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OUTFLOWS FROM SUPERNOVAE AND GRBS

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RESUMEN

Las Supernovas de tipo Ic asociadas con Destellos de Rayos Gama muestran líneas anchas en absorción en sus etapas tempranas. Otras SNs Ic exhiben esta propiedad pero sin estar asociadas a un DRG. Con espectros sintéticos tanto en las primeras etapas como en las más avanzadas se pueden determinar las propiedades de estas SNs, que indican que las explosiones no ocurren en forma esférica, y dan así una conexión natural entre las Hipernovas y los Destellos de Rayos Gama.

ABSTRACT

The Type Ic Supernovae associated with Gamma Ray Bursts show very broad absorption lines in the early phase. Other SNe Ic share this property but are not apparently linked to a GRB. Synthetic spectra in both the early and the late phase can be used to constrain the properties of these SNe and bear indications that the explosions are aspherical, providing a natural link between Hypernovae and Gamma Ray Bursts.

Key Words: **GAMMA-RAYS: BURSTS — NUCLEOSYNTHESIS — SUPERNOVAE**

1. INTRODUCTION

One of the most exciting developments in recent studies of supernovae (SNe) and Gamma-Ray Bursts (GRBs) is that the two events are intimately related. The discovery of very bright and energetic SNe, in association with the nearest long-duration GRBs has opened up a new field of study, both theoretically and observationally.

The first evidence for a SN/GRB connection came from SN 1998bw/GRB980425 (Galama et al. 1998). The SN was identified as Type Ic, and modelled as the very energetic explosion of a massive stellar core ("Hypernovae"). The isotropic kinetic energy (KE) was estimated to be $\sim 5 \times 10^{52}$ erg (Iwamoto et al. 1998; Nakamura et al. 2001), about 50 times the KE of normal core-collapse SNe (hereafter $E_{51} = E/10^{51}$ erg), while the mass in the execta is $\sim 11\,M_\odot$, indicating that the progenitor star had a main sequence mass of $\sim 40\,M_\odot$.

Other instances of the SN/GRB connection supprted by clear spectroscopic evidence are SN 2003dh/GRB030329 (Stanek et al. 2003; Hjorth et al. 2003; Matheson et al. 2003; Deng 2005) and SN2003lw/GRB031203 (Thomsen et al. 2004; Gal-Yam et al. 2004; Malesani et al. 2004).

Fitting ($\lesssim 50$ day) optical light curves and spectra of supernovae, the explosion KE and the main-sequence mass $M_{\rm ms}$ of the progenitor star can be derived. Both SNe 1998bw (Iwamoto et al. 1998) and 2003dh (Mazzali et al. 2003) have KE in excess of 10^{52} erg, and can be classified as hypernovae. Other possible SNe in GRBs have been reported, but based only on the detection of 'bumps' in GRB afterglows (Zeh 2004, and references therein).

The link to GRBs is a strong hint that hypernovae could be significantly aspherical, as is widely believed for GRBs (e.g., Frail et al. 2001). Detailed investigations of the optical properties of hypernovae give this speculation further support.

The available observational data on hypernovae are here reviewed and analysed, with particular emphasis on the indications that the explosions are aspherical, providing a natural link with GRB's.

2. THE CASE OF SN 1998BW

SN 1998bw was discovered in temporal and spacial coincidence with GRB980425, at a redshift $z = 0.0085$. The object displayed a bright, SN-like light curve, but had very unusual spectra, characterised by very broad P-Cygni lines (Galama et al. 1998). The only possible explanation for the broad features was that they were due to the extensive blending of line absorption in very high-velocity material ($v \sim 30,000$ km s^{-1}). This realisation brought us to release the assumption that all SNe explode with the same KE. Indeed, highly energetic models were required to match the observed velocities.

