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Color-color analysis of the optical counterparts of high energy sources

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Abstract. We show some possibilities of using the method of the color indices for analysis of optical counterparts of high energy sources. We focus on the types of objects for which this method is only rarely used (optical afterglows of GRBs (including the discrimination between the synchrotron emission from the jet and thermal emission from supernova), supersoft X-ray sources, microquasars, magnetars). We show that these indices are very helpful in forming the representative ensemble of events. Even variations of strong emission lines with respect to the continuum can be resolved by this method. We emphasize that not only the color indices of the object at a given moment, but also the time evolution of these indices are important for its classification and study. Combination of the color indices with the spectral energy distribution is desirable.

Key words. X-rays: binaries – Gamma rays: bursts – circumstellar matter – accretion, accretion disks – Stars: novae, cataclysmic variables – supernovae: general

1. Introduction

The method of the color indices determined from the magnitudes of an object measured in the optical filters is a powerful and sensitive approach which helps us to investigate the spectral energy distribution (SED) and its changes even using the data obtained with small or moderate telescopes. Even very faint objects often not accessible to spectroscopic observations can be studied. These indices can also be used for an analysis of optical counterparts of high energy sources. They enable us to search for the common properties of the sources of a given kind, search for the relations among colors and luminosities of a given object or a kind of objects, constrain the properties of the local medium of the source, and resolve among the individual radiation mechanisms. We will focus on the types of objects for which this method is only rarely used.

2. Colors of high energy sources

Early phase of optical afterglows (OAs) of GRBs ($t - T_0 < 10$ d). Our analysis (e.g. Šimon et al. (2001b, 2004a, 2006c,d)) show that although the brightness of the ensemble of OAs of long GRBs with redshift z between 0.17 and 3.5 falls by several magnitudes over this time interval, the time evolution of their color indices in the observer frame is negligible. Example of the color-color diagram is

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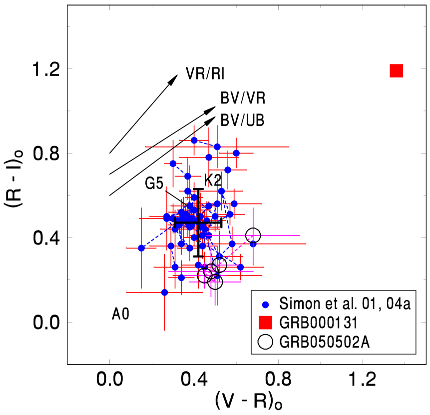

Fig. 1. $(V-R)_0$ vs. $(R-I)_0$ diagram of OAs ($t - T_0 < 10$ d), corrected for the Galactic reddening. Multiple indices of the same OA are connected by lines. The mean colors (centroid) of the ensemble of OAs ($0.17 < z < 3.5$) (except for GRB000131 and GRB050502A with $z > 3.5$) are marked. The representative reddening paths for $E_{\rm B-V} = 0.5$ mag are also shown. Positions of the main-sequence stars are included for comparison. See text for details.

