

Multiwavelength afterglows of Gamma-Ray Bursts

Elena Pian^{1,2*} and Jens Hjorth³

¹ INAF, Astronomical Observatory of Trieste, Via G.B. Tiepolo 11, I-34131 Trieste, Italy

² CNR-IASF, Via. P. Gobetti 101, I-40129 Bologna, Italy

³ Niels Bohr Institute, Astronomical Observatory, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen Ø, Denmark

Abstract Our knowledge of Gamma-Ray Burst (GRB) progenitors is based on three cases at relatively low redshift (between 0.01 and 0.2) in which the association with a supernova (SN) has been firmly established. In a number of higher redshift GRBs the presence of a SN has been suggested, although the properties of the SN could not be precisely determined. However, the study of several tens of multiwavelength afterglows has now provided evidence that GRBs are associated with star formation. The observational results which point to this connection are reviewed, and the high energy properties of afterglows and SNe are compared.

Key words: Gamma-ray bursts — Supernovae

1 INTRODUCTION

The detection and monitoring of Gamma-Ray Burst (GRB) afterglows at many wavelengths has boosted our knowledge of these high energy sources, so that the last seven years since first afterglow detection have witnessed an incomparably larger progress in the understanding of GRB physics than afforded by gamma-ray observations of the prompt events only (Fishman & Meegan 1995). The basic ingredient of this success is the determination of the GRB distance scale. This has been made possible by the redshift measurements, thanks to accurate spectroscopy of the afterglows and by the detection of host galaxies, through deep optical and infrared imaging. The cosmological distance scale of GRBs has thus been firmly established¹. At an average redshift of $\langle z \rangle = 1.4 \pm 0.2$, GRBs have energy outputs of the order of $10^{52} - 10^{53}$ erg, assuming the radiation is emitted isotropically (Fig. 1). These energies are reminiscent of those emitted by supernovae (SNe), although at least one order of magnitude larger. This has reinforced the hypothesis that GRBs are originated in powerful SN explosions. Specifically, very massive stars should end their lives via core collapse by leaving behind a $2-3 M_{\odot}$ black hole (MacFadyen & Woosley 1999). Part of the envelope promptly forms an accretion disk which feeds a (probably two-sided) jet. The rotational energy extracted from the black hole is carried

* E-mail: pian@ts.astro.it

¹ We refer here to long GRBs, i.e. those with duration larger than ~ 2 seconds, as opposed to sub-second GRBs, which represent $\sim 30\%$ of the GRB population and have no detected counterparts at energies lower than the gamma-rays (Kouveliotou et al. 1993).

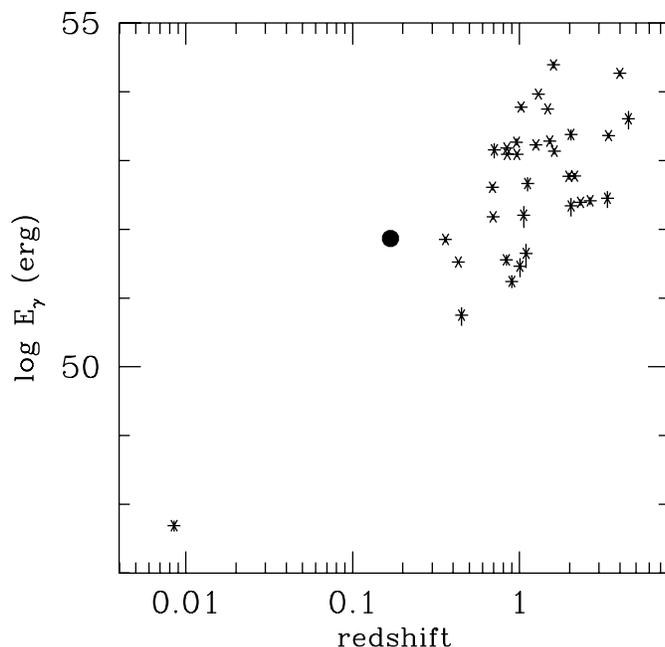


Fig. 1 Isotropic gamma-ray output of GRBs vs redshift, computed assuming $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\lambda = 0.7$. The filled circle represents GRB 030329 (see Sect. 2.2).

along the jet as a relativistic outflow which produces the GRB via internal hydrodynamical shocks and the multiwavelength afterglow via interaction of the decelerating blast wave with the circumstellar medium (external shock, Piran 1999). One consequence of this scenario is that GRBs should be expected to trace massive star formation, so that their distribution as a function of redshift should be correlated with the history of star formation in the Universe. The basic observational evidence for the relationship between GRBs and the final evolutionary phases of massive stars is reviewed in Section 2.