However, once the constant energy assumption is released, light curves become degenerate: the characteristic time-scale τ of the light curve peak of a

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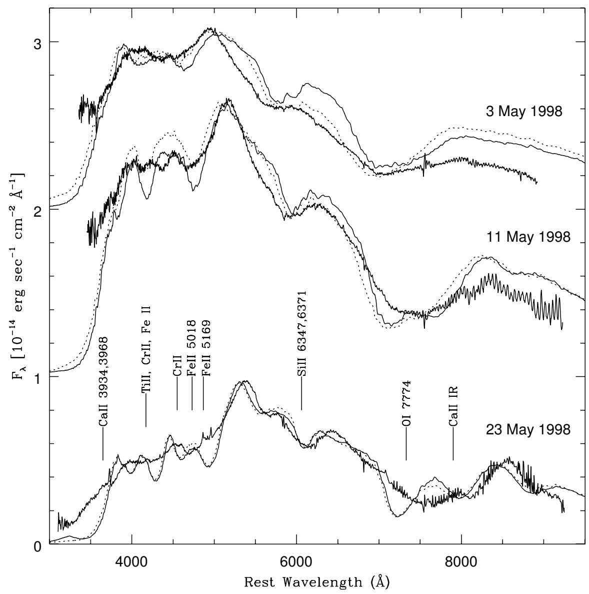

Fig. 1. Synthetic early-time spectra of SN 1998bw.

H-free SN depends infact on the kinetic energy E, the ejected mass M_{ej} and the opacity κ, as follows (Arnett 1996):

$$\tau \propto \frac{\kappa^{1/2} M_{ej}^{3/4}}{E^{1/4}}. \tag{1}$$

Therefore, different models of the explosion, all of which matched the light curve, had to be tested on the spectra. Spectra are in fact directly sensitive to E, allowing us to resolve the discrepancy. Synthetic spectra were computed using a Montecarlo code (Mazzali 2000 and references therein). Our best fit was for $E_{51} = 50$, $M_{ej} = 11 M_{\odot}$ (Figure 1). The mass of ^{56}Ni synthesised by this bright SN was very large for a core-collapse event, $\sim 0.5\, M_{\odot}$(Iwamoto et al. 1998; Nakamura et al. 2000).

The late light curve showed a surprisingly slow decline, that cannot be explained by a 1D explosion model. Maeda et al. (2003) suggested that an inner region of high density traps photons. This was the first suggestion that the SN explosion was not well described by a spherical model.

The later evolution to the nebular phase offered even more surprises. The nebular spectrum was dominated by strong [O I] 6300Å, as in all SNe Ib/c, but it also showed strong [Fe II] lines, a feature of SNe Ia. Unlike SNe Ia, however, [Fe III] lines were missing. While the presence of Fe lines was to be expected given the unusually high ^{56}Ni production in SN 1998bw, the absence of [Fe III] can only be explained if the density in the Fe region is higher than that of the average model, as would be the case if the ejecta were clumped or if the Fe were concentrated in a small region, of size $\sim 10\%$ of the total ejecta volume, suggestive of an asymmetric ejection.

