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We present an update of our systematic analyses of all Gamma-Ray Burst (GRB) afterglow data, now published through the end of 2004, in an attempt to detect the predicted supernova light component. We fit the observed photometric light curves as the sum of an afterglow, an underlying host galaxy, and a supernova component. The latter is modeled using published $UBVRI$ light curves of SN 1998bw as a template. The total sample of afterglows with established redshifts contains now 29 bursts (GRB 970228 - GRB 041006). For 13 of them a weak supernova excess (scaled to SN 1998bw) was found. In agreement with our earlier result [47] we find that also in the updated sample all bursts with redshift $\lesssim 0.7$ show a supernova excess in their afterglow light curves. The general lack of a detection of a supernova component at larger redshifts can be explained with selection effects. These results strongly support our previous conclusion based on all afterglow data of the years 1997 to 2002 [47] that in fact *all* afterglows of long-duration GRBs contain light from an associated supernova.

1. Introduction

Significant progress towards understanding the nature of GRBs and their progenitors came with the discovery of GRB afterglows in 1997 [16, 43]. First observational evidence for the underlying source population was provided by GRB 970828, which showed a bright X-ray afterglow but no optical counterpart down to faint magnitudes [17]. This led to the suggestion that the optical light was blocked by cosmic dust in the GRB host galaxy, linking the burster to a dusty star-forming region, i.e., most likely to the explosion of a massive star [31]. The discovery of a near-by type Ibc supernova (SN 1998bw) in the error circle of the X-ray afterglow for GRB 980425 [11, 25], provided strong support for this idea, and is consistent with our current understanding of type Ibc SNe and their progenitors (e.g., [8, 19]).

From the observational site, the supernova picture is further supported by the fact that all GRB hosts are star-forming, and in some cases even star-bursting galaxies (e.g., [7, 40]). Evidence for host extinction by cosmic dust in GRB afterglows and the discovery of an ensemble of optically 'dark bursts' (for a recent discussion, see [9, 23, 27]) also is consistent with the picture that GRB progenitors are young, massive stars. Furthermore, for several GRB afterglows X-ray lines may hint at a period of nucleosynthesis preceding or accompanying the burst [1, 26, 30]. The positions of the afterglows with respect to their hosts also favors a relation to young, massive stars to GRBs [4].

As a natural consequence of a physical relation between the explosion of massive stars and GRBs supernova light should contribute to the afterglow flux, and even dominate under favorable conditions. The most convincing example is GRB 030329 [32] at z=0.1685 [14] with spectral confirmation of supernova light in its afterglow [20, 22, 29, 41]. Spectroscopic evidence for SN light in a GRB afterglow was later also reported for GRB 021211 [6], GRB 031203 [28] and most recently for XRF 020903 [39].

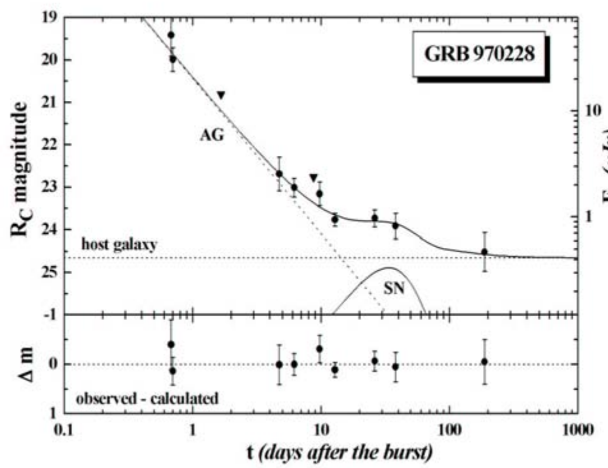

Figure 1: The late-time bump in the optical afterglow of GRB 970228, the first optical afterglow ever found (data collected from the literature). Interpreted as a signature from a SN explosion makes this event one of the most distant core-collapse SNe ever seen at that time. See also [12, 33].

In contrast to direct spectroscopic evidence, several cases of *photometric* indication of extra light in GRB afterglows have been reported, starting with the pioneering work on GRB 980326 [3]. Inspired by this finding, the discovery of extra light in archived data of the afterglow of GRB 970228 [12, 33] made it clear that a search for late-time bumps in optical afterglow light curves provides a powerful tool to constrain or even reveal the nature of the underlying sources. Since then various groups successfully fit SN 1998bw templates to explain these late-time bumps (e.g., [5]), the most convincing case being that of GRB 011121 [4, 13, 15].