shown in Fig. 1. Increasing effect of the Lyman break occurs only for the events with $z > 3.5$, starting from the blue passband. While OA of GRB000131 is largely influenced by this break in Fig. 1, OA of GRB050502A is almost unaffected. Positions of main sequence stars are useful for observational differentiation of OAs from other kinds of objects. The color indices of OAs give us important information on their spectra and environment in their host galaxies, especially in combination with the rest-frame SEDs. They show that the spectral shape of OAs is very smooth, with no bumps or strong lines, between the observed B to I passbands (2000–5600 Å in rest frame). Spectra of most OAs are mutually very similar while their luminosity in a given $t - T_0$ largely differs: the spectral shape of the synchrotron emission in the "fireball" model (Sari et al. 1998) does not depend on the input energy, while the luminosity of OA at a particular epoch does depend on it. The statistical distribution for $(U-B)_0$ is much broader than that for $(R-I)_0$, $(V-R)_0$, and $(B-V)_0$. The theoretical spectrum of OA (Sari et al. 1998) consists of several parts, each of them having a power-law shape with a specific spectral index. Our analysis shows that the observed high-frequency boundary remains almost stable during the decay of the light curve of a given OA. The prominent concentration of colors is caused by the fact that most of the available ground-based measurements cover a part of the spectrum of OAs with a very similar slope (see Šimon et al. (2006c) for details). Characterization of spectra of OAs by spectral index of the power-law function is thus valid only for a limited part of the real spectrum of OA. Color indices are thus an important method for the study of the spectral properties of OAs, including spectral breaks. Colors of OAs also give us an information about the environment of GRBs. Strong concentration of the colors of the OAs in this ensemble suggests that the intrinsic reddening (inside their host galaxies) must be quite similar and relatively small. In case of a large reddening it would be quite unlikely to obtain such similar values of absorption in all cases. Several possibilities can play a role: (a) GRBs lie on earth-watching side of a star-forming region; (b) density and dust abundance of the local interstellar medium are substantially reduced by intense high energy radiation of GRB trigger (models by Waxman & Draine (2000)). This situation is true for the above-mentioned ensemble, but it may differ for the "dark bursts.

GRB-supernova connection. The often used methods to resolve the contribution of a supernova (SN) in OA are spectroscopic (only for brighter OAs, large telescopes needed), and searching for the late bump in the light curve of OA (this is not a certain classification of SN, because also inhomogeneities in the circumburst medium can give rise to a bump (Eldridge et al. 2006)). Investigation of the color indices appears to be a promising approach (Šimon et al. 2004b). The resolution and time evolution of the synchrotron and SN component by the colors of the OA of GRB011121 is shown in Fig. 2a. This SN 2001ke appears as a bump in the light curve of the OA (Garnavich et al. 2003); the color indices enable us a deeper insight into the spectra of SNe associated with GRBs. GRB060218/SN 2006aj represents a special

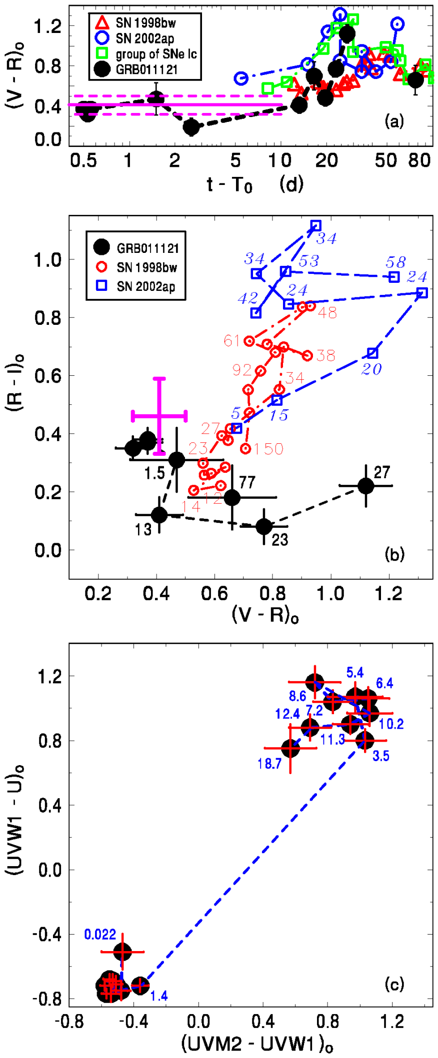

Fig. 2. (a) Time evolution of the color indices of the OA of GRB011121. The horizontal solid line with the error bars marks the mean color indices of the ensemble of OAs (Šimon et al. 2004a). The synthetic colors of SNe with the passbands and $t - T_0$ for $z = 0.36$ come from Poznanski et al. (2002). **(b)** Color-color diagram of the OA of GRB011121. The large cross denotes the centroid and standard deviations of the colors of the ensemble of OAs. The numbers denote $t - T_0$ in days for $z = 0.36$, starting from the GRB or SN. Adapted from Šimon et al. (2004b) and Šimon et al. (2006d). **(c)** UVOT color-color diagram for the OA of GRB060218 reaching to cosmic UV passband. Numbers denote $t - T_0$ in days for $z = 0.033$.

