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Anisotropies in Core Collapse Supernovae

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Abstract Core-collapse supernovae are the final stage of the evolution of massive stars. When these have previously lost their hydrogen and helium envelopes, the supernova explosion is classified as Type Ic. This class of supernovae are particularly interesting because of the link with long-duration Gamma-Ray Bursts. It is commonly believed that these explosions, especially when associated with a Gamma-Ray Burst, must be aspherical. Late-time observations of SN 2003jd, a luminous Type Ic supernova, provide direct evidence of this asphericity. Subaru and Keck spectra have revealed double-peaked profiles in the nebular lines of neutral oxygen and magnesium. These profiles are different from those of known Type Ic supernovae, with or without a gamma-ray burst, and they can be understood if SN 2003jd was an aspherical, axisymmetric explosion viewed from near the equatorial plane. We will discuss the implications of this observation for the association between GRBs and supernovae.

Key words: stars – supernovae – Gamma-Ray Bursts

1 INTRODUCTION: THE SUPERNOVA-GAMMA-RAY BURST CONNECTION

The observations of the optical afterglows of long[1] GRBs suggest that they are intimately connected with the death of massive stars (Woosley et al. 1999; Bloom et al. 2002; Mirabal et al. 2003). Optical spectroscopy indicates unambiguously that the progenitors of the three long GRBs at the lowest redshift (GRB 980425/SN 1998bw, Galama et al. 1998, $z = 0.0085$; GRB 030329/SN 2003dh, Hjorth et al. 2003; Matheson et al. 2003; Stanek et al. 2003, $z = 0.168$; GRB 031203/SN 2003lw, Malesani et al. 2004; Thomsen et al. 2004; Cobb et al. 2004; Gal-Yam et al. 2004, $z = 0.105$) are supernovae of unusually large kinetic energy and ejected mass of radioactive ^{56}Ni synthesized, the so called "hypernovae" (Iwamoto et al. 1998; Paczyński 1998). In addition, those three supernovae have remarkably similar appearances and properties: they are all of Type Ic, have comparable luminosities, their maximum photospheric velocities are $\sim 0.1c$, their ^{56}Ni ejected masses are about 0.4–0.5 $M_\odot$ (Iwamoto et al. 1998; Mazzali et al. 2003; Mazzali et al. 2006). In contrast, the three GRBs are rather different in total emitted energy, temporal profile and spectral hardness.

For few GRBs at higher redshifts, spectroscopic observations of the optical counterparts in search of a supernova underlying the non-thermal afterglow source are more arduous, and the signal-to-noise ratio of the data is limited (Greiner et al. 2003; Garnavich et al. 2003; Della Valle et al. 2003). In a larger number of GRBs at high redshift, the presence of an associated supernova is generally based on photometric evidence, and is therefore not completely unequivocal, but still highly suggestive. Photometry has in many cases

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[1] The distribution of Gamma-Ray Bursts (GRBs) durations is bi-modal, with a minimum around 2 s (Kouveliotou et al. 1993). The majority of GRBs (∼70%) have durations longer than ∼2 s, with an average around 30 s. The rest have sub-second durations and harder gamma-ray spectra than long-duration GRBs, and clearly represent a separate population, as also suggested by observations of their environments and host galaxies (e.g., Hjorth et al. 2005; Castro-Tirado et al. 2005; Covino et al. 2006; Berger et al. 2005; Bloom et al. 2006).

allowed the detection of re-brightenings in the light curves of the optical counterparts. These can typically be compared to down- or up-scaled versions of a SN 1998bw template (Zeh et al. 2004), implying that the properties of the supernovae potentially underlying the GRBs span a very wide range, from powerful hypernovae to "normal" supernovae. Furthermore, an estimate of GRB and hypernova rates in the Universe shows that they are statistically coincident (Podsiadlowski et al. 2004; see also Guetta et al. 2005). The connection between GRBs and supernovae seems therefore well established.

About one third of all GRBs, the so called X-ray Flashes (XRF), have very soft spectra (peak energies of $\sim$10 keV instead of $\sim$200 keV), and prominent X-ray emission with respect to gamma-ray emission, XRFs often going untriggered or undetected in the gamma-rays (Heise et al. 2001). Interestingly, the optical light curve of the counterpart of XRF030723 (one of the few XRFs for which an optical afterglow has been detected) was well sampled at late epochs and exhibited the typical profile of a normal or slightly overenergetic Ic supernova at $z = 0.6$ (Fynbo et al. 2004; Tominaga et al. 2004). Analogous findings (a modest redshift and an underlying supernova with a relatively small ^{56}Ni mass) were reported for GRB 020410 (intermediate between a GRB and an XRF), which has been monitored both from the ground and with HST (Levan et al. 2005). Another possible association with supernova has been reported for XRF020903, at $z = 0.25$ (Soderberg et al. 2005).

