Stellar Forensics with the Supernova-GRB Connection
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Long-duration gamma-ray bursts (GRBs) and Type Ib/c Supernovae (SNe Ib/c) are amongst nature’s most magnificent explosions. While GRBs launch relativistic jets, SNe Ib/c are core-collapse explosions whose progenitors have been stripped of their hydrogen and helium envelopes. Yet for over a decade, one of the key outstanding questions is which conditions lead to each kind of explosion and death in massive stars. Determining the fates of massive stars is not only a vibrant topic in itself, but also impacts using GRBs as star formation indicators over distances of up to 13 billion light-years and for mapping the chemical enrichment history of the universe. This article reviews a number of comprehensive observational studies that probe the progenitor environments, their metallicities and the explosion geometries of SN with and without GRBs, as well as the emerging field of SN environmental studies. Furthermore, it discusses SN 2008D/XRT 080109 which was discovered serendipitously with the Swift satellite via its X-ray emission from shock breakout, and which has generated great interest amongst both observers and theorists while illustrating a novel technique for stellar forensics. The article concludes with an outlook on how the most promising venues of research - with the many existing and upcoming large-scale surveys such as the Palomar Transient Factory and LSST - will shed new light on the diverse deaths of massive stars.

1 Introduction: The Importance of Stellar Forensics

Stripped supernovae (SNe) and long-duration Gamma-Ray Bursts (GRBs) are nature’s most powerful explosions from massive stars. They energize and enrich the ISM, and, like beacons, they are visible over large cosmological distances. However, the exact mass and metallicity range of their progenitors is not known, nor the detailed physics of the explosion (see reviews by Woosley & Bloom 2006, and by Smartt 2009). Stripped-envelope SNe (i.e, SN Ib, Ib, Ic and Ic-bl, e.g., Uomoto & Kirshner 1985; Wheeler & Harkness 1990; Clocchiatti et al. 1996; Filippenko 1997) are core-collapse events whose massive progenitors have been stripped of progressively larger amounts of their outermost H and He envelopes (Fig. 1). In particular, broad-lined SNe Ic (SNe Ic-bl) are SNe Ic whose line widths approach 30,000 km s−1 around maximum light and whose optical spectra show no trace of H and He.

The exciting connection between long GRBs and SNe Ic-bl (for a review, see Woosley & Bloom 2006, Hjorth & Bloom 2011 and below) and the existence of SNe Ic-bl without observed GRBs, as well as that of GRBs that surprisingly lack SN signatures, raises the question of what distinguishes a GRB progenitor from that of an ordinary SN Ic-bl with and without a GRB.

Understanding the progenitors of SNe Ib/c and of GRB is important on a number of levels:

(1) Stellar and High-Energy Astrophysics: These stellar explosions leave behind extreme remnants, such as Black Holes, Neutron Stars, and Magnetars, which in themselves are a rich set of phenomena studied over the full wavelength spectrum from Gamma-rays to radio. Ideally we would like to construct a map that connects the mass and make-up of a massive star to the kind of death it undergoes and to the kind of remnant it leaves behind. Furthermore, these stellar explosions are sources of gravitational waves and of neutrino emission, and specifically GRBs are leading candidate sites for high-energy cosmic ray acceleration (e.g., Waxman 2004). Thus, it is of broad astrophysical importance to understand the specific progenitor and production conditions for different kinds of cosmic explosions.

(2) Chemical Enrichment History of Universe: The universe’s first- and second-generation stars were massive. Since GRBs and SNe probably contribute differently to the enrichment of heavy elements (e.g., Pruet et al. 2006; Nomoto et al. 2006), determining the fate of massive stars is fundamental to tracing the chemical history of the universe.

(3) Cosmology: GRBs are beacons and can illuminate the early universe. Indeed, until recently, the object with the highest spectroscopic redshift was a GRB, GRB090423 at z ~8.2 (Tanvir et al. 2009; Salvaterra et al. 2009), which means that this explosion occurred merely 630 million years after the Big Bang. Thus, a clear understanding of the stellar
progenitors of SNe and GRBs is an essential foundation for using them as indicators of star formation over cosmological distances.

Various progenitor channels have been proposed for stripped SNe and GRBs: either single massive Wolf-Rayet (WR) stars with main-sequence (MS) masses of \( \gtrsim 30 \, M_\odot \) that have experienced mass loss during the MS and WR stages (e.g., Woosley et al. 1993), or binaries from lower-mass He stars that have been stripped of their outer envelopes through interaction (Podsiadlowski et al. 2004; Fryer et al. 2007 and references therein), possibly given rise to run-away stars as GRB progenitors (e.g., Cantiello et al. 2007; Eldridge et al. 2011). For long GRBs, the main models for a central engine that is powering the GRB include the popular collapsar model (Woosley 1993; MacFadyen & Woosley 1999) and the magnetar model (e.g., Usov 1992 for a good summary see Metzger et al. 2010), while rapid rotation of the pre-explosion stellar core appears to be a necessary ingredient for both scenarios.

Attempts to directly identify SN Ib/c progenitors in pre-explosion images obtained with the Hubble Space Telescope or ground-based telescopes have not yet been successful (e.g., Gal-Yam et al. 2005; Maund et al. 2005; Smartt 2009), and do not conclusively distinguish between the two suggested progenitor scenarios. However, the progenitor non-detections of 10 SNe Ib/c strongly indicate that the single massive WR progenitor channel (as we observe in the Local Group) cannot be the only progenitor channel for stripped stars.

