The GRB-SN connection: GRB 030329 and XRF 030723

J. P. U. Fynbo[*], J. Hjorth[†], J. Sollerman[**], P. Møller[‡], J. Gorosabel[§], F. Grundahl[*], B. L. Jensen[†], Michael I. Andersen[¶], P. Vreeswijk[‖], A. Castro-Tirado[§] and the GRACE collaboration[††]

[*]*Department of Physics and Astronomy, Ny Munkegade, DK-8000 Aarhus C, Denmark*
[†]*Astronomical Observatory, Juliane Maries Vej 30, DK–2100 Copenhagen Ø, Denmark*
[**]*Stockholm Observatory, Department of Astronomy, AlbaNova, S-106 91 Stockholm, Sweden*
[‡]*European Southern Observatory, Karl Schwarzschild-Strasse 2, D-85748 Garching, Germany*
[§]*Instituto de Astrofísica de Andalucía, IAA-CSIC, P.O. Box 03004, 18080 Granada, Spain*
[¶]*Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany*
[‖]*European Southern Observatory, Casilla 19001, Santiago 19, Chile*
[††]*http://zon.wins.uva.nl/ grb/grace/*

Abstract. The attempt to secure conclusive, spectroscopic evidence for the GRB/SN connection has been a central theme in most GRB observing time proposals since the discovery of the very unusual GRB 980425 associated with the peculiar type Ib/c SN 1998bw. GRB 030329 provided this evidence to everybody's satisfaction. In this contribution we show the results of a spectroscopic campaign of the supernova associated with GRB 030329 carried out at ESOs Very Large Telescope. We also present preliminary results from a photometric and spectroscopic campaign targeting the X-ray Flash of July 23.

INTRODUCTION

Like GRB 980425, the Gamma Ray Burst (GRB) detected by the Hete-II satellite on March 29, 2003 was born famous. It was so bright in γ-rays that the duty astronomer on the Hete-2 team designated it 'monster GRB'. The fluence alone places GRB 030329 in the top 0.2% of the 2704 GRBs detected with the Burst And Transient Source Experiment (BATSE) during its nine years of operation. The designation was further justified by the detection of the very bright Optical Afterglow (OA) with an optical magnitude around 12.4 (e.g. Price et al. 2003; Torii et al. 2003; Sato et al. 2003). Its redshift was determined with the high resolution UVES spectrograph at the European Southern Observatory (ESO) to be $z = 0.1685$ (Greiner et al. 2003a), the lowest redshift ever measured for a normal (excluding GRB 980425), long duration GRB. From that point on it was clear to everybody that GRB 030329 offered a unique chance to finally obtain spectroscopic proof of the connection between long duration GRBs and core collapse supernovae (SNe). This connection was believed to exist both from theoretical expectation (e.g. MacFadyen & Woosley 1999; Dado et al. 2003 and references therein) and observational hints. The strongest but also most elusive observational hint came from the very unusual GRB 980425 that was associated with the very energetic type Ib/c SN 1998bw (Galama et al. 1998; Patat et al. 2001). However, the fact that GRB 980425 had a total equivalent isotropic energy release four orders of magnitude smaller than any other well studied long duration GRB left the reasonable doubt that it possibly was not representative for other GRBs.

Another important set of observations were bumps seen superimposed on the OA lightcurves (e.g. Bloom et al. 1999; Castro-Tirado & Gorosabel 1999). For GRB 011121 and GRB 021211 there were, in addition to photometric evidence, also tentative but not conclusive spectroscopic evidence for an underlying core collapse SN (Garnavich et al. 2003a; Greiner et al. 2003b; Della Vella et al. 2003). The attempt to secure conclusive, spectroscopic evidence for the GRB/SN connection was therefore a central theme in GRB science, especially from 1999 and onwards.

In this contribution we describe the observations of the afterglow and SN associated with GRB 030329 within the context of GRACE[1]. These results have been published in Hjorth et al. (2003) and will be more thoroughly described in a paper in preparation. We also briefly review the results obtained by other groups. Finally, we show preliminary results from an extensive GRACE follow-up of the X-Ray Flash (XRF) from July 23 2003. In this case there is photometric evidence for an associated SN.