2 THE LINK BETWEEN GAMMA-RAY BURSTS AND STAR FORMATION

Observations of GRB afterglows and of their host galaxies from radio to X-ray frequencies have provided various independent suggestions that GRBs tend to explode in sites where active star formation is taking place. One of these is represented by the detection of metal lines in the X-ray afterglows, both in emission and absorption (e.g., Piro et al. 1999; Antonelli et al. 2000; Piro et al. 2000; Amati et al. 2000; Reeves et al. 2003; Butler et al. 2003; Watson et al. 2003). These are interpreted as signatures of a medium enriched by explosive nucleosynthesis, such as that occurring in SN events. For GRB 021004, spectroscopy of the optical afterglow has revealed absorption lines with multiple velocity components, indicating the presence of shells around a massive progenitor star (Schaefer et al. 2003; Mirabal et al. 2003; Castro-Tirado et al. 2004). Many properties of the GRB host galaxies support the link between GRBs and star formation

(see Subsection 2.1). However, the strongest indication that GRBs are related to a massive star population comes from the direct connection between some GRBs and SN features (Subsection 2.2).

2.1 Host galaxies of Gamma-Ray Bursts

Whenever the position of an afterglow has been determined to arcsecond precision (through imaging in the optical, radio, or X-rays with the Chandra or XMM-Newton satellites) a galaxy has been detected at angular distance not exceeding few arcseconds from the afterglow. This is usually identified with the GRB host galaxy, and generally the spectroscopy of both afterglow and galaxy confirm the association. Accurate astrometry of the point-like afterglow source indicates that the projected distance of the GRB from the center of its host is on average a fraction of an arcsecond, but almost never consistent with zero (Bloom et al. 2002a; see however Fruchter et al. 2000). This excludes that GRBs are caused by nuclear events, and points to their association with the peripheral regions of the host stellar disks, where most of the star formation takes place.

GRB host galaxies are generally underluminous and have blue colors, indicative of ongoing intense star formation (Fruchter et al. 1999a; Le Floch et al. 2003). For those having extensive broad band optical and IR photometry, the modeling of the spectral energy distribution is well accounted for by starburst template spectra (Gorosabel et al. 2003a; Gorosabel et al. 2003b; Christensen et al. 2004). The morphologies of GRB host galaxies are often irregular or disky, typical of late type galaxies, where most of the star formation is occurring. In some cases they are found to belong to small groups or clusters or to weakly interacting systems, an environmental characteristic thought to favour or trigger star formation (Fruchter et al. 1999b; Djorgovski et al. 2001a; Jaunsen et al. 2003).

The spectra of GRB host galaxies often exhibit strong emission lines considered to be star formation tracers: [O II], [O III], Lyman α , Balmer and Paschen series, [Ne III] (Kulkarni et al. 1998a; Bloom et al. 1998; Hjorth et al. 2003; Christensen et al. 2004; Castro-Tirado et al. 2004; Greiner et al. 2003). In particular, the [O II] line equivalent widths measured for GRB hosts are among the largest in an unbiased sample such as the Hubble Deep Field (Fig. 2). The star formation rates derived from the spectral continua of host galaxies or from the emission line strengths range between 0.1 to $10 M_{\odot} \text{ yr}^{-1}$, remarkable for small and underluminous galaxies, although not exceptionally high. However, those are likely to underestimate the true values, due to intrinsic extinction affecting the continuum and line fluxes, emitted at UV restframe wavelengths. The star formation rate estimates based on radio and millimetric observations can exceed those derived in the optical by as much as a factor 100 (Chary et al. 2002; Frail et al. 2002; Berger et al. 2003), although it is not clear why sub-millimeter host galaxies such as those of GRB 000210 and GRB 000418 are typical faint blue galaxies (Gorosabel et al. 2003a; Gorosabel. 2003b).

That significant intrinsic obscuration must occasionally be present in GRB hosts is indicated by the afterglow optical and soft X-ray spectra, often affected by small additional extinction on top of the Galactic one. This however may be local to the GRB. In fact, a gas- and dust-rich close environment could cause many GRB counterparts (nearly 10% of the total, Lamb et al. 2003) to be unobservable at optical frequencies. Whether the optical “darkness” of this fraction of afterglows is due to a higher density of the circumburst medium with respect to optically bright counterparts is not clear. The difference may in fact also arise from the geometry of the source itself: a more collimated jet may have sufficient power to destroy efficiently the surrounding dust and carve a path for optical light to reach the observer, while less collimated, and thus less powerful, jets would leave the dust grains unaltered, and optical light would be absorbed (Reichart & Yost 2004). In conclusion, although the role played by dust in “dark”