Fig. 1 Mapping between different types of core-collapse SNe (left) and their corresponding progenitor stars (right). Left: Representative observed spectra of different types of SNe. Broad-lined SN Ic are the only type of SNe seen in conjunction with GRBs. Not shown are some of the other H-rich SN members (SNe In and very luminous SNe). Right: Schematic drawing of massive (\( \gtrsim 8 - 10 \, M_\odot \)) stars before explosion, with different amounts of intact outer layers, showing the "onion-structure" of different layers of elements that result from successive stages of nuclear fusion during the massive stars’ lifetimes (except for H). The envelope sizes are not drawn to scale; in particular, the outermost Hydrogen envelope at the top can be up to 100–1000 times larger than shown. Furthermore, many real massive stars rotate rapidly and are therefore oblate, as well as show much less chemical stratification due to convection and overshoot mixing (e.g., see review by Woosley et al. 2002) than is drawn here. The bottom star constitute the most stripped (or "naked") star, with a typical size of \( \sim R_\odot \), whose demise produces a SN Ic and sometimes, a SN Ic-bl and even more rarely, a SN Ic-bl accompanied by GRBs. One of the outstanding questions in the field is the dominant mechanism with which the outer H and He layers got removed. This figure can be downloaded at [http://www.astro.columbia.edu/~mmodjaz/research.html](http://www.astro.columbia.edu/~mmodjaz/research.html).
SNe (Smartt 2009). Similar pre-explosion imaging technique is not possible for GRB progenitors given the large distances at which they are observed.

Thus, in order to fully exploit the potential and power of SNe and GRBs, we have to first figure out their stellar progenitors and the explosions conditions that lead to the various kinds of stellar death in a massive star, in form of a "stellar forensics" investigation. In the following review, we will be looking at a number of inferred physical properties of the progenitor and of the explosion in the hopes of finding those that set apart SN-GRB (Section 2) from SNe without GRBs. They are geometry of the explosion (Section 4), progenitor mass (Section 5) and metallicity (Section 6), while the role of binaries are discussed through-out, but not that of magnetic fields. In addition, I will discuss the exciting and emerging field of SN metality studies as a promising new tool to probe the progenitors of different kinds of SNe and transients, as well as the story of SN 2008D/XRT 080109 (Section 7) that generated great interest amongst both observers and theorists while illustrating a novel technique for stellar forensics.

Necessarily, this review will not be complete given the page limit, and is driven by the interest and work of the author, so omissions and simplifications will necessarily arise. Furthermore, given the excellent reviews by e.g., Woosley & Bloom (2006) and most recently, Hjorth & Bloom (2011), I will concentrate on developments in the field since 2006 and in complimentary areas.

2 Solid Cases of SN-GRB: SNe Ic-bl with GRBs

While the explanation for GRBs after their initial discovery included a vast array of different theories, intensive follow-up observations of GRBs over the last two decades have established that long-duration soft-spectra GRBs (Kouveliotou et al. 1993), or at least a significant fraction of them, are directly connected with supernovae and result from the cataclysmic death of massive, stripped stars (see review by Woosley & Bloom 2006). The most direct proof of the SN-GRB association comes from spectra taken of the GRB afterglows, where the spectral fingerprint of a SN, specifically that of a broad-lined SN Ic, emerges over time in the spectrum of the GRB afterglow. Near maximum light, GRB-SNe appear to show broad absorption lines of O I, Ca II, and Fe II (see Fig. 1), while there is no photospheric spectrum of the GRB afterglow. Near maximum light, GRB-SNe show optical lines of He I (see also below). What's more, it remains note-worthy and peculiar that almost all of the solid SN-GRB connections are with GRBs that are usually regarded as non-classical: i.e., GRBs that are less beamed (opening angles with \( \theta \leq 30 \) deg), have low gamma-ray luminosity (i.e., \( L_{\gamma}^{iso} \leq 10^{49} \text{ erg s}^{-1} \)), soft spectra, and thus, are also sometimes called X-ray Flashes (XRFs) or X-ray rich GRBs, being perhaps more common than cosmological GRBs (Cobb et al. 2006; Soderberg et al. 2006; Guetta & Della Valle 2007). Only GRB 030329 connected with SN 2003dh is a classical GRB whose kin we see at high-\( z \). Either those cosmological high-luminosity GRs are rare at low-\( z \), where we can see the SN signatures spectroscopically, or the SN-GRB connection is confined to only GRBs that are more isotropic and of low luminosity. For reference, a SN with the same large luminosity as SN 1998bw/GRB 980425 will appear at \( R \sim 22 \) mag at \( z=0.5 \), so approaching the limit of obtaining a spectrum with a large-aperture telescope and reasonable exposure times.

The second broad class encompasses cases with only one epoch of low S/N spectra, which are at higher \( z \): XRF 020903 at \( z = 0.25 \) (Soderberg et al. 2005; Bersier et al. 2006), SN 2002lt/GRB 021211 at \( z = 1.006 \) (Della Valle et al. 2003), SN 2005nc/GRB 050525A at \( z = 0.606 \) (Della Valle et al. 2006b). The following last class of possible SN-GRB connections is based on observed rebrightening in the light curves of GRB afterglows that are consistent with emerging SN light curves (e.g., Bloom et al. 1999), and in some cases with multi-color light curves that constrain the SED. While a few high-\( z \) cases have high-quality data that make them convincing (e.g., most recently Cobb et al. 2010; Cano et al. 2010), there are many more
where the data is of lower quality (e.g., Zeh et al. 2004), making the SN interpretation in all cases less secure. The earliest, but more indirect, hints for the existence of a link between GRBs and the death of massive stars was the detection of star-formation features in the host galaxies of GRBs (Djorgovski et al. 1998; Fruchter et al. 1999) and correlation of GRB positions in their host galaxies with starforming regions (Bloom et al. 2002).

While two GRBs, GRBs 060505 and 060614, have been observed without a bright SN (Della Valle et al. 2006a; Fynbo et al. 2006; Gal-Yam et al. 2006), it is debated whether those were indeed bona fide long-GRBs (Gehrels et al. 2006; Zhang et al. 2007; Bloom et al. 2008), posing another challenge to the GRB classification scheme (Bloom et al. 2008). In any case, it is fair to say that for any bona fide and un-ambiguous long-GRB with a sufficiently low redshift to enable a spectroscopic SN detection, a broad-lined SN Ic has been detected. This does not apply to X-ray afterglow searches for them in the optical and radio wavebands (e.g., Levinson et al. 2002; Malacrino et al. 2007), but none has been detected at high significance. Among the same vein, specifically Soderberg et al. (2006b) and Soderberg et al. (2010b) targeted as part of their survey 143 SN Ic-bl that are discovered by various SN surveys, which are not observed to have an accompanied GRB or to be engine-driven (except SN Ic-bl 2009bb, see below). One plausible explanation may be that all SN Ic-bl have an accompanied GRB, but are not observed by us due to viewing-angle effects: our line-of-sight may not intersect the collimated jet of GRB emission and thus, we may not detect gamma rays for these so-called "off-axis" GRBs. Various investigations have been trying to address this viewing angle effect and to find off-axis GRBs.