Therefore it appears that, while the robust, spectroscopically identified cases of GRB-supernova association point to very similar supernovae with typical hypernova characteristics, there are a much larger number of GRB-supernova candidates exhibiting a broad range of properties. The picture is compounded by the detection of supernovae having clear hypernova features (i.e., large kinetic energy), but no detected GRB accompanying them (Iwamoto et al. 2000; Mazzali et al. 2002; Mazzali et al. 2004; Mazzali et al. 2005). All of these supernovae have in common a higher-than-normal kinetic energy and a large progenitor mass ($> 20 M_\odot$), suggesting that they may be related to the formation of a black hole.

The observed large variety of behaviors may have both an intrinsic and an extrinsic explanation: supernovae of different intrinsic properties (progenitor masses, explosion kinetic energy and synthesized ^{56}Ni masses) may produce GRB events of different strength. In addition, since GRBs are jetted sources, and the supernovae themselves are probably anisotropic, viewing angle effects may be important in determining the observed properties of the supernovae, and their association (or lack thereof) with GRBs and XRFs. Speculations in favour of either interpretation have been proposed (see e.g., Kouveliotou et al. 2004; Waxman 2004; Soderberg et al. 2004; Ramirez-Ruiz et al. 2005).

In order to get insight into this problem, it is critical to disentangle intrinsic differences from viewing angle effects, and to investigate whether it is possible to construct a unifying scenario for hypernovae and GRBs. In particular, we would like to test the hypothesis that all hypernovae have jets and produce GRBs, and only those aligned with the line of sight are detected.

2 ASPHERICITIES IN SUPERNOVAE: THE HYPERNOVA 2003JD

Evidence that Ib/c supernovae are aspherical comes from the fact that they are observed to be highly polarized (Leonard & Filippenko 2001; Wang et al. 2001). Polarization increases with time, as deeper ejecta layers are exposed, suggesting that the highest asphericity is found near the core of the exploding star. This is most effectively investigated through observations in the nebular phase. Each supernova undergoes first a photospheric phase, and few months after the explosion, when the ejecta have become sufficiently transparent to allow a view of the inner regions, a nebular phase, during which emission lines, often forbidden, appear.

The observation that the nebular iron lines in SN 1998bw, associated with GRB 980425, were broader than the [O I] emission line indicates that iron was ejected at higher velocities than oxygen (Maeda et al. 2002). This cannot be accounted for in a spherically symmetric explosion, but it can be interpreted as the result of an aspherical explosion viewed near, but not exactly on the jet axis, consistent with the detection of a weak GRB (Mazzali et al. 2001; Maeda et al. 2002). Interestingly, a lower-energy (but still higher than normal) Ic supernova like SN 2002ap does not show this peculiarity (Foley et al. 2003).

Direct evidence that Type Ib/c supernovae are highly aspherical comes from SN 2003jd, a bright and highly energetic Ic supernova without an accompanying detected GRB (Hurley et al. 2003). SN 2003jd was detected on 25 October 2003; at maximum, it was as luminous as SN 1998bw and had broad lined early time spectra, similar to the hypernova SN 2002ap (Fig. 1). Subaru and Keck spectra of SN 2003jd acquired