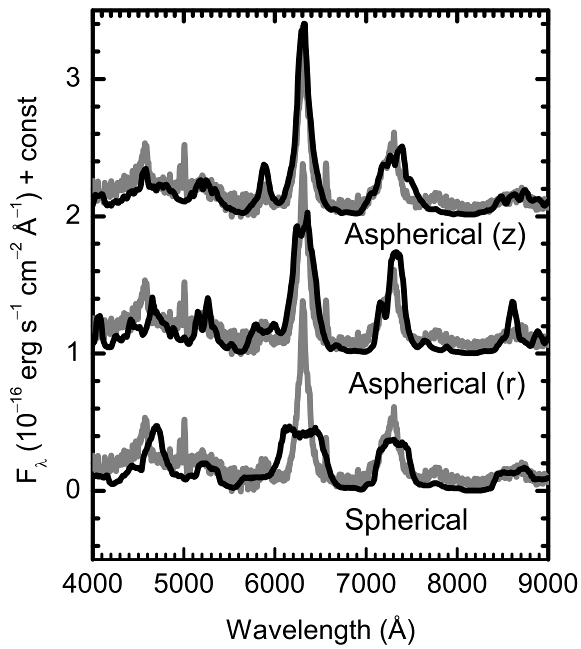

Fig. 2. Synthetic nebular spectra of the explosion of a $16 M_{\odot}$He star ($M_{\rm ms} = 40 M_{\odot}$) on day 200. Spectra for the aspherical model ($E_{51} = 9.5$) are shown for polar and equatorial orientation. A spherical model ($E_{51} = 8.5$) is also shown, as is the observed spectrum of SN 1998bw on day 216 (bottom). Note the double-peaked [O I] line in the aspherical model viewed on the equator,and the flat top profile of the same line in the spherical model.

Even more surprising, however, was the fact that the [O I] line was significantly narrower than the [Fe II] ones (Mazzali et al. 2001). This cannot occur in the onion-shell structure of 1D models. We therefore built two-dimensional explosion models, where we injected more kinetic energy in a specific direction – the jet. Here, burning was more effective, producing a funnel of ^{56}Ni. This is reminiscent of the typical GRB picture. We used a 3D nebular emission code to compute synthetic spectra that match this situation (Figure 2). Not only could we successfully reproduce the observations, but we could also place constraints on the degree of asymmetry (roughly 2:1), the total kinetic energy (reduced to $\sim 10^{52}$ erg, and the viewing angle ($\sim 15 - 30°$ from the jet axis; Maeda et al. 2002).

The success of these models confirms that SN 1998bw was highly aspherical, supporting its link to GRB980425. The progenitor of SN 1998bw must have been a massive star, with $M_{ZAMS} \sim 40 M_{\odot}$.

3. OTHER HYPERNOVAE IN GRB'S

While the single case of SN 1998bw was a strong indication that long duration GRB's and some SNe are related, it took another burst, GRB030329, to prove this conclusively. A supernova was predicted to appear in this relatively nearby burst ($z = 0.167$), and was indeed observed (Stanek et al. 2003; Hjorth et al. 2003). The SN showed spectral features very similar to those of SN 1998bw (Matheson et al. 2003), and was also interpreted as an energetic explosion (Mazzali et al. 2003), although somewhat weaker than SN 1998bw. In particular, the derived properties of SN 2003dh are $E_{51} \simeq 35$, $M_{ej} \simeq 8\, M_{\odot}$, and M(^{56}Ni)$\simeq 0.35\, M_{\odot}$. These values again point to a massive progenitor, of $M_{ZAMS} \sim 35 M_{\odot}$.

Since the two nearest GRB's were hosted in Hypernova explosions, it could be expected that another nearby case, GRB031203 ($z = 0.105$) may contain a SN. Although the search was made difficult by the large reddening ($E(B-V) \sim 1$) a SN bump was detected in the afterglow light curve (Tagliaferri et al. 2004). This was confirmed by Thomsen et al. (2004) and Gal-Yam et al. (2004), and, with full VLT spectral information, by Malesani et al. (2004). The spectra of the SN (SN 2003lw) are strikingly similar to those of SN 1998bw. The parameters of the SN are very similar to those of SNe 1998bw and 2003dh (Mazzali et al. 2006, in preparation).

4. HYPERNOVAE WITHOUT GRB'S

Other SNe Ic with the broad lines typical of hypernovae have been observed for which the connection with a GRB is not clear or is even absent. The first such case, SN 1997ef, was highly enegetic, but dimmer than SN 1998bw ($E_{51} = 20$; $M_{ej} = 10 M_{\odot}$; M(^{56}Ni) $= 0.13 M_{\odot}$; Mazzali et al. 2000). Its progenitor was probably a $\simeq 35 M_{\odot}$ star. Although strong signatures of asymmetry are not present in SN 1997ef, it is interesting that line formation extends to velocities well below the lower velocity of the 1D model, corresponding to the somewhat arbitrary mass cut that is imposed in 1D models to produce the required amount of ^{56}Ni. Unfortunately, nebular phase spectra of this SN are not available.