3. Do all SNe Ic-bl have an accompanied GRB?

While the list of SN-GRB connections is short, there is a growing number of SN Ic-bl that are discovered by various SN surveys, which are not observed to have an accompanied GRB or to be engine-driven (except SN Ic-bl 2009bb, see below). One plausible explanation may be that all SN Ic-bl have an accompanied GRB, but are not observed by us due to viewing-angle effects: our line-of-sight may not intersect the collimated jet of GRB emission and thus, we may not detect gamma rays for these so-called "off-axis" GRBs. Various investigations have been trying to address this viewing angle effect and to find off-axis GRBs.

3.1 Search for Off-Axis GRBs

Even for the most highly-beamed GRB, the GRB jet gets decelerated over time and becomes effectively an isotropic blast wave such that the jet that was initially beamed away from our line of sight produces afterglow emission (so-called "orphan afterglows") which we may see to increase over time scales from months to several years (e.g., Perna & Loeb 1998; van Eerten et al. 2010). If GRB jets are highly beamed, off-axis GRBs and their subsequent orphan afterglow are a natural prediction. Thus, various wide-field searches have looked for them in the optical and radio wavelengths (e.g., Levinson et al. 2002; Malacrino et al. 2007), but none has been detected at high significance. Among the same vein, specifically Soderberg et al. (2006b) and Soderberg et al. (2010b) targeted as part of their survey 143 SN Ic (including SN Ic-bl) for late-time VLA observations to search for off-axis GRB afterglows, but none of their objects showed evidence for bright, late-time radio emission that could be attributed to off-axis jets coming into our line of sight, until 2009. In 2009, SN Ic-bl 2009bb was discovered optically and exhibited a large radio luminosity (Soderberg et al. 2010b; Pignata et al. 2011) that requires substantial relativistic outflow with 10^3 more matter coupled to relativistic ejecta than expected from normal core-collapse, and thus, arguing for an engine-driven SN. While no coincident GRB was detected, it is not clear whether it is because there was a weak GRB that went undetected or the GRB was off-axis or there were no gamma-rays produced during the SN. While also SN Ic 2007gr was claimed to indicate an engine-driven explosion without an observed GRB (Paragi et al. 2010), its radio light curves and X-ray data indicate that it may well be an ordinary SN Ib/c explosion (Soderberg et al. 2010a).

3.2 Relative Rates of SN Ic-bl vs LGRB

A statistical approach for understanding the SN-GRB connection is to compare the explosion rates of broad-lined SN Ic to those of Long GRBs and see if they are comparable. While this line of argument is very reasonable, it is not very conclusive at this point, given that both kinds of rates are somewhat uncertain. On the GRB side, the beaming angle is uncertain, given the possible 2 different populations of GRBs (high-luminosity, highly-beamed vs. low-luminosity and nearly isotropic) - on the SN side, the rates of SN subtypes are not well known, specifically those of SN Ic-bl (Li et al. 2010), as well as how selection effects may enter differently for GRB and SN searches (Woosley & Bloom 2006). Nevertheless, Guetta & Della Valle (2007) investigated this question by distinguishing between High- and Low-luminosity GRBs and by deriving the SN Ic-bl rate from a heterogeneous list of SNe discovered by different surveys. They estimate that the ratio of low-luminosity GRBs to SN Ic-bl is in the range of ~1%–10%, assuming that SN Ic-bl live in the same environments as SN-GRBs and have the same host galaxy luminosity, M_B, which is at odds with recent observations (Section 6). Independently, the extensive radio search for off-axis GRBs in 143 optically discovered SN Ib/c (not strictly only SN Ic-bl) yields that less than ~1% of SN Ib/c harbor central engines (Soderberg et al. 2010b), thus broadly consistent with the above estimates, depending on the SN Ic-bl rate.

In conclusion, it appears that SN-GRB are intrinsically rare and that certain conditions must be fulfilled for an exploding, massive and stripped star to simultaneously produce a GRB jet and to release a large amount of energy.

4 Aspherical Explosions: Only in SN-GRBs?

One of the fundamental questions in the SN-GRB field is whether aspherical explosions are the exclusive and distin-
A distinguishing property of GRB-SN, or whether they are generic to the core-collapse process. Besides polarization measurements, late-time spectroscopy is a premier observational tool for studying the geometry of the SN explosion. At late times (> 3 – 6 months), the whole SN ejecta become optically thin in the continuum and hence affords a deeper view into the core of the explosion than spectra taken during the early photospheric phase. Moreover, the emission line shapes provide information about the velocity distribution of the ejecta (Fransson & Chevalier 1987, Schlegel & Kirshner 1989), and thus its radial extent, since the ejecta are in homologous expansion (where \( v_r \propto r \)). A radially expanding spherical shell of gas produces a square-topped profile, while a filled uniform sphere produces a parabolic profile. In contrast, a cylindrical ring, or torus, that expands in the equatorial plane gives rise to a “double-peaked” profile as there is very little low-velocity emission in the system, while the bulk of the emitting gas is located at \( \pm v_t \), where \( v_t \) is the projected expansion velocity at the torus.

Thus, a number of studies embarked on the difficult undertaking of obtaining such nebular spectra with adequate resolution and signal for a number of stripped SNe. As the objects are usually faint at that stage (19–23 mag), they call for large-aperture telescopes. First, Mazzali et al. (2005) and then Maeda et al. (2007) reported that SN Ic-bl 2003jd and the peculiar SN Ib 2005bf, respectively, displayed a double-peaked profile of \([\text{O I}] \lambda \lambda 6300,6364\) in nebular spectra. Subsequently, Modjaz et al. (2008b) and Maeda et al. (2008) independently presented a large number of stripped SNe displaying pronounced double-peaked profiles of \([\text{O I}] \lambda \lambda 6300,6364\), the strongest line in late-time spectra of SNe without H, with velocity separations ranging between 2000 to 4000 km s\(^{-1}\) (see Fig. 2). Those profiles were interpreted as indicating an aspherical distribution of oxygen, possibly in a torus or flattened disc seen edge-on, suggesting that strong asphericity is ubiquitous in core-collapse SNe, and not necessarily a signature of an association with a GRB. For SN spectra with sufficient S/N in some of the additional lines ( \( \text{O I} \lambda 7774, \text{Mg I} \lambda 4571 \)) and with multiple epochs (e.g., SNe 2004ao, 2008D, Modjaz et al. 2009, Tanaka et al. 2009b), the double-peaked profiles are unlikely to be caused by known optical depth effects. Furthermore, Taubenberger et al. (2009) presented and analyzed a large set of 98 late-time spectra of a total of stripped SNe (some of which were taken from the literature) and found a rich phenomenology of line structures. The results of their statistical analysis suggest that probably at least half of all stripped SNe are aspherical and that line profiles are indeed determined by the ejecta geometry, with Mg and O similarly distributed within the SN ejecta.

