Death of Massive Stars: Supernovae and Gamma-Ray Bursts
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Type Ib/c Supernovae with and without Gamma-Ray Bursts

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Abstract. While the connection between Long Gamma-Ray Bursts (GRBs) and Type Ib/c Supernovae (SNe Ib/c) from stripped stars has been well-established, one key outstanding question is what conditions and factors lead to each kind of explosion in massive stripped stars. One promising line of attack is to investigate what sets apart SNe Ib/c **with** GRBs from those **without** GRBs. Here, I briefly present two observational studies that probe the SN properties and the environmental metallicities of SNe Ib/c (specifically broad-lined SNe Ic) with and without GRBs. I present an analysis of expansion velocities based on published spectra and on the homogeneous spectroscopic CfA data set of over 70 SNe of Types IIb, Ib, Ic and Ic-bl, which triples the world supply of well-observed Stripped SNe. Moreover, I demonstrate that a meta-analysis of the three published SN 1b/c metallicity data sets when including only values at the SN positions to probe natal oxygen abundances, indicates at very high significance that indeed SNe Ic erupt from more metal-rich environments than SNe Ib, while SNe Ic-bl with GRBs still prefer, on average, more metal-poor sites than those without GRBs.

Keywords. (stars:) supernovae: general, gamma rays: bursts

1. Introduction

Stripped supernovae (SNe) and long-duration Gamma-Ray Bursts (long GRBs) are nature's most powerful explosions from massive stars. They energize and enrich the interstellar medium, and, like beacons, they are visible over large cosmological distances. However, the mass and metallicity range of their progenitors is not known, nor the detailed physics of the explosion (see reviews by Woosley & Bloom 2006; Smartt 2009). Stripped-envelope SNe (i.e, SNe of Types IIb, Ib, and Ic, e.g., 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 20,000−30,000 km s^{-1} around maximum light (see below) and whose optical spectra show no trace of H and He.

For the last 15 years, the exciting connection between long GRBs and SNe Ic-bl, the only type of SNe observed accompanying long GRBs (for reviews, see Woosley & Bloom 2006; Hjorth & Bloom 2011; Modjaz 2011), and the existence of many more SNe Ic-bl **without** GRBs raises the question of what distinguishes SN-GRB progenitors from those of ordinary SNe Ic-bl without GRBs. Viewing angle effects are probably not the reason why SNe Ic-bl do not show an accompanied GRB (Soderberg *et al.* 2006). Based on radio upper-limits, only $\sim 1\%$ of SNe Ib/c appear to be accompanied by GRBs (Soderberg *et al.* 2010). One promising line of attack is to investigate what sets apart SNe Ib/c **with** GRBs from those **without** GRBs to elucidate the conditions and progenitors of these two types of explosions. While of course there are numerous possible avenues (for a recent review see e.g., Modjaz 2011), I will here adopt a two-pronged approach, given the short amount of

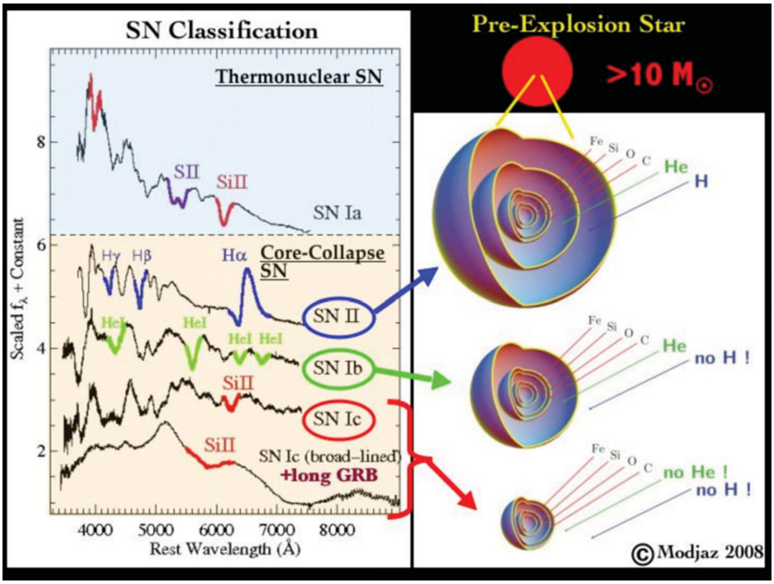

Figure 1. Mapping between different types of core-collapse SNe (*left*) and their corresponding progenitor stars (*right*). *Left*: Representative observed spectra of different types of SNe. Broad-lined SN Ic are the only type of SNe seen in conjunction with GRBs. Not shown are some of the other H-rich SN members (SNe IIn 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). This figure is found at http://cosmo.nyu.edu/ mmodjaz/research.html.

