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The relation of the colors of the optical afterglow of GRB030329/ SN 2003dh to other afterglows(*)

V. Šimon(1), R. Hudec(1) and G. Pizzichini(2)(**)

(1) *Astronomical Institute, Academy of Sciences of the Czech Republic 251 65 Ondřejov, Czech Republic*
(2) *INAF/IASF, Sezione di Bologna - via Gobetti 101, 40129 Bologna, Italy*

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Summary. — We find that the color indices $(B-V)_0$, $(V-R)_0$, $(R-I)_0$, $(I-J)_0$ in the observer frame of the optical afterglow (OA) of GRB030329 during $t-T_0 < 10$ days are consistent with those of a uniform group of 25 OAs of GRBs (Šimon V. *et al. A&A* **377** (2001) 450; *AIP Conf. Proc.*, **727** (2004) 487). Large color variations of this OA for $t - T_0 > 12$ days are plausibly matched only by those of SN 1998bw although SN 2003dh develops an excess light in the red/IR spectral region. We also emphasize the discordance with other Type-Ic SNe which are not known to be associated with GRBs. The colors thus can help us to resolve the synchrotron component from the contribution of SN and to discriminate between various types of SN (especially important for faint OAs). We also note that the strong concentration of color indices of the ensemble of 26 OAs (including GRB030329) suggests that the local reddening inside their host galaxies is quite similar and relatively small for these events.

PACS 98.70.Rz – γ-ray sources; γ-ray bursts.
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PACS 95.30.Gv – Radiation mechanisms; polarization.
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1. – Introduction

GRB030329 possessed an exceptionally bright and milestone optical afterglow (OA) ($\sim 13\,\mathrm{mag}(R)$), discovered at $t - T_0 \approx 1.25$ hr [14,16]. Low redshift $z = 0.168$ [5,7] made the observations at late epochs possible. GRB030329 is an event particularly important, because it is sure to coincide with a supernova (SN). The features of Type-Ic SN 2003dh appeared in the spectrum after about a week (*e.g.*, [18,7]).

Our analysis of the OA using color indices enables us to resolve small variations of the profile of the spectra of the OA from the measurements in the commonly used $UBVRIJ$

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(**) simon@asu.cas.cz, rhudec@asu.cas.cz, pizzichini@bo.iasf.cnr.it.

filters. In addition, it allows us to distinguish between the individual mechanisms of radiation (*e.g.*, synchrotron *vs.* supernova).

2. – Collection and analysis of the data

We used the following data sources for our analysis: [11, 3, 10, 22, 23, 8, 9, 1, 4]. The whole R band light curve is displayed in fig. 1a while for other filters only those (usually averaged) points which were used for the calculation of the color indices are plotted. Examples of the color evolution are shown in fig. 1c, d.

Since the Galactic reddening toward GRB030329 is only $E_{\mathrm{B-V}} = 0.02$ mag according to [17], and smaller than the standard deviations of the indices, it could be neglected for our purposes. Also any light contribution of the host galaxy was quite small (upper limit $R \approx 23.1$ mag [2]) and could be neglected.

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` [15]. Both the wavelengths of the passbands and $t - T_0$ were scaled to the redshift $z = 0.168$ of GRB030329. The 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 [13].

3. – Results

Since we find that the color variations of the OA of GRB030329 are small for $t - T_0 \approx 10$ days, we can determine the following mean color indices: $(B-V)_0 = 0.34 \pm 0.08$ mag, $(V-R)_0 = 0.35 \pm 0.04$ mag, $(R-I)_0 = 0.47 \pm 0.04$ mag, $(I-J)_0 = 0.82 \pm 0.07$ mag. These indices are in very good agreement with those of a uniform group of 25 OAs with $z = 0.36$–3.5 [19, 20]; synchrotron component with parameters comparable to other OAs was thus initially dominant in the spectrum of the OA of GRB030329.

We note a larger shift of the OA of GRB030329 in $B-V$ than in $V-R$ for $t - T_0 < 10$ days (fig. 1e). Also the standard deviation of $B-V$ of the ensemble of 25 OAs is larger than that of $V-R$, which may suggest that the spectral variations increasing toward shorter wavelengths can be rather common in the OAs.

The reddening of GRB030329 inside its host galaxy is quite low ($E_{\mathrm{B-V}} < 0.1$ mag) since the colors of this OA in the first 10 days are in good agreement with those of the ensemble of 25 OAs which possess z up to 3.5 (fig. 1b) (see [19] for more details). The agreement between the colors and reddening of the OAs over a large range of z (0.168–3.5) (fig. 1b) implies that these GRBs presumably occur in largely different times of the evolution of their host galaxies. The dust content (and the reddening law) in the host galaxies can be thus expected to be different for the individual OAs. The observed clustering of the OAs in their color-color diagrams can be explained if these GRBs lie on the Earth-watching side of the star-forming regions or, alternatively, the dust is destroyed by the initial energetic flash. The low polarization of the OA of GRB030329 [6] yields another support for the first alternative in the case of this event.