Recently, Milisavljevic et al. (2010) presented high S/N and multi-epoch nebular spectra of a select number of stripped SNe (including published data) and, coupled with detailed spectral line analysis and fitting, raised important questions about the interpretation of the indicated geometry. They suggested that alternative geometries beyond torus or highly flattened disks are possible for some of the SNe, where the double-peaked oxygen profile could be either coming only from preferentially blueshifted emission with internal obscuration in the red, or could consist of two separate emission components (a broad emission source centered around zero velocity and a narrow, blue-shifted source). Future high-S/N, multi-epoch and multiple-line observations of a large sample of SNe II/IIb/Ib/Ic coupled with radiative transfer models should help to elucidate the observed blue- and redshifts of the line profiles and constrain the exact geometry.

In conclusions, observed double-peaked oxygen lines are not necessarily a proxy of a mis-directed GRB jet and they suggest that asphericities (of whatever exact geometry they may be) are most likely prevalent in normal core-
collapse events. This result that asphericites are an ubiquitous feature during core-collapse is in line with similar conclusions based on polarization studies of SN II, Ib and SN Ic e.g., Leonard & Filippenko 2005, Maund et al. 2009a, neutron-star kick velocities (Wang et al. 2006), young SN remnant morphologies (Fesen et al. 2006), and theoretical modeling efforts (Scheck et al. 2006; Burrows et al. 2006; Dessart et al. 2008). Aspherical explosion geometry does not appear to be distinguishing feature of SN-GRBs, though SN-GRBs may have the highest degree of asphericity according to some models (Maeda et al. 2008).

5 Progenitor Mass as the Culprit?

One obvious possibility is that progenitor mass, one of the most fundamental properties of a star, may set apart SN with GRBs from those without GRBs. Specifically, the SN-GRB progenitors could be of high mass (enough to produce a BH required for the collapsar model) and higher than the progenitors of SN without GRBs. In order to estimate the mass of the SN-GRB progenitors, one has to use a different method than the direct pre-explosion imaging technique (which even with HST’s exquisite resolution can only be used for SN progenitor searches for up to ∼20 Mpc), since the GRB and SN progenitors are at much larger, cosmological distances and since even in the local universe, detection attempts of stripped SN progenitors have failed (Smartt et al. 2009). There are two different techniques for indirectly estimating the main sequence (MS) mass of a SN/GRB progenitor. The first one consists of modeling the spectra and light curves of the individual SN/GRB in order to constrain the ejecta mass and core-mass before explosion and then use stellar evolutionary codes (e.g., see Fig. 1 in Tanaka et al. 2009a) to infer the MS mass, subject to the caveats of uncertain mass loss rates and rotation. The second technique entails studying the stellar population at the SN/GRB position as a proxy for the SN/GRB progenitor.

The first technique has been performed for a small number of SN/GRBs (e.g., Mazzali et al. 2006 for a review see Tanaka et al. 2009a; Nomoto et al. 2010), mostly for the nearby GRB-SN and a few peculiar SN and its results suggest that the SN-GRB are from the more massive end of stellar masses (∼20–50 M⊙), but not necessarily from the most massive stars. However, so far only data of two SNe Ic-bl without an observed GRB (SNe 1997ef and 2002ap) have been modeled, and thus, it is not clear from this line of research whether the GRB-less SN Ic-bl progenitors are as massive as those of SN-GRB.

On the other hand, the second technique of studying the stellar populations at the explosion sites has been performed on a statistical set of different types of SN, SN-GRB and GRBs (those that are at higher redshifts) by comparing the amount of light at the position of the GRB or SN (after it had faded) to that of the rest of the host galaxy, as a proxy for the amount of star formation. Fruchter et al. (2006) and Svensson et al. (2010) found that GRBs are more concentrated towards the brightest regions of their host galaxies than are SN II (for the same range of high-z), and took their data to indicate larger progenitor masses for GRBs than for SN II, which is consistent with SN II pre-explosion detections that indicate modest MS-progenitor masses of 8–16 M⊙ for SN IIP (see Smartt et al. 2009 for a review). Importantly, Kelly et al. (2008) demonstrate, using the same technique as Fruchter et al. (2006), that nearby (z < 0.06) SNe Ic are also highly concentrated on the brightest regions within their host galaxies, thus implying similarly high progenitor masses for SNe Ic without GRBs, as for GRBs themselves. Thus, these observations suggest another ingredient for GRB production besides higher mass progenitors. While Anderson & James (2008; 2009) have similar findings, their interpretation differs, as they regard the increased centralization of a SN distribution to imply increased progenitor metallicity, not increased progenitor mass. We will turn to the question of metallicity in the next section.

6 Metallicity as the Culprit?

Metallicity is expected to influence not only the lives of massive stars but also the outcome of their deaths as supernovae (SNe) and as gamma-ray bursts (GRBs). However, before 2008, there were surprisingly few direct measurements of the local metallicities of SN-GRBs, and virtually none for the various types of core-collapse SNe.