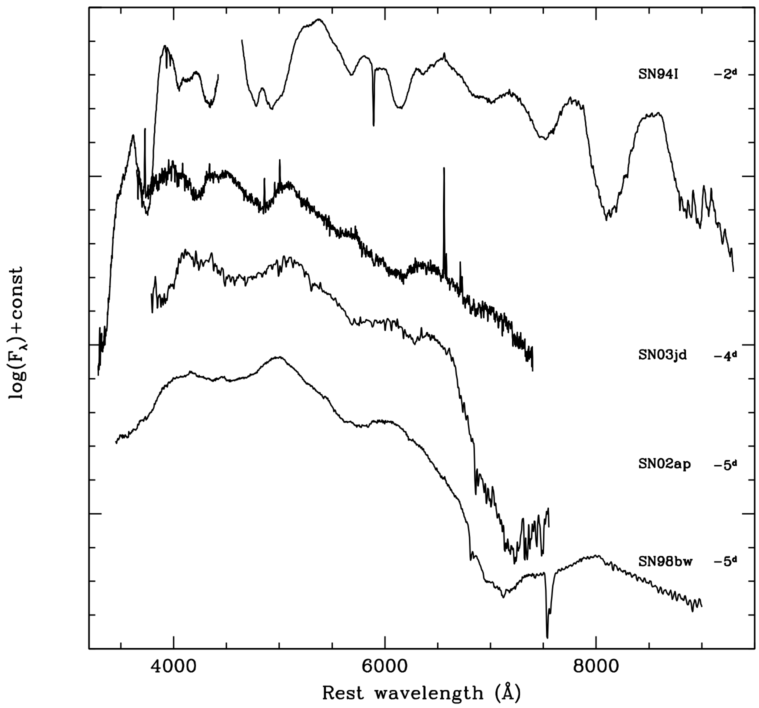

Fig. 1 The near-maximum optical spectrum of SN 2003jd compared with spectra of other Type Ic supernovae at a similar phase (F_λ is the flux per unit wavelength). The dates are the days relative to the optical maximum (i.e., the minus sign means before the maximum light). Spectra are ordered by increasing line width (implying increasing kinetic energy per unit mass), ranging from the normal SN 1994I (Filippenko et al. 1995), to the energetic SN 2002ap (Mazzali et al. 2002; Foley et al. 2003), and to the hyper-energetic GRB/SN 1998bw (Patat et al. 2001). The absorption line near 7600 Å in the spectrum of SN 1998bw is telluric (from Mazzali et al. 2005).

one year after the explosion show a double-peaked [O I] emission line profile, which is typical of disc-like ejecta (Mazzali et al. 2005, see Fig. 2). This can be interpreted if the hypernova was an aspherical explosion very similar to the hypernova SN 1998bw, but viewed almost along the equator rather than near the pole (Fig. 3), implying that a possible GRB associated with SN 2003jd would be at a large angle with respect to the line of sight, and therefore undetected. This discovery emphasizes the role played by orientation.

If the explosion was very off-axis we presume that we would not have been able to detect gamma-rays. However, a GRB is expected to produce a long-lived radiative output through synchrotron emission. X-ray and radio emissions are produced by the deceleration of the relativistic jet as it expands into the wind emitted by the progenitor star before it exploded. This afterglow emission is very weak until the Doppler cone of the beam intersects our line of sight, making off-axis GRB jets directly detectable only months after the event, and at long wavelengths. SN 2003jd was observed in X-rays with Chandra on 10 November 2004, about 30 days after the explosion, and was not detected to a limit $L_{\rm X} \leq 3.8 \times 10^{38}$ erg s^{-1} in the energy interval 0.3 to 2 keV (Watson et al. 2003). It was also observed in the radio regime (8.4 GHz) at various epochs after the explosion, and again not detected (Soderberg et al. 2006).

While the X-ray upper limit is still compatible with the presence of a uniform jet with an energy of 10^{51} erg and an opening angle of 5 degrees seen at a large angle, the latest radio upper limit is only marginally consistent with a jet, even for a nearly perpendicular view (Fig. 4). More generally, Soderberg et al. (2006) have surveyed in the radio 74 supernovae and found that none of the 6 hypernovae included in the sample

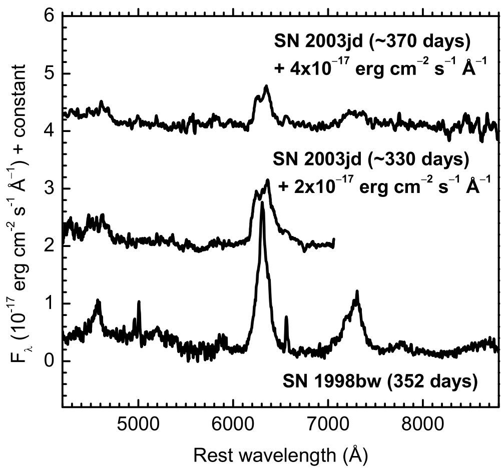

Fig. 2 Nebular spectra of Ic supernovae. Bottom: nebular spectrum of SN 1998bw (Patat et al. 2001) taken 337 days after maximum light (352 days after the explosion). Notice the Mg I], [Fe II], [O I], and [Ca II] lines near 4570, 5100, 6300, and 7300 Å, respectively. Middle: Subaru+FOCAS spectrum of SN 2003jd, ∼330 days after the putative time of explosion. Top: Keck spectrum of SN 2003jd at an epoch of ∼370 days. The [O I] 6300, 6363 Å line in SN 2003jd clearly exhibits a double-peaked profi le. Marginal evidence of a double peak is also present in the profi les of Mg I] 4570 Å and [Ca II] 7300 Å. The spectrum of SN 1998bw has been shifted in flux to make it consistent with the distance of SN 2003jd (from Mazzali et al. 2005b).

