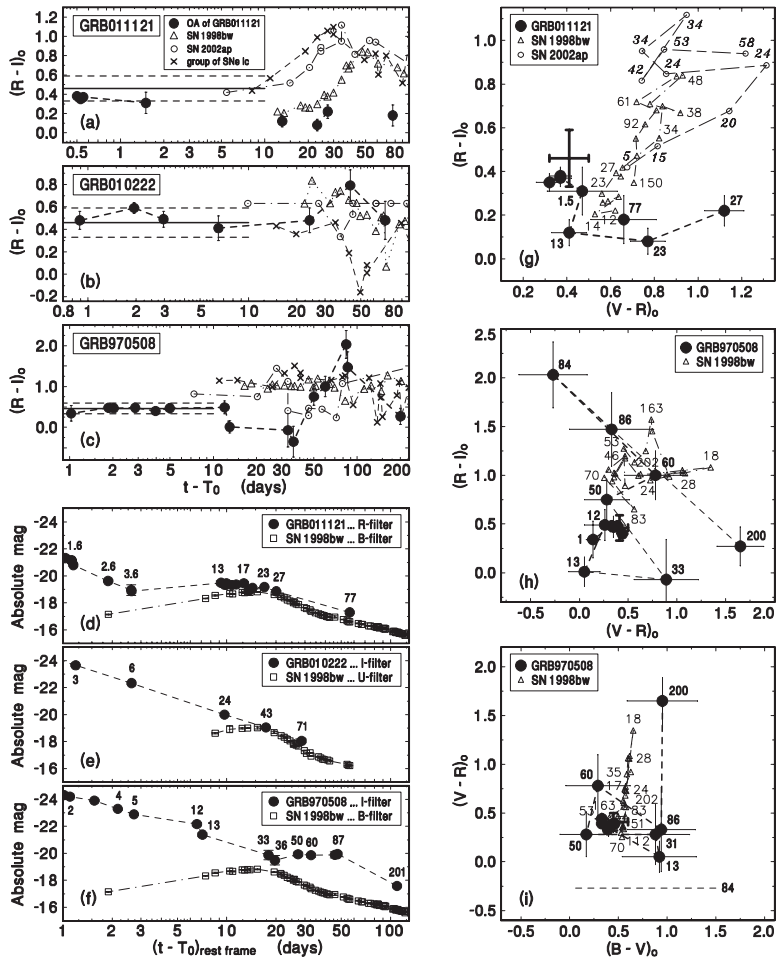

Fig. 1. – (a, b, c) Time evolution of the color indices of the OAs of GRB011121, GRB010222 and GRB970508. The horizontal solid line with the dashed error bars marks the mean color indices of the ensemble of 25 OAs [13]. The synthetic colors of SN 1998bw, SN 2002ap and the group of Type-Ic SNe, with the passbands and $t - T_0$ recalculated for z appropriate for a given OA, are also plotted (GRB011121: $z = 0.36$ [4]; GRB010222: $z = 1.477$ [3]; GRB970508: $z = 0.835$ [6]). The colors of 25 OAs are found to be independent on the redshift. (d, e, f) Comparison of the light curves of these OAs with those of SN 1998bw. The abscissa represents the rest-frame time interval but the labels display $t - T_0$ in the observer frame for comparison. The passbands were chosen so that the rest-frame wavelengths of the individual objects in each panel were close to each other. (g, h, i) Color-color diagrams. The points are connected by the line to show the time evolution. The large cross denotes the centroid and standard deviations of the colors of the ensemble of 25 OAs for $t - T_0 < 10$ days [13]. The numbers denote $t - T_0$ in days, starting from the corresponding GRBs. Only $(V - R)_0$ was available at $t - T_0 = 84$ days in (i).

the individual mechanisms of radiation (*e.g.*, synchrotron *vs.* supernova) [14]. This method allows also investigation of faint OAs or OAs recovered from archival data.

2. – Collection and analysis of the data

We used the following sources of data for our analysis: GRB970508 [10, 11, 6]; GRB010222 [2, 3]; GRB011121 [1, 4]. The magnitudes and color indices were corrected for the Galactic reddening according to [9]. The contributions of the host galaxies of GRB011121 and GRB010222 were eliminated because we used the data from HST for the late phase. The magnitudes for the OA of GRB970508 were corrected for the light contribution of the host using its magnitudes from [11].