Before delving into the details of the metallicity studies, let us explain what we refer to when using the term metallicity. Theorists usually refer to the iron mass fraction of the SN progenitor, which is important for setting the mass loss rate of the pre-explosion massive star, since the bulk of the opacity is provided by iron and its huge number of lines (Vink & de Koter 2005). Observers, on the other hand, usually measure the oxygen abundance of HII regions of some (usually central) part of the host galaxy or, in the best-case-scenario, that at the SN position. The nebular oxygen abundance is the canonical choice of metallicity indicator for ISM studies, since oxygen is the most abundant metal, only weakly depleted onto dust grains (in contrast to refractory elements such as Mg, Si, Fe, with e.g., Fe being depleted by more than a factor of 10 in Orion; see Simón-Díaz & Stasinska 2011), and exhibits very strong nebular lines in the optical wavelength range (e.g., Pagel et al. 1979; Osterbrock 1989; Tremonti et al. 2004). Thus, well-established diagnostic techniques have been developed (e.g., Kewley & Dopita 2002; Pettini & Pagel 2004; Kobulnicky & Kewley 2004; Kewley & Ellison 2008). Due to the short lifetimes

2 We also note that when we discuss oxygen, we do not refer to the oxygen that was released during explosion (Section 4), since it usually takes 105 – 106 years of settling time for the SN yields to be incorporated into the ISM, and we are observing the environments only months to years after explosion. While there may be concerns about ‘self-enrichment’, i.e., by evolved stars in HII region before explosion (such that the measurements would not reflect the natal metallicity but some self-polluted, higher value), many HII regions do not show clear signs of self-enrichment (Wof- ford 2009).
of the massive SN and GRB progenitor stars ($\leq$ 10 million years for 20 $M_\odot$ stars, Woosley et al. 2002), we do not expect them to move far from their birth HH region sites (but see Hammer et al. 2006; Eldridge et al. 2011 and below) and thus, we take the abundance of the HH region at the SN site to indicate the natal metallicity of the SN or GRB progenitor. In one GRB case, where there is an independent metallicity measurement from absorption-line ratios in the X-ray spectra from the circumburst medium of SN 2006aj/XRF 060218 (Campana et al. 2008) and the common nebular oxygen-abundance measurement (e.g., Modjaz et al. 2006), the two completely independently derived values are in broad agreement. Furthermore, it appears that gas-phase oxygen abundances track the abundances of massive stars well, as seen in a number of studies for the Orion nebula (see Simon-Díaz & Stasinska 2011 for a good review) and for blue supergiants in NGC 300 (Bresolin et al. 2009).

When considering oxygen abundance measurements, one has to remember the long-standing debate about which diagnostic to use, as there are systematic metallicity offsets between different methods (recombination lines vs. collisionally excited lines vs. “direct” method) and different strong-line diagnostics (see Kewley & Ellison 2008 and Moustakas et al. 2010 for detailed discussions), as well as the debate about the solar oxygen abundance value (Asplund et al. 2009). Nevertheless, the (relative) metallicity trends can be considered robust, if the analysis is performed self-consistently in the same scale, and trends are seen across different scales. We demonstrate the power and potential of this approach in the next subchapters.

6.1 Metallicity of SNe with and without GRBs

Many theoretical GRB models favor rapidly rotating massive stars at low metallicity (Hirschi et al. 2005; Yoon & Langer 2005; Woosley & Heger 2006; Langer & Norman 2006) as likely progenitors. Low metallicity seems to be a promising route for some stars to avoid losing angular momentum from mass loss (Vink & de Koter 2005; Crowther & Hadfield 2006) if the mass loss mode is set by line-driven, and therefore, metallicity-driven winds (but see Smith & Owocki 2006 for eruptions in some massive stars). If the stellar core is coupled to the outer envelope via, e.g., magnetic torques (Spruit 2002), it is able to retain its high angular momentum preferentially at low metallicity. In turn, high angular momentum in the core appears to be a key ingredient for producing a GRB jet for both the collapsar and the magnetar models.

If the GRB progenitor is supposed to be at low metallicity for minimal mass loss, then how does it remove its outer layers, especially the large Hydrogen envelope, for we do not see any trace of H or He in the optical spectra of SN-GRB? Either via binaries (e.g., Fryer et al. 2007; Podsiadlowski et al. 2010) or, if the abundances in the star are sufficiently low, and thus, the star rotates rapidly enough, then quasi-chemical homogeneous evolution may set in, where hydrogen gets mix into the burning zones of the star via rotational mixing (Maeder 1987; Langer 1992; Heger & Langer 2000; Maeder & Meynet 2000), such that the star has low hydrogen abundance and a large core mass just before explosion. This mechanism seems plausible for producing a GRB and a broad-lined SN Ic at the same time, though it is debated whether it can explain all observed trends in the VLT FLAMES survey of massive stars at different metallicities (Hunter et al. 2009; Frischknecht et al. 2010; Brott et al. 2011).

Before 2007, a number of studies showed observationally that GRB hosts are of lower luminosity compared to core-collapse SN hosts (Fruchter et al. 2006; Wolf & Podsiadlowski 2007) and, when measurable, of low metallicity (e.g., Fynbo et al. 2003; Prochaska et al. 2004; Sollerman et al. 2005; Modjaz et al. 2006), especially compared to the vast majority of SDSS galaxies (Stanek et al. 2006). The next step was to compare the abundances of SNe Ic-bl with GRBs to SNe Ic-bl intrinsically without GRBs to test whether low metallicity is a necessary condition for GRB production. In 2007 and 2008 we embarked on directly measuring metallicities of a statistically significant sample of broad-lined SN Ic environments and deriving them in the same fashion, which we presented in our study of Modjaz et al. (2008a), the first of its kind. There, we compared the chemical abundances at the sites of 5 nearby ($z < 0.25$) broad-lined SN Ic that accompany nearby GRBs with those of 12 nearby ($z < 0.14$) broad-lined SN Ic that have no observed GRBs. We showed that the oxygen abundances at the GRB sites are systematically lower than those found at the sites of ordinary broad-lined SN Ic (Fig. 3). Unique features of our analysis included presenting new spectra of the host galaxies and analyzing the measurements of both samples in the same set of ways, via three independent metallicity diagnostics, namely those of Kewley & Dopita (2002) (KD02), McGaugh (1991) (M91) and Pettini & Pagel (2004) (PP04). We demonstrated that neither SN selection effects (SN found via targeted vs. non-targeted surveys, for an extensive discussion see Section 8) nor the choice of strong-line metallicity diagnostic could cause the observed trend. Though our sample size was small, the observations (before 2009) were consistent with the hypothesis that low metal abundance is the cause of some massive stars becoming SN-GRB. While each metallicity diagnostic has its own short-coming, if we use the scale of PP04, which has been suggested by Bresolin et al. (2009) to be the strong-line method in most agreement with abundances from stars, then the “cut-off” metallicity value would be $\sim 0.3$ $Z_\odot$. Furthermore, a comparison between the local metallicity of the GRB-SN site and the global host galaxy value via resolved metallicity maps yields that the GRB-SN local values track the global host value, but are also amongst the most metal-poor site of the galaxy (Christensen et al. 2008; Levesque et al. 2011).
Fig. 3  Host-galaxy luminosity ($M_B$) and host-galaxy metallicity (in terms of oxygen abundance) at the sites of nearby ordinary broad-lined SNe Ic (SN Ic (broad): blue filled circles) and broad-lined SNe Ic connected with GRBs (SN (broad & GRB): red filled squares) in three different, independent metallicity scales. Host environments of SNe-GRBs are more metal poor than host environments of broad-lined SNe Ic where no GRB was observed, for a similar range of host-galaxy luminosities and independent of the abundance scale used. For reference, the yellow points are nuclear values for local star-forming galaxies in SDSS (Tremonti et al. 2004), re-calculated in the respective metallicity scales, and illustrate the empirical luminosity-metallicity relationship for galaxies. The host environment of the most recent SN-GRB (Chornock et al. 2011; Starling et al. 2011) is consistent with this trend. From Modjaz et al. (2008a).