case. This OA displayed two peaks of a comparable height, the latter one corresponding to SN 2006aj (Campana et al. 2006). The very large difference between the values of the color indices of the early OA and SN 2006aj (Fig. 2b) speaks against the influence of a possible prolonged early OA on the SN light. The time evolution of the color indices (from the data of Campana et al. (2006); Brown et al. (2007)) shows no variations of reddening even in the initial phase of the early, slowly rising OA. The color indices show that the clustering of the individual OAs in the color-color diagrams suggests quite a low reddening. A very low abundance of the pre-GRB dust abundance is suggested particularly in GRB060218, because the dust destruction is unlikely in this case. The underlying SNe of all these OAs are thus not reddened either. The luminosity differences of SNe at a given $t - T_0$ in rest frame are real, unless the composition of the dust is quite exotic (e.g. only large grains which only absorb the light without reddening remain after the initial flash). These indices give us the possibility to separate the contributions of synchrotron radiation of a jet and thermal emission of SN using the commonly available multiband photometry. This is important mainly for analysis of faint OAs. Even a single data point in the color evolution can yield a very important information, as we have shown for OA of XRF030723 (Šimon et al. 2006b). This approach is even possible for archival data of OAs. The color indices and their time evolution differ for the individual SNe associated with GRBs, so these SNe are not identical copies of the canonical SN 1998bw. Good match of the colors of SN 2001ke to those of the canonical SN 1998bw occurs only for $t - T_0 = 13 - 23$ d in the observer frame (Fig. 2a). The almost monochromatic evolution including the declining branch of SN 2006aj in cosmic UV suggests that line blanketing varies only a little, and the UV emitting area shrinks. It thus emerges that the color indices are a much better tool to resolve and investigate the evolution of SN in the profile of an OA than the light curves themselves.

Supersoft X-ray sources (SXSs) are unique binary systems in which the mass trans-

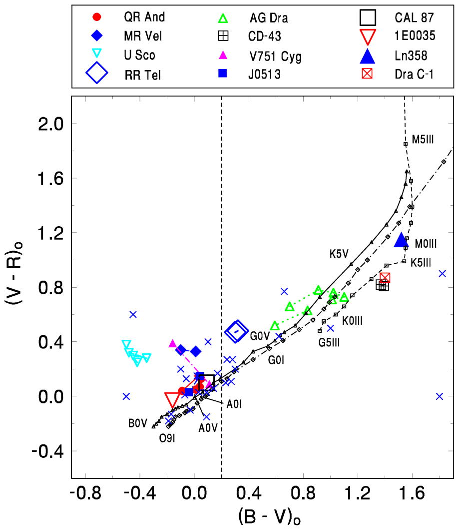

Fig. 3. $(B-V)_0$ vs. $(V-R)_0$ diagram for SXSs and their relatives. The vertical dashed line separates the region of the short-period systems ($P_{orb} \leq 4$ d) from the long-period ones. For comparison, $\times$ denote the dereddened colors of old novae given by Szkody (1994).

