Investigation of the evolution of SN 2006aj/GRB060218 using color indices

Vojtěch Šimon[1], Graziella Pizzichini[2], René Hudec[1]

[1] Astronomical Institute, Academy of Sciences of the Czech Republic, 25165 Ondřejov, Czech Republic

[2] INAF/IASF Bologna, via Gobetti 101, 40129 Bologna, Italy

Abstract

We apply the method of color indices from multiband photometry on SN2006aj/GRB060218. We show that this is a much better tool to analyze the evolution of supernovae (SNe) than the light curves themselves. We present the color evolution of a Type Ic SN in the cosmic UV region. We find that the color indices of the early phase (t-T_0 < 2 d) are not consistent with those of the ensemble of 25 optical afterglows (OAs) of GRBs, but their time evolution is, and are suggestive of a similar physical nature of these events. We show a rapid and complicated evolution of SN2006aj from UV to the infrared. A stretching of the time evolution of the color indices of the group of 'ordinary' Type Ic SNe by a factor of 1.2 matches the evolution of SN2006aj over a broader spectral range than stretching of SN1998bw (the canonical SN of GRB) by a factor of 0.5. Our approach is important also for investigation of SNe in late phases of OAs for which obtaining spectra with good signal to noise ratio is often impossible.

Sources of long gamma-ray bursts (GRBs) – **core-collapse of massive stars (supernova (SN) explosion)** (Stanek et al. 2003,ApJ,591,L17)
Currently used methods to resolve SN contribution in OA:

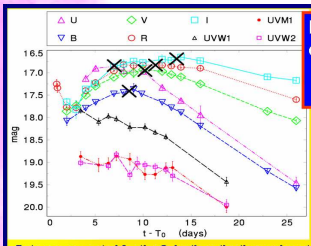
(a) **Spectroscopic – only for brighter OAs, large telescopes needed;**

(b) **Late bump in light curve of OA – not certain classification of SN, also inhomogeneities in circumburst medium can give rise to a bump** (Eldridge et al. 2006, MNRAS, 367, 186)

GRB060218

- **Remarkable long GRB** (Cusumano et al. 2006,GCN4775, Campana et al. 2006,Nat,442,1008)
- **Redshift z=0.03345 (e.g.** Mirabal et al. 2006,ApJ,643,L99)
- **GRB associated with the supernova SN2006aj.**
- **Luminosity and velocity of ejecta intermediate between SNe associated with GRB and those lacking GRB. GRB of SN2006aj was less luminous and softer than the 'classical' GRBs, and it was an intrinsically weak and soft event, rather than a classical GRB observed off-axis** (Pian et al. 2006,Nat,442,1011)

Light curves of SN 2006aj from far UV to IR

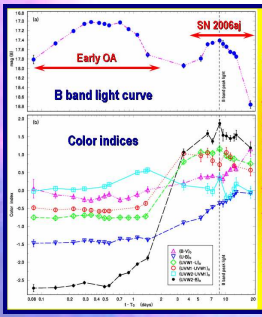


Data sources:

- Mirabal et al. 2006, ApJ, 643,L99
- UVOT obs.

Data are corrected for the Galactic extinction and contribution of the host galaxy. This diagram concentrates on the evolution of SN 2006aj, so most early data (t-T_0 < 2 d) are skipped to avoid overcrowding. Large crosses denote the moment of the peak light in a given filter.

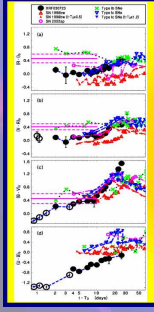
UVOT data



Data were corrected for reddening and light contribution of the host galaxy.

Data were interpolated to determine the color indices. Separation of colors appropriate to early OA and SN 2006aj is clear (with decreasing amplitude) for *UVW2-B*, *UVW1-U*, *UVM1 - UVW1*. Especially *UVW1-U* and *UVM1-UVW1* display only quite small variations during early OA; their evolution during the SN phase is almost achromatic, too, but at the values very different from those of early OA. The situation is very different for *UVW2 - UVM1* (almost identical mean values for both phases).