2010b) and one radio-relativistic SN, SN 2009bb (Soderberg et al. 2010b; Levesque et al. 2010a) have been observed at high, super-solar, metallicity. Even if one includes those higher metallicity explosions regardless of whether they share the same progenitor channels as SN-GRBs, Levesque et al. (2010a) show that the M-Z relationship for GRBs lies systematically below that of the bulk of the normal star-forming galaxies in the corresponding redshift ranges (see their Fig. 1). While there are suggestions that the observed low-metallicity trend could be partly produced by the newly-discovered relationship between host galaxy metallicity, mass and star formation rate (so-called "fundamental" metallicity relation, Mannucci et al. 2010) such that low metallicity galaxies have high star formation rates (Mannucci et al. 2011; Kocevski & West 2010), it does not explain why there are not more GRBs in intermediate- and high-mass galaxies (Kocevski et al. 2009; Kocevski & West 2010) and the observed evolution in the GRB rate density with increasing redshifts (Butler et al. 2010). It is currently hotly debated whether dust may be the reason for the metallicity offset (e.g., Fynbo et al. 2009), since it could obscure the optical afterglows of GRBs at high metallicity, thus explaining the lack of high-mass and high-metallicity GRB host galaxies (since usually optical afterglows are needed for precise localization of the host).

An obvious test will be to construct the $M-Z$ relationship for other explosions that track massive star formation, such as normal SN Ib and SN Ic, found in the same fashion as GRBs, namely in non-targeted surveys such as the Palomar Transient Factory (see Section 8), and to compare it to that of GRBs.

6.2 Metallicity of various regular types of CCSN

For illuminating the SN-GRB connection and for pursuing stellar forensics on the specific SNe Ic-bl with and without GRBs, it is also important to gain an understanding of the progenitors of "normal" stripped SNe. Here too, the two outstanding progenitor channels are either single massive Wolf-Rayet (WR) stars with main-sequence (MS) masses
of $\gtrsim 30 \, M_\odot$ that have experienced mass loss during the MS and WR stages (e.g., Woosley et al. 1993), or binaries from lower-mass He stars that have been stripped of their outer envelopes through interaction (Podsiadlowski et al. 2004 and references therein), or a combination of both. Attempts to directly identify SN Ib/c progenitors in pre-explosion images have not yet been successful (e.g., Gal-Yam et al. 2005, Maund et al. 2005; Smartt 2009).

A more indirect but very powerful approach is to study the environments of a large sample of CCSNe in order to discern any systematic trends that characterize their stellar populations. Discussed already was the study of the amount of blue light at the position of different types of explosions (Section 5), which indicates that stripped SNe, and especially SNe Ic, are more concentrated towards the brightest regions of their host galaxies than SN II (Kelly et al. 2008, Anderson & James 2008), possibly suggesting the progenitors of SNe Ib/c may thus be more massive than those of SNe II, which are $\sim 8$–$16 \, M_\odot$ (see Smartt 2009 for a review).

There exist a few metallicity studies of CCSN host environment that either indirectly probe the metallicities of a large set of SNe II, Ib and Ic or that directly probe the local metallicity of a small and select set of interesting/peculiar stripped SNe. Nevertheless, interesting trends have emerged: Studies to measure the metallicity by using the SN host-galaxy luminosity as a proxy (Prantzos & Boissier 2003; Arcavi et al. 2010), or by using the metallicity of the galaxy center measured from Sloan Digital Sky Survey (SDSS) spectra (Prieto et al. 2008) to extrapolate to that at the SN position (Boissier & Prantzos 2009) find a) that host galaxies of SNe Ib/c found in targeted surveys seem to be in more luminous and more metal-rich galaxies than those of SNe II (Prieto et al. 2008; Boissier & Prantzos 2009) and b) that SNe Ic are missing in low-luminosity and presumably low-metallicity galaxies of the untargeted survey PTF, while SN II, Ib, and Ic-bl are abundant there (Arcavi et al. 2010). Those prior metallicity studies do not directly probe the local environment of each SN (which can be different from the galaxy center due to metallicity gradients) nor do some differentiate between the different SN subtypes. In Modjaz et al. (2011), we presented the largest existing set of host-galaxy spectra with H II region emission lines at the sites of 35 stripped-envelope core-collapse SNe and including those from the literature and from Modjaz et al. (2008a), we analyzed the metallicity environments of a total of 47 stripped SNe. We derived local oxygen abundances in a robust manner in order to constrain the SN Ib/c progenitor population. We obtained spectra at the SN sites, included SNe from targeted and untargeted surveys, and performed the abundance determinations using the same three different oxygen-abundance calibrations as in Modjaz et al. (2008a). We found that the sites of SNe Ic (the demise of the most heavily stripped stars having lost both H and He layers) are systematically more metal-rich than those of SNe Ib (arising from stars that retained their He layer) in all calibrations. A Kolmogorov-Smirnov-test yielded the low probability of 1% that SN Ib and SN Ic environment abundances, which are different on average by $\sim 0.2$ dex (in the Pettini & Pagel scale), are drawn from the same parent population. Broad-lined SNe Ic (without GRBs) occur at metallicities between those of SNe Ib and SNe Ic. Lastly, we found that the host-galaxy central oxygen abundance is not a good indicator of the local SN metallicity (introducing differences up to 0.24 dex), and concluded that large-scale SN surveys need to obtain local abundance measurements in order to quantify the impact of metallicity on stellar death.