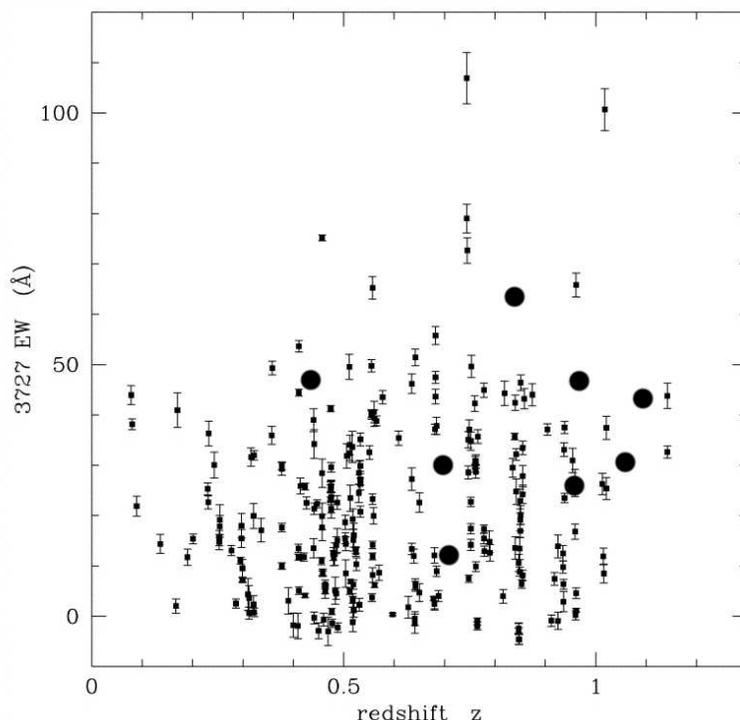


Fig. 2 Rest-frame equivalent widths of [O II] 3727 line emission for a set of GRB host galaxies (filled circles) compared with those of galaxies in the Hubble Deep Field (from Djorgovski et al. 2001b).

GRBs is still unexplained, there is little doubt about its presence, which again points to a star forming environment.

2.2 The connection between Gamma-Ray Bursts and Supernovae

While the hypothesis that GRBs originate in SN explosions dates from the time of GRB discovery (Colgate 1974), only in the last six years could this scenario be confirmed observationally, at least for some GRBs. The detection of a peculiar Type Ic SN, 1998bw, in the error box of GRB 980425 has been regarded as a strong indication of causality between the two events (Galama et al. 1998; Kulkarni et al. 1998b; Woosley et al. 1999; Pian et al. 2000). However, due to the remarkably short distance to the SN ($z = 0.0085$) as compared to that of the majority of GRBs with measured redshift ($z \sim 1$), and to the lack of a “classical” multiwavelength afterglow, the association between GRB 980425 and SN 1998bw has been controversial. A number of GRB optical/NIR counterparts clearly exhibited re-brightenings in their light curves, which have been attributed to the contribution of an underlying SN (Castro-Tirado & Gorosabel 1999; Bloom et al. 1999; Galama et al. 2000; Bjornsson et al. 2001; Castro-Tirado et al. 2001; Lazzati et al. 2001; Bloom et al. 2002b; Dado et al. 2002a; Dado et al. 2002b; Price et al. 2003; Della Valle et al. 2003; Garnavich et al. 2003; Greiner et al. 2003; Masetti et al. 2003; Dado et al. 2003a; Dado et al. 2003b; Thomsen et al. 2004). However, detailed spectroscopy

during the re-brightening was only rarely feasible owing to the faintness of the fluxes and/or the contamination from the host galaxy, and when accomplished the presence of a SN could not be confirmed.

A bright optical afterglow was identified for the GRB of 29 March 2003 (Price & Peterson 2003; Torii et al. 2003; Matheson et al. 2003; Guzyi et al. 2004). Its redshift ($z = 0.168$) was very low with respect to the average of other GRBs (~ 1), but higher than GRB 980425. This “intermediate” redshift GRB ought to be the Rosetta stone of long GRBs progenitors, since if a SN was present it would show prominently, due to its relative proximity. Spectroscopic campaigns started shortly after GRB detection, and SN absorption features superposed on the power-law afterglow spectrum were revealed within 1 week. These signatures became increasingly evident with time as the non-thermal component decayed, and were strikingly reminiscent of those exhibited by SN 1998bw (Fig. 3). The presence of a Type Ic SN (SN 2003dh) was announced by Stanek et al. (2003). Further spectroscopy with the ESO Very Large Telescope (VLT) at epochs ranging from 4 days to 1 month after the GRB allowed Hjorth et al. (2003) to confirm this finding (Fig. 4, left) and to reconstruct the SN 2003dh light curve through subtraction of the non-thermal afterglow component from the observed fluxes, and to map the temporal evolution of the photospheric velocity. This is $\sim 0.1c$ at about 1 week after the GRB, similar to the values reached in SN 1998bw, and is indicative of extreme kinematic conditions (Fig. 4, right).