GRACE OBSERVATIONS OF OA 030329

After the determination of the redshift of GRB 030329, we designed an extensive spectroscopic campaign aimed at detecting and following the supernova expected to be associated with the GRB. Spectra were obtained with the FORS1 or FORS2 spectrographs on six epochs from April 3 through May 1. In the left panel of Fig. 1 we show the six flux-calibrated spectra. As seen, the spectrum evolves from a featureless power-law spectrum to a SN-like spectrum dominated by broad features. The presence of a SN was first reported by Garnavich et al. (2003b) on April 9 2003 whereby it was designated SN 2003dh. Superimposed on the spectrum are several strong emission lines from the underlying host galaxy (shown in more detail in the right panel of Fig. 1). Shown in the left panel of Fig. 1 with a dashed line is the spectrum of SN 1998bw 33 days after GRB 980425. The similarity between this spectrum and the spectrum of SN 2003dh is striking.

In the left panel of Fig. 2 we show the V-band lightcurve of OA 030329 primarily based on observations from ESO telescopes by GRACE (Guziy et al. 2004, submitted). There is no obvious SN bump seen in the lightcurve.

To investigate the SN component in more detail we performed a spectral decomposition of the afterglow, SN and host galaxy components as follows. While the host galaxy has strong emission lines, its continuum flux upper limit is negligible at early epochs and significantly less than the total flux at the later epochs. The contribution from the host galaxy was therefore accounted for by simply removing the emission lines. Model spectra were constructed as a sum of a power law ($f^{-\beta}$) and a scaled version of one of the SN 1998bw template spectra from Patat et al. (2001). For each template, or section

[1] Gamma Ray Afterglow Collaboration at ESO, http://zon.wins.uva.nl/ grb/grace/.

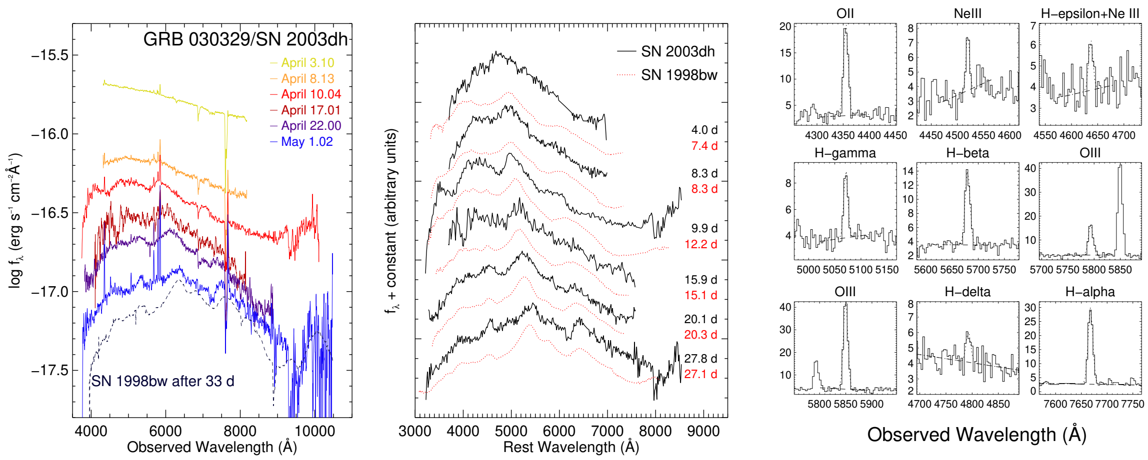

FIGURE 1.

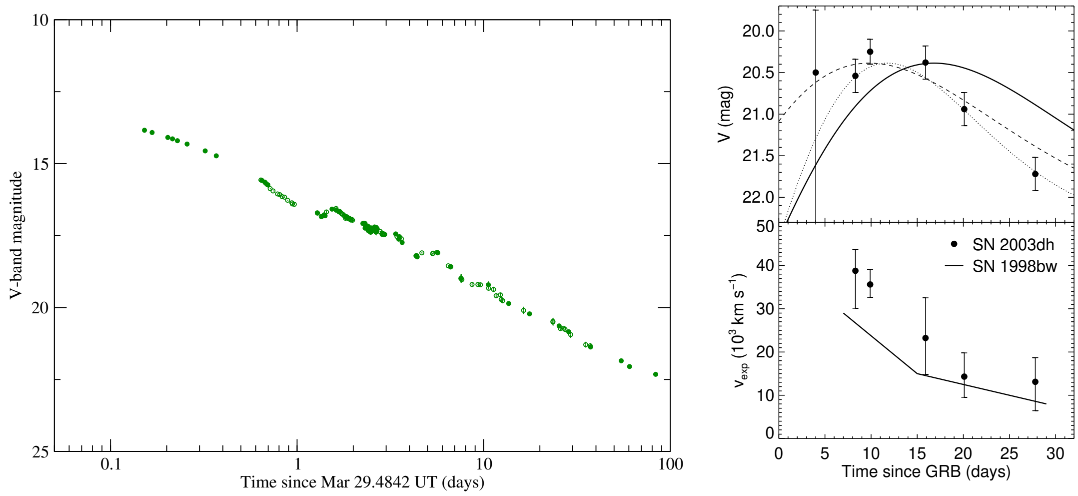

FIGURE 2.