fer onto the WD occurs at a very high rate ($\dot{m} \approx 10^{-7}\ M_{\odot}\ yr^{-1}$). This allows a steady-state hydrogen burning on the WD (van den Heuvel et al. 1992). Optical emission comes from both the reprocessing off X-rays in the disk and from the disk viscosity. Strong activity in the optical passband is common. Known SXSs are mostly located in the Magellanic Clouds and in M31, but there are several groups of their close relatives (e.g. V Sge systems (Steiner & Diaz 1998)). Our previous analysis (Šimon 2003) has shown that the mean absolute visual magnitudes M_V of SXSs, located mostly in the Magellanic Clouds, and V Sge systems, all with the orbital periods $P_{orb} < 4$ d, tend to brighten with P_{orb}. It can be seen in Fig. 3 that most of these systems, even with the different P_{orb} and M_V, form a closed group in the $(B-V)_0$ vs. $(V-R)_0$ diagram (i.e. colors corrected for the interstellar reddening), in a similar way as in the $(U-B)_0$ vs. $(B-V)_0$ diagram except for supersoft X-ray symbiotic systems (see Šimon (2003) for details). This clustering is not affected by the possible uncertainties in reddening. The relation between the color indices and absolute magnitudes can help compare the properties and configuration of the reprocessing medium in the individual SXSs. SXSs in the Magellanic clouds and V Sge systems with $P_{orb} < 4$ d have the color indices very similar each to other and form closed groups in the color-color diagrams. Systems with Roche lobe overflow with longer P_{orb} possess larger disks (e.g. Paczynski (1977)). The effective temperature of a large part of the hot, steady-state disk generally decreases toward its outer rim (e.g. Warner (1995)). Larger disks are thus expected to be cooler (redder) in their outer parts (Hack & la Dous 1993). However, this is not observed in SXSs and V Sge systems. They thus possess a flatter radial temperature profile in comparison with the standard disk, radiating purely due to the viscous processes. This can be explained by the irradiated disk and is consistent with Popham & Di Stefano (1996) who modeled the optical radiation as originating mostly from the reprocessing off the X-rays in the disk and the donor. We find that the colors of most old novae (Szkody 1994) are similar to those of the SXSs and V Sge systems, but they display a larger scatter for the individual objects. This suggests similar spectra of these types of objects. Balmer jump of SXSs and V Sge systems is frequently in emission, because some systems even lie above the line of blackbodies in the color-color diagram.

The case of V Sge. This system displays a complicated long-term activity with the amplitude ~ 2 mag, whose character changed considerably during about 40 years (e.g. Šimon & Mattei (1999)). The $U-B$ and $B-V$ indices remained almost the same for a given level of brightness in spite of the large changes of the properties of the light curve. This suggests that the spectral profiles and process which give rise to the large variations of brightness in V Sge underwent only little changes over this time period. The location of V Sge close to or behind the line of blackbodies in the color-color diagram suggests that Balmer jump is in emission and undergoes only minor changes during the high/low state transitions. The decrease of $B - V$ in the high state coincides with the changes of the X-ray spectrum from soft to hard (Greiner & van Teeseling 1998) and with formation of a circumbinary envelope (Herbig et al. 1965; Patterson et al. 1998). This envelope can be caused by the radiatively driven wind from luminous accretion disk (Hachiya et al. 1998). More details can be found in Šimon et al. (2001a).

Microquasars. The X-ray outburst of CI Cam (XTE J0421+560) (Frontera et al. 1998) can be explained by the thermal instability of the accretion disk embedding the black hole, analogous to the outbursts of soft X-ray transients (Robinson et al. 2002; Šimon et al. 2006a), but the significant reddening of the color indices longward of Balmer jump during this event (Šimon et al. 2006a) suggests that the optical emission is not dominated by a standard disk. Nevertheless, it is not caused by any significant brightening of the emission observed in quiescence. Supercritical accretion (Hynes et al. 2002) may be a solution. Significant post-outburst activity was observed in 1999–2004 (Šimon et al. 2007) (Fig. 4a). Variations of the continuum played a significant role, because the dominant line changes would lead to independent variations of the color indices. The shifts in the color-color diagram are not explicable by the changes of the reddening intrinsic to CI Cam (Fig. 4b). They can be explained as being due to several superposed spectral components. The division of their dominant contributions occurs near $\lambda = 550$ nm, that is in the V passband: free-free emission from wind and/or envelope (in the red and near-IR region; (Clark et al. 2000), and another component in the blue region: (pseudo)photospheric emission (see Šimon et al. (2007) for details). The observed hysteresis in the $V - R$ vs. $R - I$ diagram (Fig. 4c) can be explained by the variations of the strength of the observed Hα changes which are not simple variations of the combined continuum and weaker emission lines at a stable Hα emission. The Hα emitting region evolves on the time scale of hundreds of days. Huge changes of extinction in X-rays and no extinction variations in the optical suggest that the X-ray emission of CI Cam comes from the close vicinity of the mass-accreting black

