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Radioactive decay of GRB-SNe at late-times

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Abstract. We present the late-time Hubble Space Telescope observations of two Gamma Ray Burst (GRB) associated supernovae (SNe), GRB 030329/SN 2003dh and XRF 060218/SN 2006aj. Using the multi-color data up to $\sim$ 320 days after the burst, we constrain the late-time decay nature of these SNe. The decay rates of SN 2003dh are steeper than SN 2006aj. A comparison with two other GRB SNe, GRB 980425/SN 1998bw and the SN associated with XRF 020903, shows that the decay rates of SN 2003dh are similar to XRF 020903 and those of SN 2006aj are similar to SN 1998bw. The late-time decay rates are steeper than the ^{56}Co$\rightarrow^{56}$Fe radioactive decay rate indicating that there is some leakage of gamma-rays. We also compare the late-time decay rates of nine type Ic SNe, including the SNe of long GRBs, Ic broad lined and normal Ics. The decay rates of the SNe sample show a remarkable similarity in I band at late-times with a scatter of $\sim$10%.

Keywords. gamma ray bursts, (stars:) supernovae: general, (stars:) supernovae: individual (SN 2003dh, SN 2006aj)

1. Introduction

Long duration Gamma Ray Bursts (GRBs) are thought to be associated to a special type of stripped envelope supernovae (SNe) that have lost most of their outer H and He envelope (type Ic). A few SNe out of the type Ic's show broad spectral lines with very high expansion velocities ($\sim$ 30, 000 km/s) and are known as 'broad lined' type Ic SNe. Till date all SNe associated with GRBs and X-Ray Flashes (XRFs) which have been spectroscopically typed have been found to be type Ic SNe. Because of the energetic nature of explosion, the SNe associated to GRBs are often termed as 'hypernovae'. While there is accumulating evidence that nearly all low redshift GRBs have an underlying broad lined type Ic SN, not all energetic broad lined type Ic's show a GRB association.

The first GRB to be associated with a SN, GRB 980425, was detected by the Gamma Ray Burst Monitor onboard the *BeppoSAX* satellite and further spectroscopic observations confirmed that the new optical transient in the error box of GRB 980425 was indeed a very luminous SN (named SN 1998bw) and was classified as a type Ic SN (Galama *et al.* 1998, Iwamoto *et al.* 1998). However, it was with the discovery of GRB 030329/SN 2003dh that the association of GRBs with SNe became incontrovertible and provided the first unambiguous evidence of a SN association with a long duration GRB. Since then about a dozen more SNe have been spectroscopically confirmed to have a GRB association with spectral features which are clearly of broad lined type Ic SNe (see Cano *et al.* 2016 for a review).

The SNe light curves are powered by the radioactive decay of ^{56}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}Fe. The peak bolometric luminosity gives an estimate of ^{56}Ni synthesized in the explosion (Arnett 1982). The discovery of new GRB-SN associations and broad lined type Ic SNe is revealing a large diversity in terms of the ^{56}Ni production, ejecta mass and the explosion energy. The diversity in the ^{56}Ni produced comes in mainly because type Ic's show a lot of variability in the peak luminosity. Typically the broad lined type Ic without a GRB are found to be less luminous with smaller explosion energy and ejecta mass as compared to hypernovae associated to GRBs. The physical parameters for most of the GRB associated SNe are estimated from the information obtained using the early time light curve and spectrum. It is only in a few cases, like SN 1998bw where late-time data is available, that an estimation of physical parameters is possible (Patat *et al.* 2001) using the nebular phase data. In the case of GRBs it is not easy to construct late-time light curves of associated SNe because GRBs are typically distant objects and hence lack detailed study at late-times due to limited data.

In this paper, we examine the SNe associated with two long duration GRBs - SN 2003dh/GRB 030329 and SN 2006aj/XRF 060218 which are unique because of the availability of the *Hubble Space Telescope* (*HST*) data allowing us to constrain the decay nature of the late-time light curve of the SNe. Due to the proximity and nature of these GRB/XRF-SNe, the early afterglow and SN light curves of both SN 2003dh/GRB 030329 (z = 0.1685) and SN 2006aj/XRF 060218 (z = 0.033) have been studied by several authors in detail (Hjorth *et al.* 2003; Matheson *et al.* 2003; Stanek *et al.* 2003; Deng *et al.* 2005; Resmi *et al.* 2005; Cobb *et al.* 2006; Mazzali *et al.* 2006; Mirabal *et al.* 2006; Modjaz *et al.* 2006; Pian *et al.* 2006; Sollerman *et al.* 2006). The subset of GRB-SNe are compared with a sample of broad lined type Ic and normal type Ic supernovae which have published late-time light curves.