To reproduce these conditions, the models imply very high explosion energies, of the order of $\sim 10^{52}$ erg (in spherical symmetry), which is more than an order of magnitude larger than the kinetic energy of normal SNe (Iwamoto et al. 1998; Mazzali et al. 2003; Woosley & Heger 2003). Also, for both SN 1998bw and SN 2003dh, modelling of the light curve yielded the result that the mass of radioactive ^{56}Ni synthesised — which is necessary to produce the luminosity of the SNe — was much larger than in normal core-collapse SNe (0.5 and $0.35 M_{\odot}$, respectively, vs. $0.1 M_{\odot}$). In these powerful SNe, also dubbed “hypernovae” (Paczynski 1998; Iwamoto et al. 1998), the kinetic energy may be overestimated if the explosions were asymmetric and we observed the SNe near the direction of highest energy output, as is possible since we observed the GRBs. Very recently, a third case for spectroscopic identification of a SN similar to SN 1998bw coinciding with a low-redshift GRB has been reported, GRB 031203/SN 2003lw (Tagliaferri et al. 2004).

Other SNe Ic which exhibited the broad lines typical of hypernovae have been studied (Iwamoto et al. 2000; Mazzali et al. 2000; Mazzali et al. 2002). Although these SNe apparently were not associated with a GRB, this could be due to an unfavourable orientation and/or a less energetic explosion. All of these objects have in common a higher-than-normal kinetic energy and a large progenitor mass ($> 20 M_{\odot}$), suggesting that these events may be related to the formation of a black hole. This is in line with the theory for the birth of GRBs, which favours Type Ib/c SNe as GRB progenitors (MacFadyen & Woosley 1999; Zhang et al. 2003). SNe Ib/c have smaller envelopes than SNe II, making it easier for relativistic jets to break out. Jets may originate in the collapse of a neutron star to a black hole, which points to massive progenitors.

3 X-RAY OBSERVATIONS OF SN 1998BW

In light of the recent findings on SN-GRB association (Subsection 2.2), it is instructive to re-examine the X-ray behavior of SN 1998bw. This was sampled by the BeppoSAX Narrow Field Instruments at various epochs in 1998 (Pian et al. 2000), by Chandra in October 2001 (Kouveliotou et al. 2004), and by the XMM-Newton EPIC camera in March 2002 (Pian et al. 2003). The X-ray flux of SN 1998bw measured by XMM-Newton is contaminated by the emission of a nearby source (Kouveliotou et al. 2004).

In Fig. 5 the luminosity of SN 1998bw in the 0.3–2 keV range is compared to that of other core-collapse SNe decently monitored in X-rays. The late epoch X-ray fluxes of the counterpart

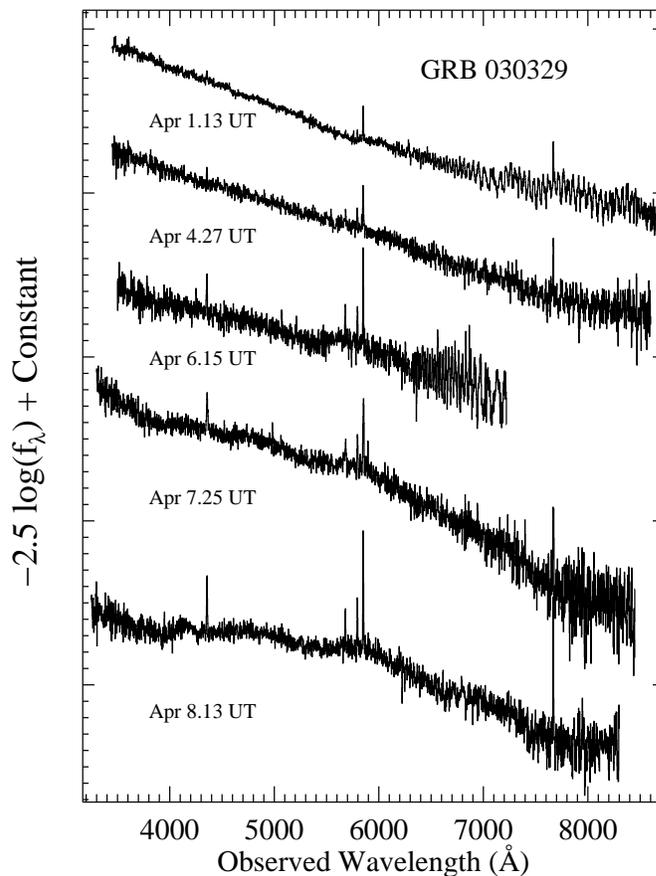


Fig. 3 Multiple Mirror Telescope spectra of GRB 030329 in April 2003. Spectra taken after April 5 show the development of broad peaks, characteristic of a SN (from Stanek et al. 2003).