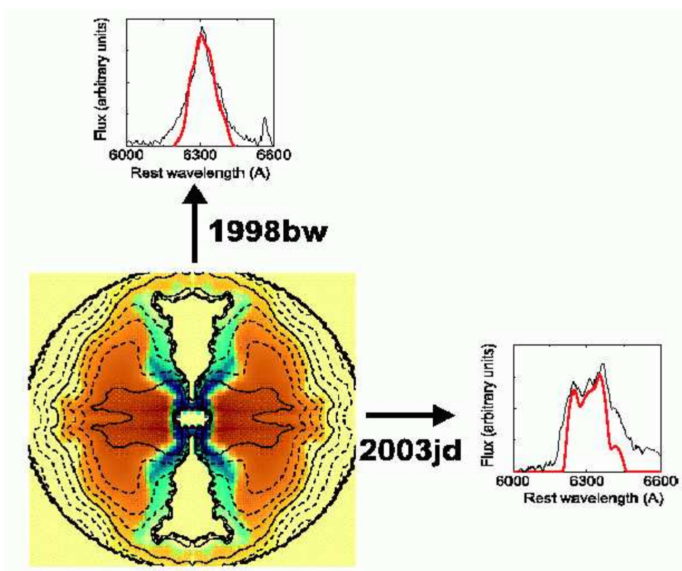

Fig. 3 Nebular line profi les observed from an aspherical explosion model depend on the orientation. The fi gure shows the properties of the explosion model computed in 2D (Maeda et al. 2002): iron is ejected near the jet direction and oxygen in a disc-like structure on and near the equatorial plane. Density contours (covering 2 orders of magnitude and divided into 10 equal intervals in log scale) reflect the dense disc-like structure. Synthetic [O I] 6300, 6363 Å lines (red lines) computed in 2D are compared with the spectra of SN 1998bw and SN 2003jd (black lines). (From Mazzali et al. 2005).

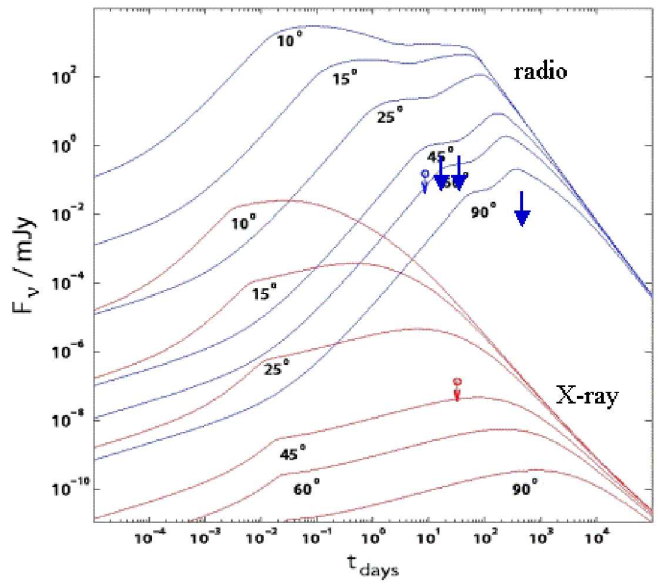

Fig. 4 Afterglow emission from a sharp-edged, uniform jet in SN 2003jd. X-ray (0.3–2 keV, black) and radio (8.4 GHz, gray) light curves are calculated for various viewing angles $\theta_{\rm obs}$ for a GRB with the standard parameters $E_{\rm jet} = 10^{51}$ erg, $\epsilon_{\rm e} = 0.1$, $\epsilon_{\rm B} = 0.1$, $\theta_0 = 5°$, and $A_* = 1$ (where $E_{\rm jet}$ is the energy in the jet, $\epsilon_{\rm e}$ and $\epsilon_{\rm B}$ are the fraction of the internal energy in the electrons and magnetic field, respectively, and θ_0 is the opening half-angle of the jet). The synchrotron spectrum is taken to be a piecewise power law with the usual self-absorption, cooling, and injection frequencies calculated from the cooled electron distribution and magnetic field (Ramirez-Ruiz & Madau 2004; Granot & Ramirez). The observed radio and X-ray upper limits for SN 2003jd are marked by open circles. Cosmological parameters taken in the model are $\Omega_{\rm m} = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 72$ km s^{-1} Mpc^{-1} (from Mazzali et al. 2005).