However, another SN Ic, 1997dq, is a close analogue of SN 1997ef (Matheson et al. 2001). Analysis of the nebular lines of this SN shows no significant differences in the profiles of [O I] and [Fe II], indicating that either the explosion was not strongly aspherical, or that it was viewed far from the jet axis, a possibility which we find more appealing (Mazzali et al. 2004). Maybe, had SNe 1997ef and 1997dq been viewed from a different vantage point, they would have displayed an associated GRB.

Another case of a Hypernova without a GRB is that of the very nearby SN 2002ap. Apart from the broad lines (which are however narrower than in either SN 1998bw or SN 1997ef, indicating expansion velocities of ~ 25000km s^{-1}), this was a rather normal SN Ic, producing a normal 0.1 $M_{\odot}$of ^{56}Ni. However, the kinetic energy, $E_{51} \sim 4$, was larger than the normal value, and the progenitor mass, $\sim$ 20–25 $M_{\odot}$, places SN 2002ap in the hypernova branch (Mazzali et al. 2002). In the nebular phase, only a narrow core in [O I] may be indicative of an inner density concentration where O dominates, suggestive of a mildly aspherical explosion. Some indication that the explosion was aspherical come from the slow decay of the light curve at advanced phases, similar to SN 1998bw (Maeda et al. 2003), and from the detection of significant polarization (Kawabata et al. 2002). The nebular [O I] line of SN 2002ap was also very narrow, like in SN 1998bw (Foley et al. 2003).

Plotting the kinetic energy, or the mass of ^{56}Ni, of the various hypernovae versus progenitor mass (Figure 3) clearly shows a trend for the more massive stars to produce brighter, more energetic explosions. The GRB connection is only observed at the high-energy end of the distribution.

5. INNER DENSITY CORES AS INDICATIONS OF ASPHERICITY

Not only do many hypernovae show narrow [O I] lines, or line cores, but they also show a flattening in the light curve at intermediate phases (day 50-200). This is again not explained by 1D models. Maeda et al. (2003) built models where an inner high-density core traps γ-rays emitted at advanced phases. This way, we could obtain good fits to the observed light curves. Again this is different from the spherically symmetric picture. In a jet-induced explosion, however, the equatorial region is less burned, and so it remains Oxygen-dominated, and moves out at a low velocity, similar to what the observations suggest.

6. RATES OF HNE AND GRB'S

Since all three nearby GRB's were hosted by hypernovae, it is only natural to ask what the rates of GRB's and hypernovae are. Making conservative assumptions for the beaming angle, Podsiadlowski et al. (2004) derived a GRB rate $R(GRB) \sim 10^{-5}\,\mathrm{yr}^{-1}$ in a normal galaxy.