of GRB 030329, measured by XMM-Newton, are also reported (while the early, very bright RXTE-measured fluxes are omitted). The comparison with SNe 1980K and 1994I suggests that the late epoch X-ray behavior of normal SNe and hypernovae may be different: the temporal decline of the X-ray emission from the hypernova SN 1998bw and from the GRB 030329 counterpart (to which hypernova SN 2003dh is presumably also contributing) is significantly faster than in normal SNe, suggesting the dominance of a more highly variable afterglow component in X-ray hypernovae.

The early X-ray detection of the hypernova SN 2002ap suggests a difference also in the early phases: while normal SNe are often detected in X-rays with substantial delays from the explosion time (see SN 1994I), hypernovae seem to exhibit early X-ray emission (SN 1998bw, SN 2002ap). One may argue that this early X-ray emission is different in nature than classical thermal bremsstrahlung radiation from supernova, and is perhaps produced through non-thermal “afterglow-like” radiation (see also Nakamura 1999; Dado et al. 2003c).

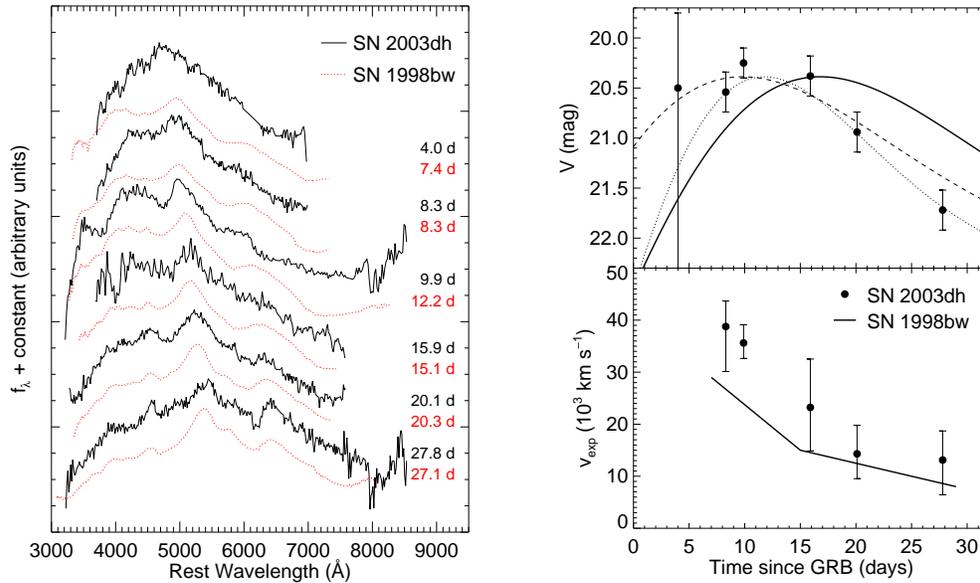


Fig. 4 *Left:* Comparison of the spectral evolution of SN 2003dh and SN 1998bw. Solid curves indicate spectra of SN 2003dh obtained through subtraction of the afterglow and host galaxy spectrum from the observed VLT spectra. Dotted curves indicate spectra of SN 1998bw taken at similar epochs. *Right-top:* V -band light curve of SN 2003dh at restframe since GRB 030329 (filled circles). The solid line represents the brightness of SN 1998bw as it would have appeared in the V band at $z = 0.168$ 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 SN exploded 7 days before the GRB. For SN 2003dh, however, this is inconsistent with its spectral evolution. Dotted line: as for solid line, but evolution speeded up by multiplying time by 0.7 (i.e., the velocity ratio of SN 2003dh to SN 1998bw). A faster rise and decay may be expected in asymmetric models in which an oblate SN is seen pole-on. A 0.2 mag extinction is assumed for SN 1998bw and none for SN 2003dh. *Right-bottom:* Si II $\lambda 6355$ expansion velocities as a function of time (restframe) of SN 2003dh (filled circles) and SN 1998bw (solid line) (from Hjorth et al. 2003).