2. Data Reduction

HST observed the afterglow of GRB 030329 and the associated supernova SN 2003dh in *F606W* and *F814W* colors from $\sim$ 17 to 772 days after the burst. The last epoch *HST* observations at $\sim$ 772 and 422 days after the burst in *F606W* and *F814W* colors respectively are used to estimate the host galaxy flux. At late-times the contribution of the afterglow to the total flux becomes negligible and the supernova flux dominates. We therefore use the *HST* data beyond $\sim$ 72 days after the burst when the contribution from the afterglow becomes insignificant. The late-time observations of XRF 060218/SN 2006aj spanning $\sim$ 150–260 days after the burst were carried out at four epochs in four colors - *F435W, F555W, F625W* and *F814W*. We do not have SN 2006aj host galaxy images free from supernova flux to estimate the host galaxy flux.

The *HST* data were processed using the `multidrizzle` routine within the `stsdas` package in IRAF (Fruchter & Hook 2002). We used a `pixfrac` of 0.8 and a `scale` of 0.03333 to obtain the final drizzled image. Thus, the final images have a pixel size of 0.033 arcsec/pixel. The residual image in GRB 030329 is created by subtracting the last epoch image from the early epochs and is shown in Figure 1. In the subtracted image we accurately know the position of the optical transient and estimate the supernova flux in a fixed aperture. In the case of SN 2006aj/XRF 060218 subtracting the early epochs from the last epoch gives a clear detection of the optical transient and a very accurate position as shown in Figure 1. In the case of SN 2006aj the supernova flux is measured in a small aperture; the total flux thus contains the contribution of the host galaxy within this aperture. For both the sources, the corresponding AB magnitudes are estimated using the ACS zero points.

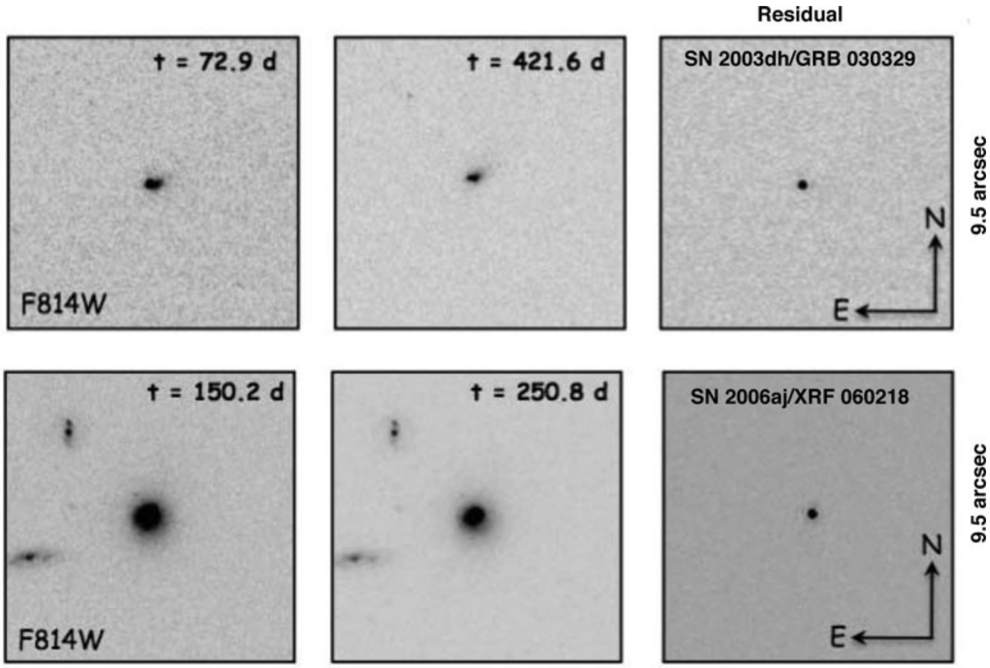

Figure 1. *HST* ACS imaging of SN 2003dh/GRB 03029 and SN 2006aj/XRF 060218 in F814W filter at two epochs as shown in the figure. The residual image is created by subtracting the last epoch image from early epochs.

3. Analysis and Preliminary Results

The unique data set of both SN 2003dh and SN 2006aj allows us to study the late-time behaviour of the light curve. The flux estimates of SN 2003dh are free of any host contamination as discussed in Section 2. To these fluxes we fit an exponential ($F(t) = Ae^{-\alpha t}$ where A is the normalization and α is the decay rate) and estimate the late-time decay rates. In the case of SN 2006aj since we do not have host galaxy flux measurements we add a constant C to the above mentioned exponential form in order to account for the host galaxy flux within the aperture. The decay rates for SN 2003dh and SN 2006aj as obtained from the exponential fits and the corresponding errors are listed in Table 1 and shown in Figure 2.