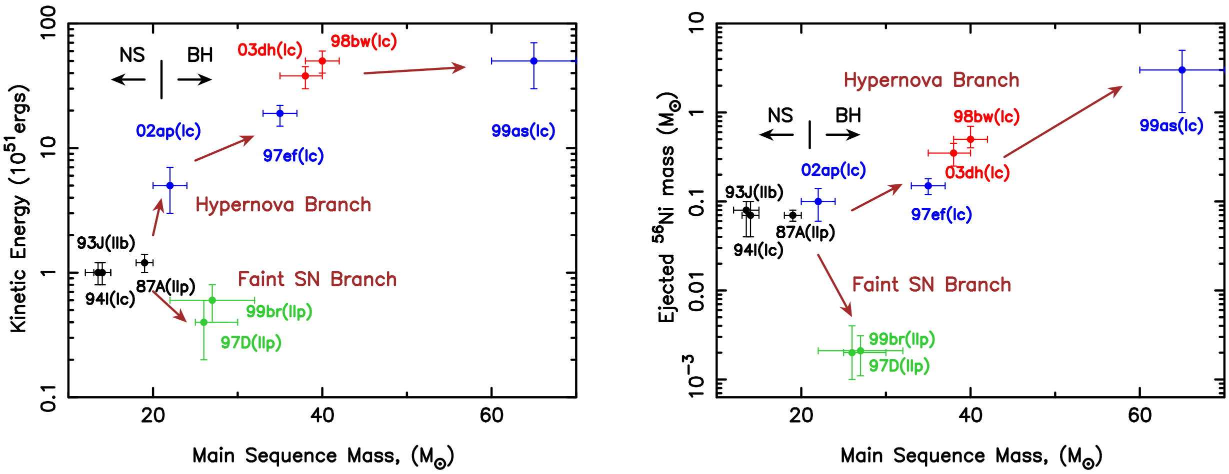

Fig. 3. Left: Explosion energies and Right: ejected ^{56}Ni mass against main sequence mass of the progenitors for several core collapse supernovae/hypernovae.

As for hypernovae, they are only $\sim$ 5% of all SNe Ib/c, which in turn are only $\sim$ 15% of all core-collapse SNe. Taking observational biases into account (hypernovae are brighter than normal SNe Ib/c), Podsiadlowski et al. (2004) derived also for hypernovae a rate $R(HN) \sim 10^{-5}\,\mathrm{yr}^{-1}$ per galaxy. These numbers are extremely suggestive. They are also much smaller than the expected SN rate for even the most massive stars (e.g. the rate of core-collapse SNe with progenitors more massive than $80M_\odot$ is $\sim 2\times10^{-4}\,\mathrm{yr}^{-1}$ per galaxy. We therefore suggest that all long-duration GRB's are produced by hypernovae.

7. PROPERTIES OF HN-HOSTED GRB'S

One striking fact is that the average energy of the GRB's with accompanying hypernovae is lower than the typical GRB energy. Perhaps this is due to a slight misalignment between the jet and the line of sight, which makes the GRB weaker as the Lorentz factor drops, without much affecting the observational properties of the associated SN (SN 1998bw/GRB980425 is a possible example of this). In this case the observed weakness of the nearby, SN-associated GRB's would be just a statistical result: it they have a finite opening angle, most GRB's will be observed off-axis. Off-axis GRB's should therefore dominate the nearby sample, but they will not be as frequent at higher redshifts as they are intrinsically fainter than on-axis ones.

The multifrequency aspect-angle dependence of GRB's is still the subject of debate (e.g. Ramirez-Ruiz et al. 2005), particularly as regards the relative behaviour of the X-ray and the radio emission.

8. A NORMAL SUPERNOVA IN A GRB?

While most observations suggest that GRB's are only seen when the hypernova is extremely powerful, there is a case where an apparently normal SN, or possibly a low-energy hypernova (similar to SN 2002ap) was seen in coincidence with a normal GRB: SN 2002lt was detected in the afterglow spectrum and light curve of GRB021211, at $z \sim 1$ (Della Valle et al. 2003). Although the data are limited, the spectrum of the SN does not appear to be compatible to that of a hypernova like SN 1998bw. This might suggest that there is a real distribution of properties of the GRB's and of the SNe that host them.

9. SNE/HNE IN X-RAY FLASHES?

X-Ray Flashes are the weak (X-ray dominated) equivalent of GRBs. Zhang et al. (2003) suggested that they may also be produced by SN events. A SN bump was observed in the light curve of XRF030723 (Fynbo et al. 2004). Tominaga et al. (2004) interpreted the light curve as comparable to that of a weak hypernova like SN 2002ap at a redshift $z \sim 0.6$.

This may suggest that XRFs are GRBs viewed far from the jet axis. However, SN 2002ap syntehsised much less ^{56}Ni than powerful HNe like SN 1998bw, a result that does not depend on viewing angle. Alternatively, XRFs may be weak manifestations of the GRB phenomenon, and may themselves be viewed on-axis. Further observations and theoretical studies are needed to distinguish the effects of orientation from real physical differences. All SNe Ic may be aspherical, and maybe all SNe Ib/c produce a GRB or an XRF. Lack of radio signatures of off-axis jets from basicall all normal SNe Ic (Soderberg et al. 2005) confirms that only the highly energetic SN Ic explosions are possible GRB hosts. XRF's might be GRB's viewed off-axis, or the result of weaker explosions, or both. In this case, the number of XRF's should far exceed that of GRB's. This might well be, since XRF's are weaker and therefore harder to detect. Indeed, stripping a stellar H (and He) envelope probably requires high rotation, which is also a requirement of the most popular models for making GRB's (e.g. Woosley & McFadyen 1999), possibly a binary companion, and so the fact that the ensuing explosion may be significantly aspherical may not come as a great surprise.