4 CONCLUSIONS

The study of GRB multiwavelength afterglows and host galaxies has offered an unprecedented insight into GRB phenomenology, demographics and progenitor population. The exploratory work accomplished by satellites and by ground-based optical and radio telescopes will soon be followed by a more systematic approach by dedicated spacecrafts and instruments.

The Swift probe, to be launched in late 2004, will increase the rate of prompt and accurate GRB localizations by nearly an order of magnitude with respect to present, and will bring GRB science into the domain of statistics. Moreover, it will open the very early afterglow epochs (minutes to hours after GRB explosion) to our view and investigation. In this sense, robotic telescopes, reacting promptly and efficiently to Swift alerts, will play a crucial role in detecting the initial optical and NIR flashes accompanying GRBs. These are expected, at least in a large fraction of cases, to be extremely bright (Sari & Piran 1999) and to represent excellent

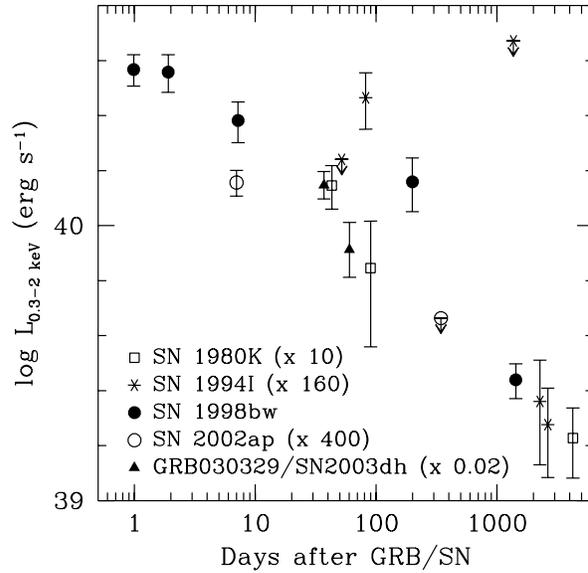


Fig. 5 X-ray light curves of various SNe (from Canizares et al. 1982, Schlegel 1994, Schlegel 1995, Immler et al. 2002, Pian et al. 2003, Soria et al. 2004, Kouveliotou et al. 2004, and references therein) and of the counterpart of GRB 030329 (Tiengo et al. 2004). When necessary, the measured fluxes have been reduced to the 0.3–2 keV range using the fitted spectral indices. Luminosities have been computed assuming $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\lambda = 0.7$. The X-ray flux of SN 1998bw measured by XMM-Newton (March 2002, Pian et al. 2003, 6th filled circle in the light curve) is contaminated by the emission of a nearby source. In the observation of October 2001 Chandra resolved the two sources. This may explain the fact that the flux measured by Chandra for SN 1998bw (5th filled circle) is substantially lower than that measured by XMM-Newton (Kouveliotou et al. 2004).

probes of the circumstellar as well as of the intervening medium, to test progenitor physics and cosmology, respectively.

In order to perform these tests, one will need accurate and good resolution spectroscopy from UV to NIR wavelengths executed in a timely fashion. This can be accomplished with an instrument similar to the Echellette Spectrograph and Imager mounted on the Keck telescope, with possibly farther extension into the NIR range. Such a spectrograph (“X-shooter”) is being implemented for the second generation of VLT instruments. Its main goals in the GRB field will be: 1) to measure routinely GRB redshifts from spectroscopy of their afterglows, in order to increase the number of known distances and build a GRB luminosity function; 2) to monitor time-dependent variations of the equivalent widths of weak absorption lines in afterglows, in order to test the progenitor models and GRB formation sites; 3) to implement a spectroscopic survey of GRB host galaxies by which we will measure redshifts, emission line intensities and broad band energy distributions, and thus catalog their distances and properties.

These new tools will allow us to tackle the many still unsolved problems of GRB physics more effectively than possible before and with a high expectation of exciting progress.

Acknowledgements EP would like to thank the organizers of the Vulcano Workshop for a pleasant and stimulating conference. Part of the work presented in this article is the result of an observing program implemented at ESO telescopes (including the VLT) by the GRACE consortium, which is here acknowledged for years of fruitful collaboration. We also acknowledge collaboration within the EU Research Training Network “GRBs: an Enigma and a Tool”.