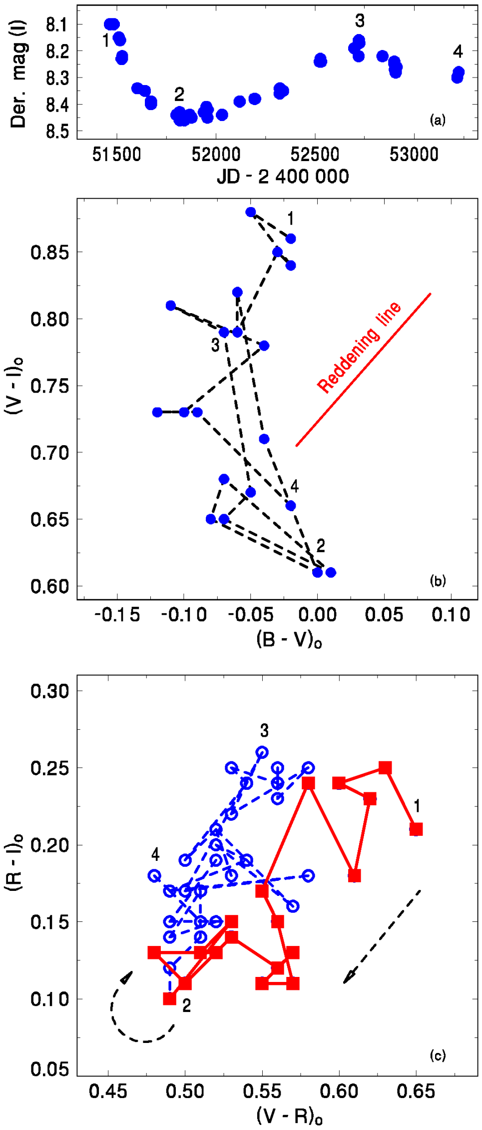

Fig. 4. **(a)** Time evolution of the I band magnitude of CI Cam in quiescence after its 1998 outburst. **(b)** The corresponding $(B-V)_0$ vs. $(V-I)_0$ diagram after the outburst. The line connecting the points denotes the time evolution. The numbers at some points enable a comparison with **a.** **(c)** $(V-R)_0$ vs. $(R-I)_0$ diagram for the quiescence. Arrows denote time evolution. The magnitudes and color indices are corrected for the reddening by $E_{\mathrm{B-V}} = 0.85$ mag of Robinson et al. (2002).

hole (re-filling of the disk after outburst?), not from the giant donor (see Šimon et al. (2007) for details).

Magnetars. The optical emission from the probable magnetar (e.g. Mereghetti (2008) GRB070610/ Swift J195509+261406 lasting for ~2 d had the form of spikes (Castro-Tirado et al. 2008). Although the dense series of the *I* and *R* data obtained on June 11, 2007, was not quite simultaneous, our analysis shows that the mean $(R-I)_0$ suggests that the optical emission of this outburst is due to the synchrotron radiation with the spectral profile very similar to the OAs of long GRBs (Castro-Tirado et al. 2009).

3. Conclusions

Dense series of observations in various filters enable to resolve the variations of the color indices accompanying the activity, and to place the observed events in the context of the long-term activity of a given system. Forming the representative ensemble of the type of systems is particularly fruitful. Even variations of strong emission lines with respect to the continuum can be resolved by the method of the color indices. Not only the color indices of the object at a given moment, but also the time evolution of these indices are important for its classification and study. Combination of the color indices with the SED for the representative and/or extreme states of activity is desirable.

4. DISCUSSION

JIM BEALL: How are your color indices affected by interstelllar reddening?

VOJTĚCH ŠIMON: The clustering of the colors of OAs suggests that the reddening inside their hosts is quite low ($E_{\rm B-V} < 0.2$ mag). As regards the galactic objects, when possible, the reddening determined from their $\lambda \approx$ 2200 Å feature was accepted.

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