We also compare the late-time light curves of SN 2003dh and SN 2006aj to two other GRB associated SNe - GRB 980425/SN 1998bw (Patat *et al.* 2001) and the supernova associated with XRF 020903 (Bersier *et al.* 2006). The decay rates of these two supernovae are taken from the literature and are listed in Table 2 for a comparison with our results on SN 2003dh and SN 2006aj. The apparent magnitudes published in the literature are converted to AB magnitudes for a direct comparison with AB magnitudes derived from the *HST* observations. The absolute magnitudes have been derived from the observed photometry using a cosmology of H_0=70 km s^{-1} Mpc^{-1}, Ω_m=0.27 and Ω_Λ=0.73. For each SNe we plot the absolute magnitudes in Figure 2 corrected for the luminosity distance and total (Galactic+Host) extinction. We see that the decay rates of SN 2006aj are remarkably similar to those of SN 1998bw at late-times except for the B band. On the other hand we see that the decay rates are steeper in SN 2003dh and they are similar to the decay seen in the supernova associated to XRF 020903 (Table 2). In Figure 2 we have also shown the ^{56}Co→^{56}Fe radioactive decay (0.0098 mag day^{-1}) in the case of complete

Table 1. Late-time decay rates of GRB associated supernovae

Object	*B*	*V*	*R*	*I*
GRB 030329/SN 2003dh	–	0.0218 ± 0.001	–	0.0189 ± 0.001
XRF 060218/SN 2006aj	0.0114 ± 0.004	0.0186 ± 0.001	0.0166 ± 0.0006	0.0170 ± 0.0008

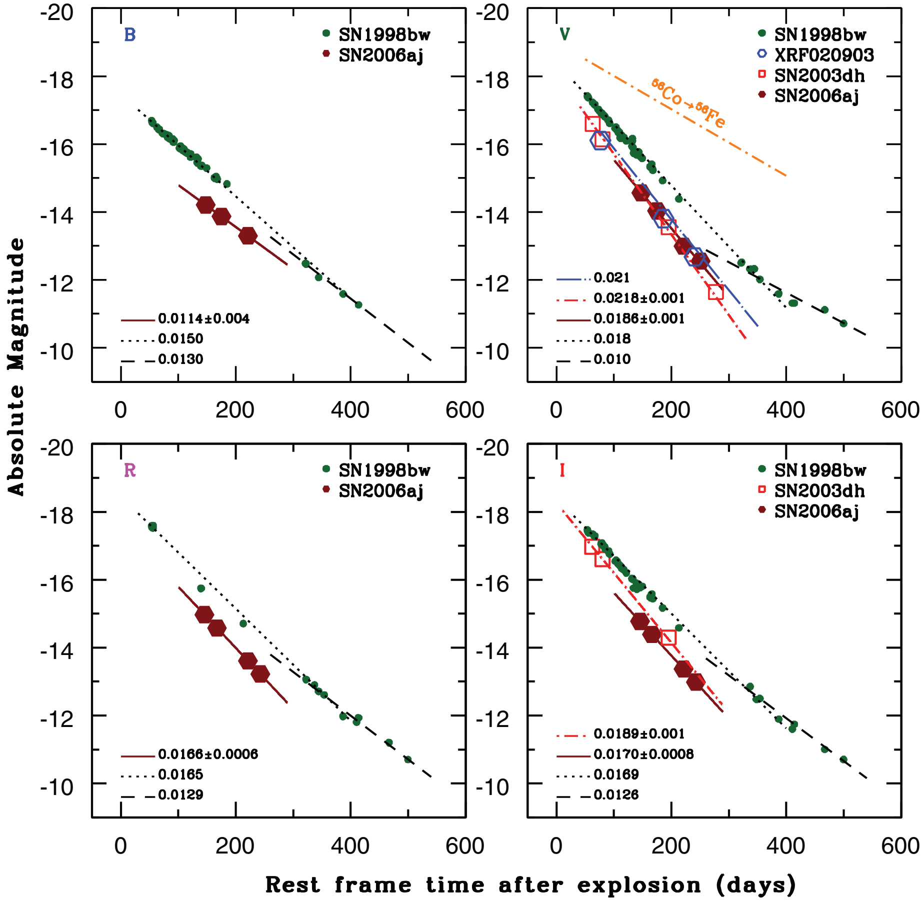

Figure 2. A comparison of multi-color absolute magnitudes of SN 1998bw (Galama *et al.* 1998; McKenzie *et al.* 1999; Sollerman *et al.* 2000; Patat *et al.* 2001), the supernova associated with XRF 020903 (Bersier *et al.* 2006), SN 2003dh (this work) and SN 2006aj (this work). The dotted and dashed lines represent the decay rates of SN 1998bw in the ranges 54-312 and 321-500 days respectively. The dash-dotted line corresponds to the ^{56}Co→^{56}Fe decay rate, as expected if there was no leakage of γ-rays.