thereof, a least-squares fit was obtained through fitting of the three parameters: power-law index β, amplitude of afterglow, and amplitude of supernova. In most cases the best fitting index was found to be $\beta = -1.2 \pm 0.05$ which was adopted throughout. We note, however, that the resulting overall spectral shape of the supernova contribution does not depend on the adopted power-law index or template spectrum. The result of this decomposition is shown in the middle panel of Fig. 1. The striking similarity between the spectra of SN 1998bw and SN 2003dh is clearly seen. The spectral peak wavelength, for both supernovae, is shifting towards the red. The shift is on average 25Å per day for SN 2003dh, which is similar to the evolution of the early spectra of SN 1998bw. The cause of this shift is the growing opacity in the absorption bluewards of 4900Å (rest wavelength).

The spectral decompositions provide the fraction of the total flux in the V-band that is due to the supernova. The resulting SN 2003dh V magnitudes are plotted in the right panel of Fig. 2. The full drawn line in this plot shows the brightness of SN 1998bw as it would have appeared in the V-band at z = 0.1685 as a function of time (restframe) since GRB 980425. Dashed line, as for the solid line but shifted 7 days earlier. Such an evolution may be expected if the supernova exploded seven days before the GRB. For SN 2003dh, however, this is inconsistent with its spectral evolution (Fig. 2). Dotted line, as for solid line, but evolution speeded up by multiplying time by 0.7. A faster rise and decay may be expected in asymmetric models in which an oblate supernova is seen pole-on (e.g. Woosley et al. in these proceedings). We assumed 0.20 mag extinction for SN 1998bw (Patat et al. 2001) and none for SN 2003dh. The bottom right plot in Fig. 2 shows the expansion velocities as a function of time in the restframe. Filled circles, SN 2003dh; solid line, SN 1998bw. The SN 2003dh values are our best estimates based on the decomposed spectra (see Hjorth et al. 2003 for details). We caution that in some cases these values are very uncertain owing to other features in the spectra around the expected minimum. The solid line shows the trend for SN 1998bw based on the data points in Patat et al. (2001). The consistent decaying trend in the ejecta velocity of SN 2003dh, together with its very high initial value, indicate that there was no delay between the GRB and the onset of the SN explosion.

Finally we note that the host galaxy is an actively star forming dwarf galaxy with a total luminosity similar to that of the SMC and with a moderate metallicity ([O/H] ≈ -1, Hjorth et al. 2003). From the OII and Hα emission lines (shown along with the other detected emission lines in the right panel of Fig. 1) we infer a star formation rate of a few tenths solar masses per year. In this respect GRB 030329/SN 2003dh is also similar to GRB 980425/SN 1998bw that was hosted by an actively star forming dwarf galaxy of type SBc (Fynbo et al. 2001).

COMPARISON WITH INDEPENDENT STUDIES

A study of SN 2003dh has been presented in the paper by Stanek et al. (2003) and in the thorough and comprehensive paper by Matheson et al. (2003). These authors follow a decomposition strategy very similar to the one described above leading to very similar results for the properties of SN 2003dh. Two spectra during the supernova dominated phase were also secured by Kawabata et al. (2003). The most significant difference between our and other works is that Matheson et al. (2003) find a lightcurve for SN 2003dh that is identical to that of SN 1998bw within the erros. This is clearly not the case in the right panel of Fig. 2. Bloom et al. (2003) speculate that there was a significant chromatic slit loss in our April 3 observation due to the fact that we did not observe at the parallactic angle. However, the FORS spectrographs are equipped with atmospheric dispersion correctors[2] that should minimize this effect. In a future paper in preparation we will study in more detail if the lightcurve of SN 2003dh is consistent with that of SN 1998bw or not.