shows radio emission at the level expected from a radio afterglow from an off-axis jet. This may either undermine the "unified scenario" for GRBs and supernovae or indicate that the parameters of the jets and of the external medium are poorly known and inadequately modeled.

3 CONCLUSIONS

Type Ib/c supernovae have smaller envelopes than Type II supernovae, making it easier for relativistic jets to break out and make GRBs (MacFadyen & Woosley 1999). Jets may originate in the collapse of a neutron star to a black hole (Zhang et al. 2003), which points to massive progenitors. The number of known hypernovae is still rather small. There are indications that properties such as kinetic energy and ^{56}Ni mass are related to the mass of the progenitor star (Nomoto et al. 2004, see Fig. 5).

There is growing consensus that asphericities in supernovae may be conducive to the formation of anisotropic structures and possibly jets. The best mechanism for anisotropic supernova formation is probably a magnetorotational explosion (LeBlanck & Wilson 1970; Moiseenko, Bisnovatyi-Kogan, & Ardeljan 2005). We have suggested here that asymmetries in supernovae may be best observed and studied during their nebular phase. The nebular spectrum of the Type Ic energetic SN 2003jd is different from that of SN 1998bw: its double-peaked [O I] emission line suggests an aspherical geometry and an equatorial view (Mazzali et al. 2005). This is consistent with the lack of a detected GRB. However, an off-axis GRB at the distance of SN 2003jd (80 Mpc) would normally be followed by bright radio afterglow emission, which is not detected. Therefore, a complete unifying scenario for GRBs and supernovae is currently not possible.

Hypernovae are not the only aspherical supernovae (polarization is detected also in normal supernovae), but are probably the most aspherical supernovae. How this characteristic is related to the presence of a GRB must be investigated with further observations of hypernovae in nebular phase.

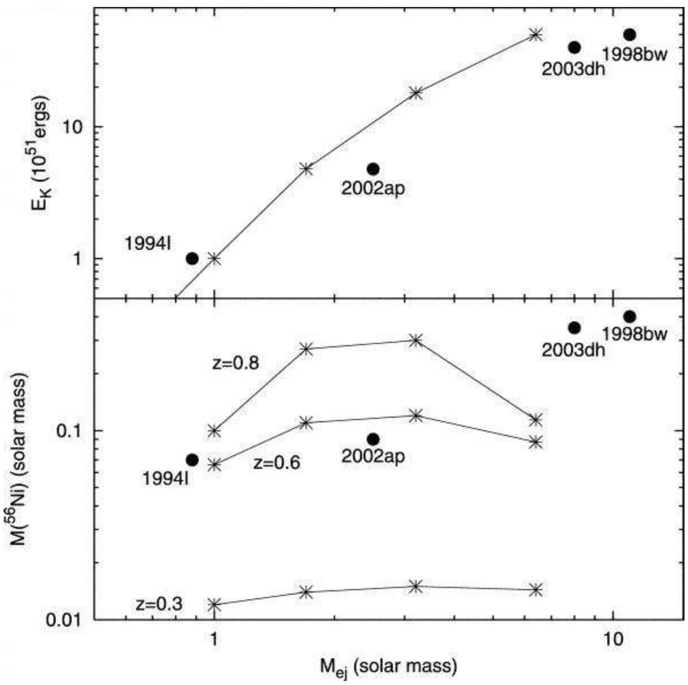

Fig. 5 Top: Kinetic energy vs ejected mass for the best-fi t explosion models of C+O stars of various masses (asterisks) and for four well-studied Ic supernovae (fi lled circles). Bottom: Mass of radioactive synthesized ^{56}Ni vs ejected mass for the best-fi t models (asterisks) at $z = 0.8$ (top), 0.6 (middle), and 0.3 (bottom), and for the Ic supernovae (fi lled circles). (From Tominaga et al. 2004).

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