time. First, I focus on comparing the optical spectra of SNe Ib/c with and without GRBs, since early-time optical spectra are used for identifying the spectral features of different explosions and probe the bulk of the ejected stellar material, in particular the outermost layers. Secondly, I present a meta-analysis of published measured metallicities at the explosion site of SNe Ib/c with and without GRBs. Metallicity is expected to strongly impact the lives and deaths of stars due to the metallicity dependence of mass loss (e.g., Vink & de Koter 2005) and its subsequent link to rotation and angular momentum content of the stellar core. The main thrust of my talk is that now a number of different groups, including ours, have contributed to gathering large data-sets, whose analysis can to lead to robust statistical conclusions and interesting insights into different populations of SNe with and without GRBs.

2. Optical Spectra and Expansion Velocities of SNe Ib/c with and without GRBs

While the observational hallmark of a SNe Ic-bl is, by definition, its high expansion velocities (which, when modeled in combination with light curves, yields high energies, sometimes above 10^{52} erg, i.e. 10 times more than the canonical CCSN, and thus motivated some to call them "HyperNovae"), there are debates within the community whether such SNe Ic-bl can be robustly distinguished from "normal" SNe Ic and whether there are systematic differences between SNe Ic-bl with and without GRBs. Prior work involving synthetic models based on Monte Carlo radiative transfer codes (Mazzali *et al.* 2009 and reference therein), while important, has included only a few normal SNe Ic and a few SN Ic-bl without GRBs, thus not yet providing a large sample.

Here we are using the spectra from the CfA sample of Stripped SNe (Modjaz *et al.*, in prep), as well as those from the literature (see references in Modjaz *et al.*, in prep) to compare the absorption velocities as traced by Fe II $\lambda5169$ of different kinds of SNe Ic. Spectral synthesis studies have shown that this and other Fe lines are good tracers of the photospheric velocity, since they do not saturate (Branch *et al.* 2002). With the largest sample of spectra to date, we find that SN Ic-bl **with** GRBs have the **highest** absorption velocities (25,000−35,000 $\mathrm{km\,s^{-1}}$ at maximum V-light), while SNe Ic-bl **without** GRBs have **lower** velocities (between 15,000−25,000 $\mathrm{km\,s^{-1}}$ at maximum V-light), and normal SN Ic have the lowest absorption velocities (8,000−15,000 $\mathrm{km\,s^{-1}}$). We caution that because of severe blending, specifically in SNe Ic-bl, the Fe II $\lambda5169$ line could be blended with other nearby lines such that it may compromise the velocity measurements. However other, more isolated, lines (e.g. Si II) also indicate high velocities for SN Ic-bl.

3. Measured Metallicities at the Explosion Sites of SNe Ib/c with and without GRBs

Since direct SN Ib/c progenitor detection attempts via deep pre-explosion images have not been successful (Smartt 2009) and are impossible for GRBs, we employ a complimentary approach: we study the host galaxy environments in order to discern any systematic trends as a function of explosion type that may characterize their stellar progenitors. Specifically, massive stars at different metallicities are expected to live and die differently, due to the metallicity dependence of mass loss and its subsequent link to rotation and angular momentum content of the stellar core (e.g., Crowther 2007). Since the early work on GRB host metallicities and their comparison with SDSS galaxies as well as with SN galaxies, the field of environmental metallicity studies has experienced a tremendous growth (see discussions in e.g., Levesque *et al.* 2010b; Modjaz 2011; and references therein, as well as contributions in this volume).