The goal of our study is to search for supernova bumps in GRB afterglow light curves using a systematic approach, allowing us to draw statistically founded conclusions on the physical properties of this new class of GRB-SNe in particular and on the GRB progenitors in general. We collected from the literature all available photometric data on GRB afterglows (including our own data), checked them for photometric consistency, and re-analyzed the data in a consistent manner. Here we report on the status of our study for all bursts that occured by the end of 2003, supplementing and expanding our previous results ([47], in the following paper I).

2. Numerical Approach

We model the light curve of the optical transient (OT) following a GRB as a composite of afterglow (AG) light, supernova (SN) light, and constant light from the underlying host galaxy. The flux density, F_ν, at a frequency ν is then given by

$$F_\nu^{\rm OT}(t) = F_\nu^{\rm AG}(t) + k\, F_\nu^{\rm SN}(t/s) + F_\nu^{\rm host}\,. \qquad (1)$$

Here, the parameter k describes the observed brightness ratio (in the host frame, i.e., including the cosmological K-correction) between the GRB-supernova, and the SN template (SN 1998bw) in the considered photometric band (in the observer frame). We allowed k to be different in every photometric band, but within a band independent of frequency. The parameter s is a stretch factor with respect to the used template. We have also explored the consequences of a shift in time between the onset of the burst and the onset of the supernova explosion, as implied by some theoretical models [44]. Then, in Eq. (1) $F_\nu^{\rm SN}(t/s)$ was replaced by $F_\nu^{\rm SN}(t+\tau)$. Here, $\tau = 0$ refers to GRB 980425/SN 1998bw [21]. If $\tau < 0$ the SN preceded the onset of the GRB.

Following [2] and [35], we describe the afterglow light curve by a broken power-law,

$$F_\nu^{\rm AG}(t) = {\rm const}\ [(t/t_b)^{\alpha_1 n} + (t/t_b)^{\alpha_2 n}]^{-1/n}\,, \qquad (2)$$

with const$=2^{1/n}\, F_\nu^{\rm AG}(t_b)$. Here t is the time after the burst (in the observer frame), α_1 is the pre-break decay slope of the afterglow light curve, α_2 is the post-break decay slope, and t_b is the break time. The parameter n characterizes the sharpness of the break; a larger n implies a sharper break. If no break is seen in the data then $\alpha_1 = \alpha_2$ and Eq. (2) simplifies correspondingly.

The results of this numerical procedure were compared with corresponding results published by others [4, 5], and we found close agreement. We used this procedure to *predict* the color evolution of GRB 030329/SN 2002dh [46], and obtained a very good numerical fit for the light curves of GRB-SN 011121 [15].

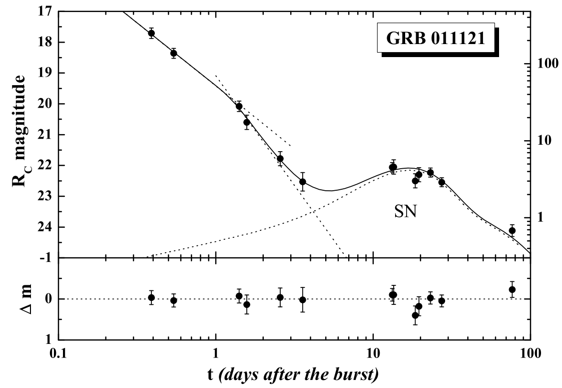

Figure 2: The afterglow of GRB 011121 showed a very clear signature of a late-time bump rising some days after the burst. Shown here are data obtained with the telescopes at ESO, Chile, and with the Hubble Space Telescope [4]). The bump can be modeled well by an underlying SN component at the redshift of the burster (z=0.36) with a peak luminosity of about 80% of the peak luminosity of SN 1998bw. Note that in the figure the flux from the underlying host galaxy was subtracted from the data (for details, see [15]).