A reasonable suggestion for why the environments of SNe Ic are more metal rich than those of SNe Ib is that metallicity-driven winds (Vink & de Koter 2005; Crowther & Hadfield 2006) in the progenitor stars prior to explosion are responsible for removing most, if not all, of the He layer whose spectroscopic nondetection distinguishes SNe Ic from SNe Ib. This explanation may favor the single massive WR progenitor scenario as the dominant mechanism for producing SNe Ib/c (Woosley et al. 1993), at least for those in large star-forming regions. While the binary scenario has been suggested as the dominant channel for numerous reasons (see Smartt 2009 for a review, Smith et al. 2011), we cannot assess it in detail, since none of the theoretical studies (e.g., Eldridge et al. 2008 and references therein) predict the metallicity dependence of the subtype of stripped SN. However, our results are consistent with the suggestion of Smith et al. (2011) that SNe Ic may come from stars with higher metallicities (and masses) than SNe Ib, even if they are in binaries. Furthermore, the finding that the metallicity environments for SN Ic-bl are different from those of SN Ic indicates that their progenitors may be physically different (perhaps because of magnetic fields or other factors) and that the presumably significant amount of mass at high velocities in SN Ic-bl are probably not only due to viewing-angle effects.

Most recently, similar studies for SN Ib and SN Ic have been conducted by Anderson et al. (2010) and Leloudas et al. (2011). While they do find small differences between SN Ib and SN Ic, with SN Ic in slightly more metal-rich environments, they conclude that their findings are not statistically significant. While the reasons for these different metallicity findings in different studies are not yet clear, some of the aspects of their studies may complicate direct SN Ib vs. SN Ic metallicity comparisons with statistical power. For example, historical SNe Ib/c without firm subtype classifications (e.g., SNe 1962L, 1964L) from only targeted surveys, some with incorrect SN offsets as announced in the IAUC (e.g., for SNe 1987M and 2002ji; S. Van Dyk 2010, private communication) are included (Anderson et al. 2010) and an unequal number of SN Ib (N=14) and SN Ic (N=5) in Leloudas et al. (2011). In any case, definite answers should be provided by future environmental metallicity studies using a very large SN crops from the same, homogeneous and galaxy-unbiased survey, such as the one we are undertaking (see Section 8), which should be ideally suited to de-
term the environmental conditions that influence the various kinds of massive stellar deaths in an unbiased fashion.

6.3 SN and GRB Host Metallicity Measurements as a Rapidly Expanding Field

Not only for stripped SNe and SN-GRBs, but also for other kinds of SNe and transients have metallicity studies emerged as a promising tool to probe their progenitor and explosion conditions. Another class of CCSN that has piqued a lot of interest in the past few years is the emerging field of over-luminous SNe, i.e., SNe defined as more luminous in absolute magnitudes than $M_V \sim -21$ mag (Smith et al. 2007, Ofek et al. 2007, Quimby et al. 2011), that are being discovered in wide-field surveys. Is is hotly debated what powers their optical brilliance, whether it’s due to circumstellar interaction, large amount of synthesized $^{56}$Ni during the explosion of a pair-instability SN or the birth of a magnetar (Kasen & Bildsten 2010). Host galaxy studies show that their host galaxies are of low luminosity, highly starforming and blue (Neill et al. 2011), similar to GRB-host galaxies, and similarly of low-metallicity, when measured (Stoll et al. 2011), with the exception of the host of SN 2006gy, the SN which was first claimed as a pair-instability SN (Smith et al. 2007, Ofek et al. 2007). Furthermore, the best candidate for a pair-instability SN, SN 2007bi (Gal-Yam et al. 2009) has a host galaxy with a metallicity of $12+\log(O/H)_{\odot} = 8.15 \pm 0.15$ in the McGaugh scale, and thus, $\sim 0.3 Z_\odot$ (Young et al. 2010), so it is a subsolar galaxy, but not of extreme subsolar metallicity, as one might expect from Pop III stars in the high-$z$ universe. Thus, if SN 2007bi is representative of pair-instability SNe, then they should be found frequently during current and next generation of wide-area surveys, which have enough volume to discover rare transients.

Furthermore, even for SN Ia, which arise from the thermonuclear explosion of a white dwarf at or near the Chandrasekhar mass limit in a binary system, host galaxy studies have uncovered trends for SN Ia luminosity with host galaxy morphology (e.g., Hamuy et al. 1996) and mass (e.g., Kelly et al. 2010, Sullivan et al. 2010), where more luminous SN Ia tend to be in more luminous and (assuming the luminosity-metallicity relationship for galaxies) metal-rich galaxies, which is consistent with measured metallicity studies (Gallagher et al. 2008). However, for SN Ia with their long delay times (200 Million yrs to a few Gigayears, e.g., Maoz 2010) and the associated large offsets between birth and explosion sites, it is not clear whether measuring the gas-phase metallicity (which reflects that of the currently starforming gas) at the SN position really reflects the natal metallicity of the old progenitor (Bravo & Badenes 2011). Nevertheless, integrated metallicities from stars in the host galaxy (Gallagher et al. 2008) or those of dwarf galaxies (Childress et al. 2011), which usually have a small spread in metallicities, may be revealing.