Here, we outline the recipe for state-of-the-art metallicity analysis, specifically of the oxygen abundance from nebular HII region emission lines, first formalized in Modjaz *et al.* (2008): 1) In order to probe the natal oxygen abundance, obtain spectra at the position of the SN or GRB (because of metallicity gradients in spiral galaxies); 2) Include only SNe with secure SN ID (i.e., ideally from multi-epoch SN spectra to monitor for any potential classification changes) and also (only) from untargetted surveys in order to mitigate any selection effects; 3) Employ spectrographs with a large wavelength range in order to observe emission lines ([OII] $\lambda3727$ to Hα and [NII] $\lambda6584$) and to compute abundances with different diagnostics, since there are systematic differences between different diagnostics (Kewley & Ellison 2008); 4) Remove stellar absorption in spectra when necessary, and 5) Obtain a good handle on uncertainty budget and propagate line flux and reddening uncertainties into abundance measurement errors via Monte Carlo simulations.

While different groups have recently arrived at different conclusions about whether there is a statistically significant trend of metallicity with Stripped SN subtype (Anderson *et al.* 2010; Modjaz *et al.* 2011; Leloudas *et al.* 2011; see also proceedings by Anderson, Leloudas in this volume), not all measured metallicities reported in the Anderson and Leloudas samples are at the position of the SNe. Thus, we conducted a meta-analysis of all samples (Modjaz *et al.* 2008; Anderson *et al.* 2010; Modjaz *et al.* 2011; Leloudas *et al.* 2011) with the best-possible quality-control and following the above state-of-the-art

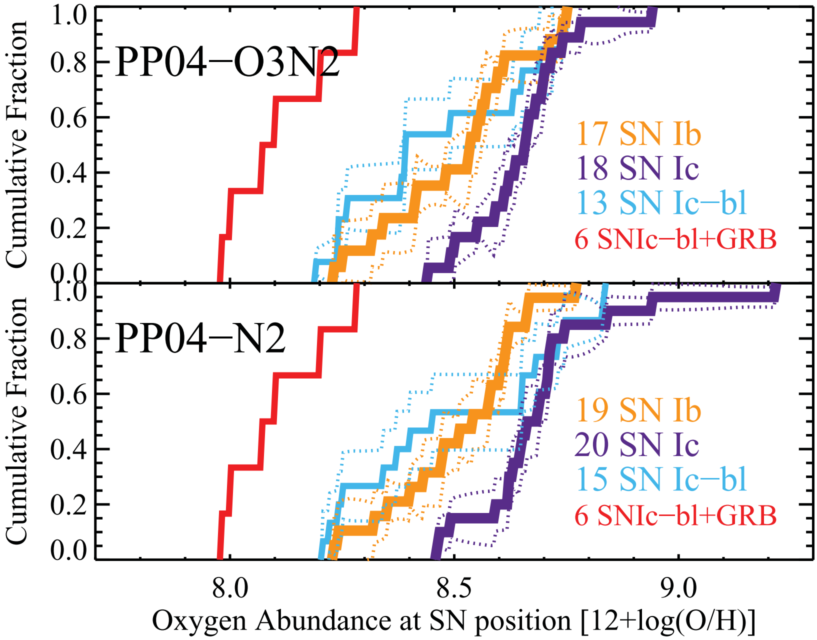

Figure 2. Cumulative fraction (solid lines) of measured oxygen abundances at the SN position of different types of SNe Ib/c with and without GRBs and their confidence bands (dotted lines), based on the meta-analysis of the SN samples in the literature (Modjaz *et al.* 2008; Anderson *et al.* 2010; Modjaz *et al.* 2011; Leloudas *et al.* 2011; and references therein) and in the two scales of Pettini & Pagel (2004) that all samples had in common. The ordinate indicates the fraction of the SN population with metallicities less than the abscissa value. The confidence bands are shown around each cumulative trend, which we computed via bootstrap with 10,000 realizations based on the metallicity measurements and their associated reported uncertainties. SNe Ic (the demise of the most heavily stripped stars that lost much, if not all, of both their H and He layers) are systematically in more metal-rich environments than SNe Ib (SNe arising from less stripped stars that retained their He layer). SN Ic-bl with GRBs are still at consistently lower oxygen abundances than SN Ic-bl without GRBs. The radio-loud SN Ic-bl 2009bb (Soderberg *et al.* 2010) is not included in this plot, since no GRB was detected, but would add one data point at $12+\log(\mathrm{O/H})_{\mathrm{PP04-O3N2}}=8.9$ (Levesque *et al.* 2010b).