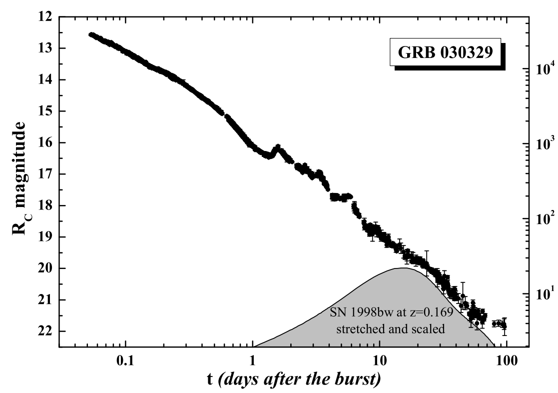

Figure 3: Scetch of the hidden SN bump in the afterglow of GRB 030329. Various re-brightening episodes of the genuine afterglow, in combination with a relatively late break-time of the light curve, made the photometric signature for the underlying SN explosion very small. Presumably, with no spectroscopic evidence at hand, the SN had easily been missed in the data. For the light curve fit α_2 was fixed at 2.5.

The limitations of the procedure are given by the chosen photometric band in combination with the redshift of the burster. Once we can no longer interpolate in between the $UBVRI$ bands, but have to extrapolate into the UV domain (cf. [3]), results become less accurate. For more details see paper I.

Before performing a numerical fit, the observational data was corrected for Galactic extinction along the

Table I The input sample of GRB afterglows. Redshifts were taken from the literature.

GRB	z	GRB	z	GRB	z	GRB	z
970228	0.695	991216	1.02	011121	0.362	030226	1.986
970508	0.835	000301C	2.04	011211	2.140	030323	3.372
971214	3.42	000418	1.118	020405	0.69	030328	1.520
980703	0.966	000911	1.058	020813	1.25	030329	0.169
990123	1.600	000926	2.066	020903	0.251	030429	2.658
990510	1.619	010222	1.477	021004	2.3	031203	0.106
990712	0.434	010921	0.450	021211	1.01	041006	0.716
991208	0.706						

line of sight using the COBE maps [37]. This also holds for SN 1998bw, where we assumed $E(B-V)=$ 0.06 mag. We calculated the Galactic visual extinction according to $A_V^{\rm Gal} = 3.1\ E(B-V)$, whereas the extinction in U and B were obtained via [36], and in R_c and I_c by means of the numerical functions compiled in [34].

Most of the light curves we investigated have been followed in more than one photometric band. For each of these GRBs we chose the best-sampled light curve as a reference light curve for the fit in the other photometric bands. In all cases this was the R band light curve. We always assumed that *afterglows* are achromatic, in reasonable agreement with observational data (e.g., [18, 24]). For every individual GRB, the afterglow parameters α_1, α_2, t_b, and n (Eq. 2) are then the same for all photometric bands. Consequently, once we fit the reference light curve of an optical transient and deduced the corresponding afterglow parameters, we treated them as fixed parameters when fitting the light curves of the optical transient in other photometric bands. In the fit the degrees of freedom are reduced correspondingly.

3. Results and Discussion

The input sample consists of 29 bursts (GRB 970228 - GRB 041006) with established redshifts and good enough photometric data in order to search for a late-time bump in their afterglows (Table I), with the most recent data for GRB 041006 [42]. These are eight bursts more than in our previous study for all bursts observed by the end of 2002 (paper I). Among these 29 bursts are 13 for which a late-time bump was found. This includes now also XRF 020903 (as already noted in [38] and now spectroscopically confirmed [39]). Note that the requirement of a known redshift excludes GRB 980326 as well as XRF 030723 from this list, which both showed a strong late-time bump. On the other hand, as already noted in [3], one can in principle constrain the redshift of a burster by fitting a redshifted SN component to the observed late-time bump in its afterglow light curve.