We detected prominent color changes of the OA of GRB030329 only for $t - T_0 > 12$ days (fig. 1), which suggests a rapid evolution of the spectrum of the underlying SN 2003dh (the SN already dominated the light of the OA at this epoch [18]). Changes of a large part of the optical and near IR continuum of SN 2003dh (and not only of the lines) must be involved in the observed complicated color variations. The rapid color evolution of $R-I$ and $V-R$ of SN 2003dh (mainly their rise) is plausibly matched only

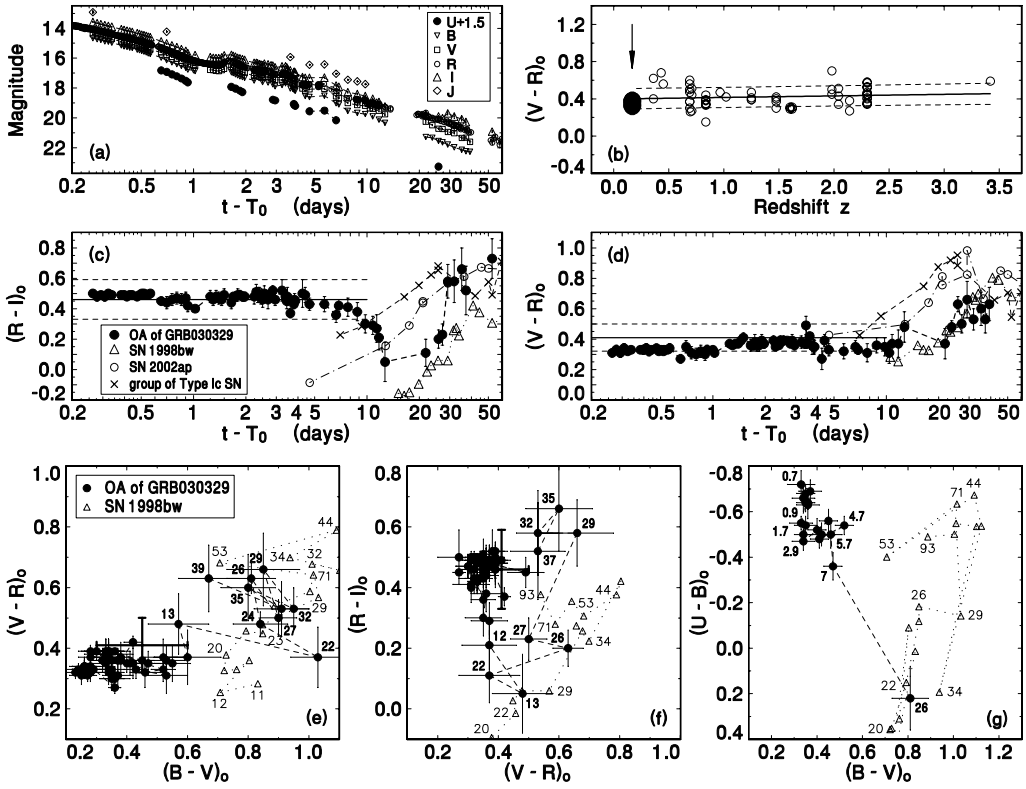

Fig. 1. – (a) The light curves of the OA of GRB030329. (b) Colors of all OAs with known redshift z plotted as a function of z (only OAs with $z < 3.5$ and $t - T_0 < 10.2$ days). The weight of each OA, used for the fit, is approximately proportional to the number of available color indices. Notice that the color of the OA of GRB030329 ($z = 0.168$), marked by the filled circles and an arrow, is in very good agreement with the colors of the events at higher z. (c, d) Examples of the time evolution of the color indices. The horizontal line with the error bars marks the mean color indices of the ensemble of 25 OAs, determined by [20]. The synthetic colors of SN 1998bw, SN 2002ap and the group of Type-Ic SNe from the database of [15], with the passbands and $t - T_0$ recalculated for $z = 0.168$, appropriate for GRB030329, are also plotted for comparison. The colors of the 25 OAs are found to be independent on the redshift. (e, f, g) Color-color diagrams. The points are connected by the lines to show the time evolution of the colors. The large cross denotes the centroid and standard deviations of the colors of the ensemble of 25 OAs for $t - T_0 < 10$ days [20]. The numbers denote $t - T_0$ in days (for $z = 0.168$), starting from the corresponding GRBs.

by that of SN 1998bw but the indices still reveal spectral differences between the two objects. The agreement between the colors of these two SNe is particularly good only at $t - T_0 = 26$ and 27 days when SN 1998bw was already on its decay from the maximum light. The brightness of SN 2003dh was thus already declining, too. This finding is in agreement with the spectroscopic dating by [7]. The evolution of SN 2003dh becomes faster than that of SN 1998bw for $t - T_0 > 27$ days (fig. 1f, g). SN 2003dh also develops an excess light in the red/IR spectral region in comparison with SN 1998bw.

Good agreement between SN 2003dh and SN 1998bw occurs in $U - B$ and suggests

a large discordance with other Type-Ic SNe which are not known to be associated with GRBs (fig. 1g).

We also note that although the photometric data for SN 2003lw, associated with GRB031203, are rather sparse, its VRI light curves are in good agreement with those of SN 1998bw after rescaling and stretching [12]. The SNe associated with GRBs thus appear to form a rather uniform group.

The absolute R magnitude of the OA of GRB030329 $M_{\mathrm{R0}} = -25.7$ mag at the rest frame $(t - T_0)_{\mathrm{rest-fr}} = 0.25$ days is in good agreement with the average M_{R0} of the ensemble of OAs [19]. Zero order k-correction [19] leads to $M_{\mathrm{R0}} \approx -26.6$ mag. Type-Ic SNe reach M_{V} only -17 to -19.4 mag at maximum (*e.g.,* [13]). The break in the light curve at $t - T_0 \approx 1$ day (fig. 1a) is thus not due to SN 2003dh.

We have shown that 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. More information is given in our companion paper [21].

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