γ-ray trapping. We see that the decay rates of all the supernovae shown in Figure 2 are steeper than the ^{56}Co→^{56}Fe decay rates indicating that there is some leakage of γ-rays. For a comparison, in SN 1998bw we also show the data in the time range of 324–504 days after the burst (Figure 2). At these late phases ($t > 300$ days), the multi-band light curves of SN 1998bw show a clear flattening and the light curve settles onto a ^{56}Co→^{56}Fe decay phase.

Table 2. A comparison of type Ic SNe late-time decay rates in the rest frame

Object	*B*	*V*	*R*	*I*	Reference
		GRB-SNe			
GRB 980425/SN 1998bw					
41-309 days	0.015 ± 0.001				Patat *et al.* 2001
41-323 days		0.018 ± 0.0006	0.0165 ± 0.0019	0.0169 ± 0.001	
308-400 days	0.013 ± 0.0008				
308-486 days		0.0101 ± 0.0008	0.0129 ± 0.0006	0.0126 ± 0.0008	
XRF 020903/SN					
76-240 days		0.021			Bersier *et al.* 2006
GRB 030329/SN 2003dh					
63-273 days		0.0218 ± 0.001			This work
63-195 days				0.0189 ± 0.001	
XRF 060218/SN 2006aj					
148-221 days	0.0114 ± 0.004				This work
148-250 days		0.0186 ± 0.001			
146-253 days			0.0166 ± 0.0006	0.0170 ± 0.0008	
		Type Ic-BL			
SN 2002ap					
135-230 days	0.017 ± 0.0004	0.021 ± 0.0002			Tomita *et al.* 2006
271-519 days	0.015 ± 0.002	0.014 ± 0.001			
136-513 days			0.016 ± 0.0001		
138-392 days				0.017 ± 0.0001	
SN 2003jd					
74-375 days	0.0144 ± 0.0013	0.0193 ± 0.0005	0.0152 ± 0.003	> 0.0163	Valenti *et al.* 2008
SN 2007ru					
>80 days		0.0154	0.0117		Sahu *et al.* 2009
		Type Ic			
SN 2004aw					
54-290 days	0.0137 ± 0.0018	0.0177 ± 0.0022	0.0138 ± 0.0014	0.0155 ± 0.0009	Taubenberger *et al.* 2006
SN 2007gr					
100-170 days	0.0153 ± 0.0003	0.0189 ± 0.0003	0.0128 ± 0.0004	0.0167 ± 0.0005	Hunter *et al.* 2009

We further increase our comparison sample by including the broad lined type Ic SNe that are not associated with any GRB/XRF and the normal type Ic SNe which have light curves published in the literature. We found three broad lined type Ic SNe (SNe 2002ap, 2003jd and 2007ru) without any GRB/XRF association and two normal type Ic SNe (SNe 2004aw and 2007gr) with published data extending out to reasonably late-times (nearly 170-500 days). Altogether we have a sample of nine type Ic SNe. In Table 2 we list the rest frame decay rates of the SNe in our sample in different colors at various time ranges. A comparison of the late-time decay rates of the SNe in our sample shows that the decay rates are fairly similar in the I band with a scatter of $\sim$ 10%. These decay rates are steeper than ^{56}Co$\rightarrow^{56}$Fe radioactive decay indicating that the γ-ray leakage seen in all type Ic SNe is standard.

4. Conclusions

We present the late-time *HST* ACS multi-color observations of two GRB associated SNe - GRB 030329/SN 2003dh and XRF 060218/SN 2006aj. Both these GRB associated supernovae are unique because of the availability of late-time data which allows us to constrain the decay behaviour at late-times. The SNe associated with GRB 980425/SN 1998bw and XRF 020903 are others for which late-time observations exist. The decay rates of SNe 2006aj and 1998bw are remarkably similar at late-times while those of SN 2003dh are steeper and similar to the SN associated with XRF 020903. In a larger sample of type Ic SNe including the broad lined type Ic with and without a GRB association and normal type Ic SNe, we find that the reported late-time decay rates (Table 2) are fairly similar in the I band with a scatter of $\sim$10%. It is also to be noted that the decay rates are steeper than ^{56}Co$\rightarrow$^{56}Fe radioactive decay indicating that the γ-ray leakage seen in all type Ic SNe is standard.

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