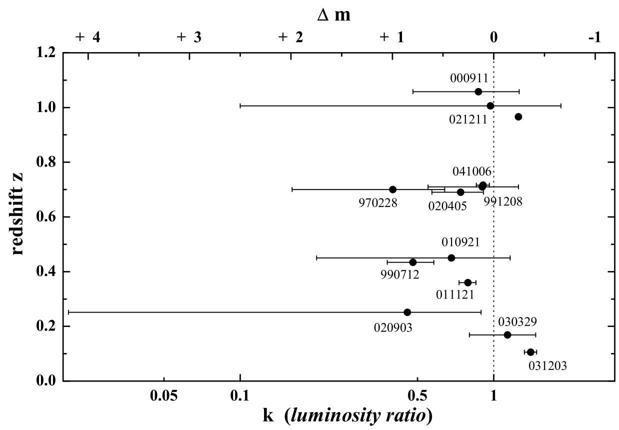

Figure 4: The deduced peak luminosities of all GRB-SNe in units of the peak luminosity of SN 1998bw. All data refer to the R_c band (in the observer frame). The dotted line corresponds to SN1998bw. The parameter Δm equals –2.5 log k, which measures the magnitude difference at maximum light between the GRB-SN and SN 1998bw in the corresponding wavelength regime. Note that the data are not corrected for a possible extinction in the GRB host galaxies. GRB 980703 is not included here and in the following figures because in this case the stretch factor was not allowed to vary freely.

Again, our key finding is photometric evidence of a late-time bump *in all* GRB afterglows with a redshift $z \lesssim 0.7$. We interprete this bump as light from an underlying supernova, and model this component as a redshifted version of SN 1998bw. The deduced luminosities for these GRB-SNe (not including extinction corrections for the host galaxy), normalized to SN 1998bw are listed in Table II. The width of the distribution of the SN peak luminosities (in units of the peak luminosity of SN 1998bw) spans over 2 photometric magnitudes with a pronounced maximum around $k = 0.5...1$ (Figs. 4, 5). The potential SN related to the X-ray flash 020903 is not unusual with respect to its peak luminosity. Interestingly, SN 1998bw is at the bright end of the GRB-SNe distribution (as already noted in paper I). Only the SNe related to GRBs 030329 and 031203 might have been slightly more luminous at peak brightness. No correlation was found of the deduced SN luminosities with the redshift or any afterglow parameter. Note, however, that we cannot exclude the existence of such a correlation since in most cases when a SN was found there is a lack of early time data in the optical light curve (resulting in an unknown break time t_b and, hence, an unknown parameter α_1; Eq. 2).

Figure 6 shows the distribution of the correspond-

Table II Best-fit parameters for the SN component found in GRB afterglows with known redshift. Columns: (1) and (2) GRB and redshift; (3) photometric band, in which the light curve was fitted; (4) central wavelength of the photometric band in the host frame in units of nm, adopting a wavelength of 659 nm for the R_c band; (5) peak luminosity of the fitted SN component in the corresponding wavelength band (observer frame) in units of SN 1998bw, after correction for Galactic extinction; (6) stretch factor s (Eq. 1); (7) goodness of fit per degree of freedom; (8) and (9) the same as (5) and (7) for $s = 1$. The low χ^2/d.o.f. for GRB 970228 is due to the small number of data points. Note that we reduced all data with our own numerical procedure, so that slight differences to the results obtained by others do naturally exist.

GRB	z	**band**	$\lambda_{\rm host}$	k	s	$\chi^2_{\rm d.o.f.}$	k **if** s**=1**	$\chi^2_{\rm d.o.f.}$
970228	0.695	R_c	389	0.40±0.24	1.46±0.80	0.70	0.33±0.30	0.71
980703	0.966	R_c	335	–	–	–	1.66±1.22	0.78
990712	0.434	R_c	459	0.48±0.10	0.89±0.10	1.00	0.43±0.08	1.01
991208	0.706	R_c	386	0.90±0.35	1.12±0.28	1.64	1.02±0.32	1.56
000911	1.058	R_c	320	0.87±0.39	1.49±0.33	0.75	0.51±0.43	1.14
010921	0.450	R_c	454	0.68±0.48	0.68±0.28	0.42	0.43±0.10	0.78
011121	0.360	R_c	484	0.79±0.06	0.85±0.06	0.92	0.74±0.05	1.32
020405	0.695	R_c	389	0.74±0.17	0.98±0.17	5.26	0.72±0.11	4.86
020903	0.251	R_c	527	0.46±0.44	1.47±0.88	1.52	0.37±0.41	1.22
021211	1.006	R_c	328	0.97±0.87	0.74±0.23	2.68	0.52±0.34	2.65
030329	0.169	R_c	563	1.13±0.33	0.82±0.13	3.10	0.98±0.01	4.49
031203	0.106	R_c	596	1.65±0.41	1.14±0.16	0.04	1.75±0.19	0.24
041006	0.716	R_c	384	0.91±0.05	1.38±0.06	1.27	1.21±0.07	1.95