Time evolution of color indices



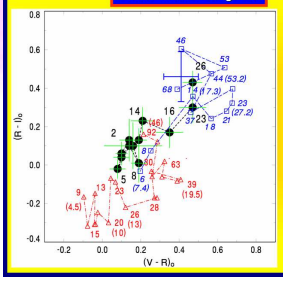
Horizontal lines – mean color indices of ensemble of 25 OAs of long GRBs (Simon et al. 2004, AIPC, 727, 487). **They are independent on redshift.**

Synthetic colors of several types of supernovae (Poznanski et al. 2002, PASP, 114, 833) **are calculated for redshift z=0.03 of GRB060218.**

Large open circles – UVOT data of SN 2006aj

Large closed circles – ground-based data of SN 2006aj

Color-color diagram



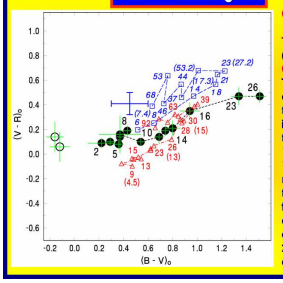
V–R vs. R–I diagram:

Circles–OA of GRB060218

Triangles – SN 1998bw (Poznanski et al. 2002, PASP, 114,833).

Open boxes – group of Type Ic SNe (Poznanski et al. 2002,PASP,114,833). **Numbers at the points denote the time interval since the onset of the SN** (SN 1998bw: $T_{max} - T_{start}$ ~ 16 d; Type Ic SNe: $T_{max} - T_{start}$ ~ 10 days). **Numbers in brackets refer to SNe evolving twice as fast. Mean colors (centroid) of the ensemble of 25 OAs of long GRBs** (Simon et al. 2004, AIPC, 727, 487) **are marked by the cross.**

Color-color diagram

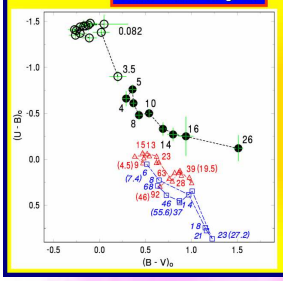


B–V vs. V–R diagram:

Circles–OA of GRB060218

Triangles – SN 1998bw (Poznanski et al. 2002), **Open boxes – group of Type Ic SNe** (Poznanski et al. 2002). **Numbers at the points mark the time interval since the onset of the SN** (SN 1998bw: $T_{max} - T_{start}$ ~ 16 d; Type Ic SNe: $T_{max} - T_{start}$ ~ 10 days). **The numbers in brackets refer to SNe evolving twice as fast.Mean colors (centroid) of the ensemble of 25 OAs of long GRBs** (Simon et al. 2004) **are marked by the cross.**

Color-color diagram

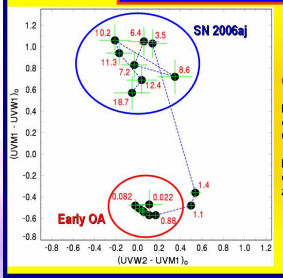


U–B vs. B–V diagram:

Circles–OA of GRB060218

Triangles – SN 1998bw (Poznanski et al. 2002), **Open boxes – group of Type Ic SNe** (Poznanski et al. 2002). **The numbers at the points mark the time interval elapsed since the onset of the SN** (SN 1998bw: $T_{max} - T_{start}$~16 d; Type Ic SNe: $T_{max} - T_{start}$~ 10 d). **The numbers in brackets refer to SNe evolving twice as fast.**

UVOT color-color diagram

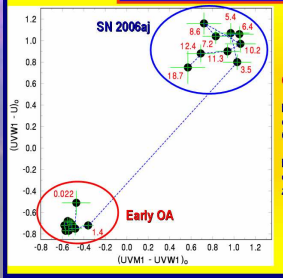


Circles–OA of GRB060218

Notice the clear separation of the colors of the early OA and SN 2006aj.

Numbers at the points denote t-T_0 in days for z=0.03345.

UVOT color-color diagram



Circles–OA of GRB060218

Notice the clear separation of the colors of the early OA and SN 2006aj.

Numbers at the points denote t-T_0 in days for z=0.03345.