Synthetic color indices of SN 1998bw, SN 2002ap and the group of Type-Ic SNe were calculated using the code at `http://wise-obs.tau.ac.il/~dovip/typing` [7]; both the wavelengths of the passbands and $t-T_0$ were scaled to the redshift z of the corresponding GRB. Time interval between the start of explosion and maximum of brightness ($z \approx 0$) was taken to be ~ 16 days for SN 1998bw, and ~ 10 days for SN 2002ap and the group of Type-Ic SNe [5].

3. – Results

We show that large color variations occur in some OAs of GRBs in the late phases ($t - T_0 > 10$ days) and we stress the great importance of multicolor photometry of the OAs in these epochs.

The late bump in the OA of GRB011121, attributed to SN 2001ke by [4], implies that this SN was slightly more luminous than SN 1998bw in all rest-frame time intervals $(t - T_0)_{\mathrm{rest-fr}}$ if it exploded close to T_0 of the GRB (fig. 1d). We find that a good match of their colors occurs only for $t - T_0 = 13$–23 days in the observer frame of GRB011121. The OA of GRB011121 remains very blue in $R - I$ in the late phase and its colors are inconsistent with either SN 1998bw or SN 2002ap, as can be seen from the $V - R$ *vs.* $R-I$ diagram in fig. 1g. For the sake of completeness, we note that a transient reddening within at most 28 days $< t - T_0 <$ 76 days might be missed due to a gap in the data.

We find the color indices of the OA of GRB010222 inside $t - T_0 < 10$ days to be consistent with the ensemble of 25 OAs [12]. The available $R - I$ curve remains almost constant even for $t - T_0 > 20$ days. Only a small transient reddening can be seen near $t - T_0 \approx 43$ days. This feature is defined only by a single point, with the other neighbouring two points being consistent with the ensemble of the OAs (fig. 1b). The late colors are thus close to those of the synchrotron radiation of the ensemble of the OAs [13]. A comparison of the absolute magnitude of this event with that of SN 1998bw reveals that the maximum brightness of SN 1998bw which occurred at $(t-T_0)_{\mathrm{rest-fr}} \approx 16$ days was close to that of the OA of GRB010222 at that $(t-T_0)_{\mathrm{rest-fr}}$. It is interesting to note that the transient reddening of $R-I$ occurred right at this moment (fig. 1b) and is compatible with the color of SN 1998bw or SN 2002ap, but not with the group of Type-Ic SNe. We offer two possible interpretations for this OA. The light curve could gradually and smoothly evolve from the synchrotron radiation to a SN without a prominent bump; the color is consistent with a SN exploding close to T_0 of the GRB. The other possibility is that the synchrotron radiation dominated the OA all the time and the underlying SN was underluminous with respect to SN 1998bw.

We find large color variations of the OA of GRB970508 in the red spectral region in its late phase (fig. 1c, h, i). The closest match of the absolute magnitude of this OA to

that of SN 1998bw occurred at $t - T_0 \approx 33$ days. We argue that although the colors in $B - V$ *vs.* $V - R$ diagram are marginally consistent with SN 1998bw (fig. 1i), they are quite inconsistent with this SN in $V - R$ *vs.* $R - I$ (fig. 1h). The difference between the absolute magnitude of this OA and SN 1998bw was increasing during the time interval between 36 and 87 days for $t - T_0$, with the maximum difference of ~ 2.7 mag. Such a high absolute magnitude is hardly consistent with a SN (fig. 1f). The most extreme values of the color indices occurred at $t - T_0 = 84$ days, with the reddest $R - I$ and the bluest $R - I$; this is inconsistent with the color and luminosity of a SN 1998bw-type SN and implies that a different explanation is necessary. An interaction of the blast wave with a pre-existing shell [8] may partly explain the observed color changes — a reddening of the spectrum is expected in this model. Nevertheless, the observed color variations of the OA of GRB970508 suggest a more complicated spectral profile, with a large reddening only in the red spectral region.

Our findings also have implications for the reddening of GRBs and their associated SNe inside the host galaxy. The clustering of the individual OAs in the color-color diagrams implies their low reddening [12]: hence the underlying SNe are not reddened either. The luminosity differences of the individual SNe at a given $(t - T_0)_{\mathrm{rest-fr}}$ are therefore real (fig. 1d, e, f).

The increasing amplitude of the color variations toward longer wavelengths shows the great importance of the deep observations of the OAs in the infrared region in late epochs.

The method of the color indices gives us a possibility to separate the contributions of the synchrotron radiation and SN, using the commonly available multiband photometry. This approach is important mainly for analysis of faint OAs for which obtaining spectra with good signal to noise at late phases is often impossible. This approach is possible even for archival data of OAs. The color indices are thus a much better tool to resolve the evolution of the supernova in the profile of an OA than the light curves themselves.

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