10. SN 2003JD: AN OFF-AXIS HYPERNOVA

As we discussed above, it is possible that all Hypernovae host a GRB. There are also very strong indications that SNe Ic in general, and Hypernovae in particular, are highjly aspherical. In order to verify these hypotheses, we have started a campaign to collect early and late-time data of as many energetic SNe Ic as possible. Surprisingly, the reported number of such object has been increasing with time, certainly owing to improved search techniques and instrument availability, but possibly also to astronomers' increased sensitivity to the issue. While hypernovae are identified in the early phase, from their brightness and from the broad-lined spectra, it is in the nebular phase that we are offered the best chance to probe the structure of the ejecta, and thus to test our models of the explosion. We have therefore collected late-time spectra at several 8m telescopes, with the expectation that the nebular lines would show a variety of profiles.

The first run already proved a success. We observed the spectra of SN 2003jd, a SN Ic at a distance of $\sim 80\,\mathrm{Mpc}$ (Burket et al. 2003) at an epoch of ~ 1 year after the explosion. The SN was very bright at maximum, reaching $M_B(\max) \simeq -18.7\,\mathrm{mag}$. Spectroscopically, SN 2003jd shows narrower lines than the hyper-energetic GRB/SNe, and it appears to be intermediate between SN 2002ap and a normal SN Ic like SN 1994I (Filippenko et al. 1995).

We observed SN 2003jd in the nebular phase with FOCAS on the Subaru telescope on 12 Sep. 2004 and with LRIS on the Keck-I telescope on 19 Oct. 2004. These dates correspond to SN ages of ∼330 and ∼370 days after explosion, respectively. In both spectra (Figure 4) the nebular line [O I] 6300, 6363 Å clearly has a double-peaked profile with FWHM $\approx 8000\,\mathrm{km\,s^{-1}}$. The Mg I] 4570 Å line shows a similar

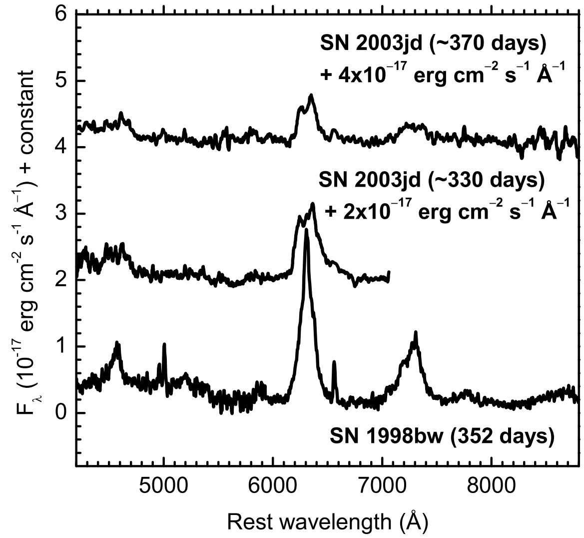

Fig. 4. Nebular spectra of SNe Ic. Bottom: nebular spectrum of SN 1998bw taken 337 days after maximum light (352 days after the explosion). Notice the Mg I], [Fe II], [O I], and [Ca II] lines near 4570, 5100, 6300, and 7300 Å, respectively. Middle: Subaru+FOCAS spectrum of SN 2003jd, ∼330 days after 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 profile. Marginal evidence of a double peak is also present in the profiles of Mg I] 4570 Å and [Ca II] 7300 Å.

profile. Magnesium is formed near oxygen in the progenitor star. The [Fe II] blend near 5100 Å is quite weak. The profile of the [O I] line is suggestive of a very aspherical explosion viewed far from the polar axis, possibly close to the equatorial plane.