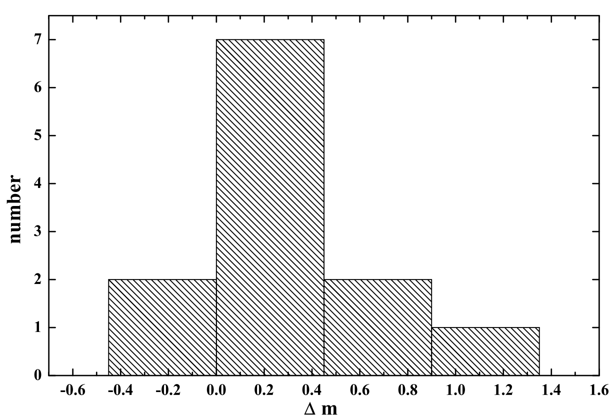

Figure 5: The distribution of the peak brightness of all GRB-SNe in units of the corresponding peak brightness of SN 1998bw in the R_c band (in the observer frame). The corresponding stretch factor is shown in Fig. 6.

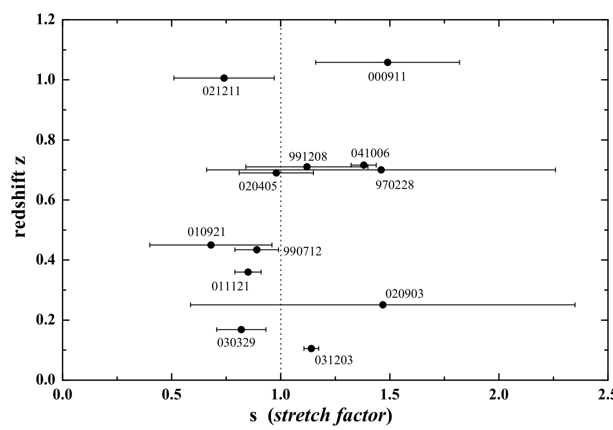

Figure 6: The distribution of the corresponding parameter s (Eq. 1) describing a stretching of the SN light curve relative to those of SN 1998bw (for which by definition $s = 1$, dotted line). In general, $s < 0$ ($s > 0$) means that the evolution of the light curve of the SN was slower (faster) than those of the light curve of SN 1998bw in the corresponding wavelength band. The mean value is $s = 1.0$.

ing stretch factor s. Since no fit was possible for the afterglow of GRB 980703 with s being a free parameter, this burst is not included in Figs. 4-6. The mean value of s is 1.0, i.e., identical to SN 1998bw.

Instead of introducing a stretch factor to have more freedom in the variety of GRB-SNe, one can also follow [44] and search for evidence of a time delay between the burst and the SN. According to this model, GRBs are the result of delayed black hole formation, which implies that the core-collapse and its subsequent supernova may significantly precede the burst. The delay could be of order months to years [44], or perhaps as short as hours [45]. For only two of the SN light curves the fit indeed improved if we allowed for a shift in time between the onset of the burst and the onset of the SN (GRBs 990712, 011121). The offsets never exceeded 5 days, and were both negative and positive. However, the uncertainties in this parameter are large, due to the poorly sampled shape of the underlying supernova (e.g., [13]).

4. Summary and Conclusions

Since the first clear evidence for extra light in a GRB afterglow light curve (GRB 980326; [3]), there is growing evidence for several such cases. Our key finding is photometric evidence of a late-time bump in *all* afterglows with a redshift $z \lesssim 0.7$, including those of the year 2003 (GRBs 030329 and 031203) and year 2004 (GRB 041006; [42]). For larger redshifts the data is usually not of sufficient quality, or the SN is simply too faint, in order to search for such a feature in the late-time afterglow light curve. This extra light is modeled well by a supernova component, peaking $(1+z)(15...20)$ days after a burst. This, together with the spectral confirmation of SN light in the afterglows of GRB 021211, 030329, and 031203 further supports the view that in fact *all* long-duration GRBs show SN bumps in their late-time optical afterglows. Given the fact that a strong late-time bump was also found for XRF 030723 [10] and a less strong bump for XRF 020903 (but with spectroscopic confirmation of underlying SN light [39]) might indicate that this conclusion holds also for X-ray flashes (even though the finding of XRF-SNe might be more difficult; see [39]).

Acknowledgments

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