References

- Amati L., et al., 2000, *Science*, 290, 953
Antonelli L.A., et al., 2000, *ApJ*, 545, L39
Berger E., et al. 2003, *ApJ*, 588, 99
Bjornsson G., Hjorth J., Jakobsson P., Christensen L., Holland S. 2001, *ApJ*, 552, L121
Bloom J.S., et al., 1998, *ApJ*, 507, L25
Bloom J.S., et al., 1999, *Nature*, 401, 453
Bloom J.S., Kulkarni S.R., Djorgovski S.G., 2002a, *AJ*, 123, 1111
Bloom J.S., et al., 2002b, *ApJ*, 572, L45
Butler N.R., et al., 2003, *ApJ*, 597, 1010
Canizares C.R., Kriss G.A., Feigelson, E.D., 1982, *ApJ*, 253, L17
Castro-Tirado A.J., Gorosabel J., 1999, *A&AS*, 138, 449
Castro-Tirado A.J., et al., 2001, *A&A*, 370, 398
Castro-Tirado A.J., et al., 2004, in preparation
Chary R., Becklin E.E., Armus, L., 2002, *ApJ*, 566, 229
Christensen L., et al., 2004, *A&A*, 413, 121
Colgate S.A., 1974, *ApJ*, 187, 333
Dado S., Dar A., De Rujula A., 2002a, *ApJ*, 572, L143
Dado S., Dar A., De Rujula A., 2002b, *A&A*, 393, L25
Dado S., Dar A., De Rujula A., 2003a, *ApJ*, 593, 961
Dado S., Dar A., De Rujula A., 2003b, *ApJ*, 594, L89
Dado S., Dar A., De Rujula A., 2003c, *A&A*, 401, 243
Della Valle M., et al., 2003, *A&A*, 406, L33
Djorgovski S.G., et al., 2001a, *ApJ*, 562, 654
Djorgovski S.G., et al., 2001b, in *Gamma-Ray Bursts in the Afterglow Era*, Proc. of the International Workshop held in Rome, Italy, 17-20 October 2000, Eds. E. Costa, F. Frontera, and J.Hjorth, p. 218 (astro-ph/0107535)
Fishman J., Meegan C., 1995, *ARA&A*, 33, 415
Frail D.A., et al., 2002, *ApJ*, 565, 829
Fruchter A.S., et al., 1999a, *ApJ*, 516, 683
Fruchter A.S., et al., 1999b, *ApJ*, 519, L13
Fruchter A.S., et al., 2000, *ApJ*, 545, 664
Galama T.J., et al., 1998, *Nature*, 395, 670
Galama T.J., et al., 2000, *ApJ*, 536, 185
Garnavich P.M., et al., 2003, *ApJ*, 582, 924
Gorosabel J., et al., 2003a, *A&A*, 400, 127
Gorosabel J., et al., 2003b, *A&A*, 409, 123
Greiner J., et al., 2003, *ApJ*, 599, 1223
Guzyi S., et al., 2003, in preparation
Hjorth J., et al., 2003, *Nature*, 423, 847

- Immler S., Wilson A.S., Terashima Y., 2002, *ApJ*, 573, L27
Iwamoto K., et al., 1998, *Nature*, 395, 672
Iwamoto K., et al., 2000, *ApJ*, 534, 660
Jaunsen A.O., et al., 2003, *A&A*, 402, 125
Kouveliotou C., et al., 1993, *ApJ*, 413, L101
Kouveliotou C., et al., 2004, *ApJ*, in press (astro-ph/0401184)
Kulkarni S.R., et al., 1998a, *Nature*, 393, 35
Kulkarni S.R., et al., 1998b, *Nature*, 395, 663
Lamb D., et al., 2003, *Proc. of the BeppoSAX Symposium: "The Restless High-Energy Universe"*,
Eds. E.P.J. van den Heuvel, J.J.M. in 't Zand, and R.A.M.J. Wijers, in press (astro-ph/0309462)
Lazzati D., et al., 2001, *A&A*, 378, 996
Le Floch E., et al., 2003, *A&A*, 400, 499
MacFadyen A.I., Woosley S.E., 1999, *ApJ*, 524, 262
Masetti N., et al., 2003, *A&A*, 404, 465
Matheson T., et al., 2003, *ApJ*, 599, 394
Mazzali P.A., et al., 2000, *ApJ*, 545, 407
Mazzali P.A., et al., 2002, *ApJ*, 572, L61
Mazzali P.A., et al., 2003, *ApJ*, subm. (astro-ph/0309555)
Mirabal N., et al., 2003, *ApJ*, 595, 935
Nakamura T., 1999, *ApJ*, 522, L101
Paczyński B., 1998, *ApJ*, 494, L45
Pian E., et al., 2000, *ApJ*, 536, 778
Pian E., et al., 2003, *Adv. Sp. Res.*, *Proc. of the 34th COSPAR Scientific Assembly, Houston, 10-19*
October 2002, Eds. N. Masetti, E. Pian, L. Piro, in press (astro-ph/0304521)
Piran T., 1999, *Physics Reports*, 314, 575
Piro L., et al., 1999, *ApJ*, 514, L73
Piro L., et al., 2000, *Science*, 290, 955
Price P.A., et al., 2003, *ApJ*, 589, 838
Price P.A., Peterson B.A., 2003, *GCN N.* 1987
Reeves J.N., et al., 2003, *A&A*, 403, 463
Reichart D.E., Yost S.A. 2003, *ApJ*, submitted (astro-ph/0107545)
Sari R., Piran T., 1999, *ApJ*, 520, 641
Schaefer B.E., et al., 2003, *ApJ*, 588, 387
Schlegel E.M., 1994, *AJ*, 108, 1893
Schlegel E.M., 1995, *Rep. Prog. Phys.*, 58, 1375
Soria R., Pian E., Mazzali P., 2004, *A&A*, 413, 107
Stanek K.Z., et al., 2003, *ApJ*, 591, L17
Tagliaferri G., et al., 2004, *IAU Circ.* 8308
Thomsen B., et al., 2004, *A&A*, in press (astro-ph/0403451)
Tiengo A., et al., 2003, *A&A*, 409, 983
Tiengo A., et al., 2004, *A&A*, submitted (astro-ph/0402644)
Torii K., et al., 2003, *ApJ*, 597, L101
Watson D., et al., 2003, *ApJ*, 595, L29
Woosley S.E., et al., 1999, *ApJ*, 516, 788
Woosley S.E., Heger, A., 2003, *ApJ*, submitted (astro-ph/0309165)
Zhang W., et al., 2003, *ApJ*, 586, 356