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[2] see http://www.eso.org/instruments/fors1/adc.html for details

XRF 030723

We end this contribution by describing our most recent results from follow-up observations of the X-Ray Flash of July 23, 2003 (Fynbo et al. 2004, in preparation). XRF 030723 was located precisely by the SXC detector on Hete-II (Prigozhin et al. 2003). We started observations 4 hrs after the burst and followed the evolution of the lightcurve during two months thereafter. In the left panel of Fig. 3 we show the R-band lightcurve from a few hours to about 70 days after the explosion. The decay curve is consistent with being very flat during the first 24 hr after the burst. Around 1 day after the burst the decay slope $dm/d\log t$ steepens to about -2 and it remains so for the following 4-5 days. Around a week after the burst the decay curve starts to deviate from the fast decay and it then quickly rises to a secondary maximum, peaked at around 16 days, followed by a new steep decay. In the middle panel of Fig. 3 we show the bump emission with an extrapolation of the afterglow lightcurve subtracted.

Spectroscopic observations were secured on July 26 and on August 8 during the steeply declining afterglow and bump phases respectively. The spectrum of the afterglow from July 26 covers the region from about 3800Å to 8500Å and it shows a featureless continuum with no significant absorption or emission lines. From the lack of Lyα absorption we infer an upper limit to the redshift of about $z = 2.1$. The spectrum taken during the bump on August 8 covers the region 5300Å to 8600Å. It also shows no significant narrow emission or absorption lines.

Multicolor imaging was secured on four epochs. The afterglow spectral energy distribution is well described by a $\beta \approx -1$ power-law over the full range from the U-band to the K-band (right panel of Fig. 3). During the bump phase the spectral energy distribution starts to deviate strongly from a power-law shape due to a strong decrease in the flux in the bluest bands.

In a sense the situation for XRF 030723 is opposite to that of GRB 030329. For GRB 030329 the lightcurve did not show a strong bump apparently due to a late break in the afterglow lightcurve that by coincidence balanced out the extra emission from the SN. On the other hand the spectroscopic evidence was unambiguous. For XRF 030723 the photometry shows the most significant late time bump ever detected in an afterglow lightcurve at the time expected for an underlying supernova, but the spectroscopic evidence is more unclear. Nevertheless, it is clear that a SN 1998bw lightcurve is inconsistent with our data at any redshift. So far the best match found is for a SN similar to the type Ic SN 1994I, which had a very early peak time and a rather narrow peak in its lightcurve, at a redshift around $z \approx 0.6$ (Fig. 3, middle panel). Interestingly, a SN similar to SN 1994I has also been proposed to be associated to GRB 021211 (Della Valle et al. 2003). However, even this SN has a too slow rise to match the data.

CONCLUSION

The connection between core collapse SN, more specifically of type Ib/c, and long duration GRBs has been demonstrated to everybody's satisfaction in the case of GRB 030329/SN 2003dh. The results for XRF 030723 show that XRFs are most likely

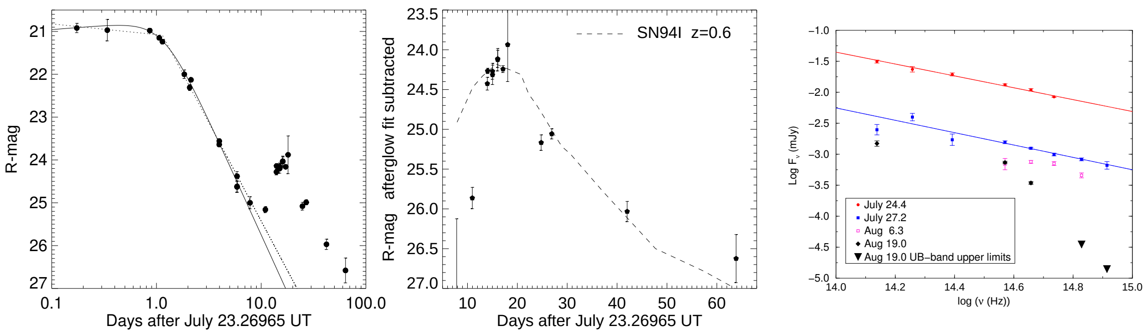

FIGURE 3.

also related to core collapse SN of type Ib/c. However, other potential explanations for the light curve bump should be investigated. A connection between XRFs and SN of type Ib/c would support the hypothesis that XRFs and GRBs are manifestations of the same underlying phenomenon seen either under different viewing angles of with different baryon loadings.

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