7 SN 2008D/XRT080109: Stellar Forensics by Witnessing the Death Throes of a Stripped Star

A complimentary stellar forensics tool is to catch the massive star during its death throes. This happened for SN 2008D/XRT080109 (where XRT stands for X-ray Transient) which was discovered by Soderberg et al. (2008). From the early light of the explosion, one can reconstruct a massive star’s pre-explosion composition and radius, which provides a powerful tool to closely investigate a single star out to cosmological distances. Besides its utility, the story of SN 2008D/XRT 080109 reminds us of the importance of serendipity in science. SN 2008D/XRT 080109 was discovered by Soderberg et al. (2008) in X-rays via the Swift satellite, because they were monitoring another SN, SN 2007uy, in the same galaxy, when suddenly XRT080109 erupted and lasted $\sim 600$ sec in X-rays. Furthermore, our program was also monitoring SN 2007uy, and the rest of the host galaxy, in the optical and NIR from the ground, providing us with stringent limits on the optical emission just hours before the onset of X-ray transient.

In Modjaz et al. (2009), we gathered extensive panchromatic observations (X-ray, UV, Optical, NIR) from 13 different telescopes to determine the nature of SN 2008D, its accompanying Swift X-ray Transient 080109, and its progenitor (see also Soderberg et al. 2008). We first established that SN 2008D is a spectroscopically normal SN Ia (i.e., showing conspicuous He lines, see Fig 4), which implies the progenitor star had an intact He layer, but had not retained its outermost H envelope. For the first time, the very early-time peak (at $\sim 1$ day, see Fig 5) could be observed for this kind of SN, from which one can deduce the progenitor radius, since that peak is due to black-body emission from the cooling and expanding stellar envelope. Using our reliable and early-time measurements of the bolometric output of this SN in conjunction with models by Waxman et al. (2007) and Chevalier & Fransson (2008), as well as published values of kinetic energy and ejecta mass, we derived a progenitor radius of $1.2 \pm 0.7 R_\odot$ (in agreement with Soderberg et al. 2008) and $12 \pm 7 R_\odot$, respectively, the latter being more in line with typical WN stars. We furthermore showed that the observed X-ray emission by which it was discovered (Soderberg et al. 2008) is different from those of X-ray flashes, the weaker cousins of GRBs, which demonstrates that even normal SN Ia, surprisingly, can give rise to high-energy phenomena (but see Mazzali et al. 2008). Lastly, our spectra obtained at three and four months after maximum light show double-peaked oxygen lines that we associate with departures from spherical symmetry, as has been suggested for the inner ejecta of a number of SN Ia cores. Our detailed observations and their analysis, as well as those of others Soderberg et al. (2008), Mazzali et al. (2008), Malesani et al. (2009), Maund et al. (2009b), Tanaka et al. (2009c) have inspired a number of theorists to develop and refine sophisticated models of SN shock breakout including relativistic-
mediated shocks (Katz et al. 2010), asphericity (Couch et al. 2011) and the impact of a wind (Balberg & Loeb 2011) aimed at reproducing the observations and predicting their appearance at high-z (Nakar & Sari 2010; Rabinak & Waxman 2011) and the impact of a wind (Balberg & Loeb 2011) to explain its X-ray shock breakout, as well as refine models of the subsequently cooling envelope (Nakar & Sari 2010; Rabinak & Waxman 2011) aimed at reproducing the observations and predicting their appearance at high-z (Tominaga et al. 2011).

\[ E(B - V)_{\text{host}} = 0.6 \text{ mag} \]

\[ t = 1.84 \text{ day} \]

\[ \Delta t = 0.84 \text{ day} \]

\[ V_{\text{max}} = \frac{t}{t_{\text{breakout}}} \]

\[ \Delta t = 0.71 \text{ day} \]

\[ t_{\text{breakout}} = 3.74 \text{ day} \]

\[ t_{\text{breakout}} = 5.70 \text{ day} \]

\[ t_{\text{breakout}} = 8.60 \text{ day} \]

\[ t_{\text{breakout}} = 10.60 \text{ day} \]

\[ t_{\text{breakout}} = 12.60 \text{ day} \]

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US undertaking and number 1 ranked ground-based project during the 2010 Decadal Survey. Because of different survey modes and detection techniques, these innovative surveys are finding known types of SNe in large numbers and with relatively little bias, as well as rare, yet astrophysically interesting events in statistically large numbers. The main innovations in survey mode are: very large field-of-view (e.g., 7.8-square-degree for PTF, up to 4000 times larger than traditional surveys), galaxy-untargeted, with different cadences, and less bias towards bright cores of galaxies.

In contrast, traditional SN surveys usually have small fields of view and thus, specifically target luminous galaxies that contain many stars in order to increase their odds of finding those that explode as SNe. For example, the prolific Lick Observatory SN Search (LOSS, Filippenko et al. 2001) monitors a list of galaxies that have a mean (median) value at the galaxy magnitude of \( M_B = -19.9 \) (\( M_B = -20.1 \)) mag. But because more luminous galaxies are more metal-rich (Tremonti et al. 2004, see also Fig. 3) such targeted SN surveys are probably biased towards finding SN in high-metallicity galaxies. However, the new surveys alleviate this galaxy- and metallicity-bias and PTF has already found over 1090 spectroscopically ID’ed SNe (as of April 2011) in this galaxy-untargeted fashion, probing SNe and transients in all kinds of galactic environments (except in highly obscured ones, of course). The difference in survey mode appears to be important: using core-collapse SN discovered with PTF, Arcavi et al. (2010) showed that different populations of galaxies may be hosting different types of stripped SNe. The least stripped SN (SN IIb) were found in the low luminosity galaxies (dwarfs), which Arcavi et al. took to indicate a metallicity effect, whereas the massive progenitor at low-metallicity did not have sufficiently strong winds to remove its He layer in order to explode as a SN Ic. While these findings are in line with Modjaz et al. (2011), in order to verify them with direct metallicity measurements, as well as for resolving some of the issues discussed in Section 6.2 it is necessary to conduct a thorough and extensive host galaxy study with a large single-survey, untargeted, spectroscopically classified, and homogeneous collection of stripped SNe, something we are currently undertaking with PTF.

For core-collapse SNe and transients, the next big frontier is to hunt for the lowest metallicity host galaxies, in order to fully confront theoretical predictions of the impact of metallicity on stellar death (Heger et al. 2003; O’Connor & Ott 2011) with observations, via the untargeted surveys or specifically low-luminosity galaxy-targeted surveys.

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