RESULTS

- **We present time evolution of color indices from multiband photometry for both the early optical afterglow (OA) (t-T_0 < 2 d) and SN 2006aj. We report on rapid and complicated evolution of SN2006aj from cosmic UV (λ > 188 A) to the infrared. Our approach provides us with more pieces of information than light curves alone.**
- **Color indices of early OA of GRB060218 suggest the spectral profile different from that of the ensemble of 25 OAs, but they share the prevailing constancy in time (optically thin synchrotron** (Sari et al. 1998, ApJ, 497, L17) **versus optically thick cyclotron** (Bjornsson 2008, ApJ, 672,443)**).**
- **Large change of *UVW2-B*, starting already at t-T_0~0.55 d, can be due to increasing light contribution of the outer layers of SN already during the early OA phase.**
- **Soft gamma-ray spectrum sorting GRB060218 to X-ray flashes (XRFs) cannot be the sole reason for the colors of its early OA different from those of the ensemble of 25 OAs. OA of XRF030723 displays the abs. magnitude at the fainter end of the ensemble (similar to that of GRB 060218) for t-T_0 =1.5 d in the rest frame and colors still consistent with the Sari et al. (1998) model** (Simon et al. 2006, Il Nuovo Cimento C, 121B, 1579).
- **No variations of reddening even in the initial phase of the early OA are present. Possible explanations: very low dust abundance in the host galaxy** (Wiersema et al. 2007, A&A, 464, 529), **density and dust abundance of interstellar medium local to GRB060218 (e.g. dust from the progenitor) reduced by intense initial flash (models by** Waxman & Draine 2000,ApJ,537,796).
- **Changes of a large part of the UV, optical and near IR continuum of SN 2006aj (not only line(s)) must be involved to explain the mutually similar shifts in the individual color-color diagrams.**
- **We use color indices instead of light curves for stretching the time evolution of SN 2006aj. It enables to investigate the evolution of the outer layers in more detail.**
- **Stretching of time evolution of color indices of SN 1998bw (canonical case of SN-GRB connection) by a factor of 0.5 (SN 2006aj evolving twice as fast as SN 1998bw) yields plausible matches between these two SNe only over the *B* to *R* passband. Between *R* and *I*, SN 2006aj systematically displayed an excess light.**
- **Stretching of group of 'ordinary' Type Ic SNe by a factor 1.2 yields a plausible fit to time evolution over a broader spectral region (*B* to *I*).**
- **Adjustment of time evolution of various color indices thus proves to be very helpful in searching for the proper SN type.**
- **Match of color indices of SN 2006aj by stretching implies that outer layers evolve faster, probably they are asymmetric** (Maeda et al. 2006, ApJ, 645, 1331) **but their spectrum between *B* to *R* remains quite similar to that of SN 1998bw.**
- **Duration, and hence time evolution of a Type Ic SN is proportional to amount of ^{56}Ni. This suggests that SN 2006aj contained significantly less ^{56}Ni than SN 1998bw, but more than ordinary Type Ic.**
- **SN 2006aj displays the largest shift in *B-V* vs. *V-R* and *U-B* vs. *B-V* diagrams. Turning point in the color-color diagram (the moment of the reddest color) occurs at the most positive indices for SN 2006aj among the displayed SNe; it is much redder than in the canonical SN 1998bw. Only the group of Type Ic SNe approaches this turning point in the plausible value of the color index. Faster evolution can be explained by less massive ejecta.**
- **The $(U\text{-}B)_0$ shift of SN 2006aj cannot be matched by any stretch factor of Type Ic or SN 1998bw. SN 2006aj thus possesses a light excess in UV. We interpret this evolution as follows. We observed simultaneously the different regions of SN 2006aj in the initial phase. A hot 'hole', caused by the emerging jet, was surrounded by cooler layers further from the axis. The 'hole' remaining after this jet was still present during the next about 10-20 days.**
- **Not only color indices of SN at a given moment, but also the evolution of these indices are important for its classification and study. Our approach is important also for investigation of SNe in late phases of OAs for which obtaining spectra with good S/N ratio is often impossible.**