DISCUSSION

DANIELE FARGION: The connection between GRBs and SNe is very relevant because it implies (by the ratio $E_{\text{GRB } 030329}/E_{\text{GRB } 980425} \simeq 10^4$ and $\dot{E}_{\text{SN } 2003\text{dh}}/\dot{E}_{\text{SN } 1998\text{bw}} \simeq 1$) a very high collimation ($\gg 10^5 (= \Omega/\Delta\Omega)$). Moreover, the peculiar “bumps” in the optical transient of GRB 030329 may imply a precessing jet rebrightening. This might explain the apparent no-power-law behavior of late X-rays of SN 1998bw. I foresee a possible rebrightening also in GRB 030329 X-ray tail (contrary to cooling power-law).

ELENA PIAN: It is an interesting possibility, which will certainly be tested with XMM-Newton observations, if the source level will still allow. [Note added in proof: XMM-Newton has re-observed the GRB 030329 afterglow in December 2003, and detected a flattening decaying trend (Tiengo et al. 2004; see also Fig. 5).

FILIPPO FRONTERA: Are there indications from the light curve that the SN 2003dh exploded before GRB 030329?

ELENA PIAN: A SN explosion preceding the GRB is consistent with the data, although the paucity of data points in the rising portion of the light curve cause some degeneracy in the model curves at those early epochs. A more intensive monitoring would have been necessary in order to constrain better the time interval between SN and GRB.

JOHN HEISE: Kevin Hurley just called the GRB association with SN 1998bw “interesting, plausible, but not convincing”. In GRB 030329 this “not-convincing” spectrum is used as a template and provides a convincing case. If these two SNe have the same spectra, why are the other properties so dramatically different (4 orders of magnitude in isotropic energy)?

ELENA PIAN: Jet collimation, relativistic beaming and viewing angle play a crucial role in producing these huge differences in the gamma-ray output. Some maintain that the low luminosity of GRB 980425 may be due to the jet being misaligned with respect to the line of sight. This scenario poses problems (because the more isotropic X-ray afterglow should then be as luminous as other X-ray afterglows, while it is very unreluminous). In general, there is no clear consensus as to the possibility of predicting or deriving the collimation angle from the observables.

NINO PANAGIA: I have a comment and a question. Comment: Great caution should be used before determining the time of the explosion by comparing spectra of SNe that may be intrinsically different. Let’s not forget that Type Ib/c SNe display spectra that may resemble those of Type Ia at a later epoch. Question: what does one understand about the nature of a GRB source by observing the structure of the interstellar medium in front of it?

ELENA PIAN: In response to the comment: the spectra of SN 1998bw have been used here as templates for empirical comparison, because of the known hypernova nature of SN 1998bw. I agree that in general a proper modeling must be made by use of a radiative transfer code. In response to the question: the GRB high energy radiation ionizes the gas and destroys the dust in front of it. Time-dependent optical spectroscopy can probe the composition and possibly variable opacity in front of the GRB and distinguish the scenarios for the formation sites of GRBs.