We computed nebular spectra of 2D explosion models for various asphericities and orientations. While a spherical model produces a flat-topped [O I] profile, which is not compatible with either SN 1998bw or SN 2003jd, Figure 5 shows that a highly aspherical model can explain the [O I] line profiles in both SN 1998bw and SN 2003jd. Since SN 2003jd was not as luminous as SN 1998bw, to reproduce the double-peaked profile of the [O I] line in SN 2003jd we we rescaled the synthetic spectra to the appropriate ^{56}Ni mass, the best value for which was $\sim 0.3\,M_\odot$. This is actually very similar to that derived for the GRB-associated SN 2003dh. We found that SN 2003jd must be oriented $\gtrsim 70°$ away from our line of sight. In contrast, for SN 1998bw this angle was only $\sim$ 15–30°, and it was even smaller for SN 2003dh. Less aspherical models do not produce sufficiently sharp [O I] in SN 1998bw.

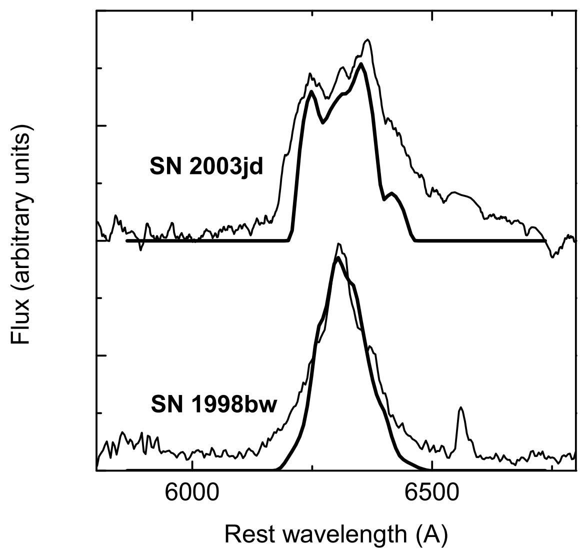

Fig. 5. Nebular line profiles observed from an aspherical explosion model depend on the orientation. Synthetic [O I] 6300, 6363 Å lines computed in 2D are compared with the spectra of SN 1998bw and SN 2003jd: the orientation of SN 1998bw is $\sim 20°$ from the polar direction, while for SN 2003jd the inclination is $\gtrsim 70°$.

This result confirms that SN 2003jd is a significantly aspherical explosion, and raises the interesting question of whether SN 2003jd was itself a GRB/SN. A GRB was not detected in coincidence with SN 2003jd. If the explosion was very off-axis, we do not anticipate to have been able to detect γ-rays. However, a GRB is expected to produce a long-lived radiative output through synchrotron emission. X-ray and radio emission 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 not detected either in the X-rays (Watson et al. 2003) or in the radio (Soderberg et al. 2003, 2005), which suggests that either it did not make a GRB, or that the material surrounding the SN had a very low density, or both.

The bright SN 2003jd is the first SN Ic showing double peaks in the [O I] line, suggesting that the degree of asphericity is not the same in all SNe Ic. The GRB/SNe (1998bw, 2003dh), which are probably highly aspherical, have been discovered thanks to a GRB trigger; their orientation is therefore such that the [O I] profile must be single-peaked. For normal SNe Ic, which are on average closer and easier to discover, the lack of observed double-peaked profiles suggests that they are not as strongly aspherical. SN 2003jd appears to share many of the properties (energetics, luminosity) of the GRB/SNe, but it was discovered independent of a GRB, and it is likely to be an aspherical SN viewed off-axis. There have been three energetic SNe Ic without a GRB trigger (therefore less biased) — SNe 1997dq, 1997ef, and 2002ap — whose nebular spectra did not show the double peaks in the [O I] 6300 Å. Given the small sample, the number (one out of four) is not inconsistent with our interpretation that the viewing angle $\gtrsim 70°$ results in the double-peaked [O I].

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