recipe. Now that we have larger samples to draw from, we only included oxygen abundance measurements at the exact SN explosion sites (within the slit) of SNe with solid IDs and also from untargeted surveys, to have the best handle possible on the natal metallicity estimates of SNe with well-determined SN types over a large metallicity baseline, the ultimate goal of the study. Figure 2 shows the result of our metal-analysis, namely the cumulative distributions of local metallicities for different types of stripped CCSNe (SNe Ib, Ic, Ic-bl without GRBs, SNe Ic-bl with GRBs) from the combined samples. We find that with a combined and large sample size, the sites of SNe Ic do indeed have higher oxygen abundances than SNe Ib, and with a higher statistical significance than in the individual samples. There is only a 0.1% (2%) probability in the PP04-N2 (PP04-O3N2) scale that the oxygen abundances of the 19 (17) SNe Ib and of 20 (18) SNe Ic are drawn from the same parent population, which are different on average by ~ 0.2 dex. Here we have taken advantage of the power of statistics by combining the hard work of three different groups.

In addition, SN Ic-bl with GRBs still prefer, on average, more metal-poor environments than those without GRBs (see Fig. 2 in Modjaz *et al.* 2011), with the GRB metallicity-luminosity relation offset to lower metallicities, but without a cut-off metallicity above which GRB production would be suppressed (Levesque *et al.* 2010a). Since the host galaxies of both samples span similar ranges in galaxy luminosity (i.e., even to luminous GRB host galaxies of $M_B = -21\,\mathrm{mag}$), dust effects are most likely not the reason for the offset to low metallicity. However, while these results are intriguing, the next step is 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 the Palomar Transient Factory (PTF).

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References

Anderson, J. P. *et al.* 2010, *MNRAS*, 407, 2660
Branch, D., *et al.* 2002, *ApJ*, 566, 1005
Crowther, P. A. 2007, *ARAA*, 45, 177
Filippenko, A. V. 1997, *ARAA*, 35, 309
Hjorth, J. & Bloom, J. S. 2011, Chapter 9 in "Gamma-Ray Bursts" (arXiv:1104.2274)
Kewley, L. J. & Ellison, S. L. 2008, *ApJ*, 681, 1183
Leloudas, G., *et al.* 2011, *A&A*, 530, A95
Levesque, E. M., Berger, E., Kewley, L. J., & Bagley, M. M. 2010a, *AJ*, 139, 694
Levesque, E. M., *et al.* 2010b, *ApJ*, 709, L26
Mazzali, P. A., Deng, J., Hamuy, M., & Nomoto, K. 2009, *ApJ*, 703, 1624
Modjaz, M., *et al.* 2008, *AJ*, 135, 1136
Modjaz, M., *et al.* 2011, *ApJ*, 731, L4
Modjaz, M. 2011, *AN*, 332, 434
Pettini, M. & Pagel, B. E. J. 2004, *MNRAS*, 348, L59
Smartt, S. J. 2009, *ARAA*, 47, 63
Soderberg, A. M., *et al.* 2006, *ApJ*, 638, 930
Soderberg, A. M., *et al.* 2010, *Nature*, 463, 513
Vink, J. S. & de Koter, A. 2005, *A&A*, 442, 587
Woosley, S. E. & Bloom, J. S. 2006, *ARAA*, 44, 507

Discussion

ANDERSON (Q): Is there a bias in PTF for studying SNe in dim hosts? As a community we have to be careful not to over-emphasize them.

MODJAZ (A): As we had discussed in Sydney, PTF has the current strategy of making sure to obtain spectroscopic classification of SNe in low-luminosity hosts, so that we have a complete view of what kinds of SNe erupt in the neglected bin of low-luminosity galaxies. However, this selection should not skew the results of demographic studies – the SN IDs are obtained in those low-luminosity galaxies independent of the SN type. But I agree that this strategy would not lend itself well for computing SN rates if there is no well-defined selection function.

RYAN CHORNOCK (Q): Do you see signs of Wolf-Rayet stars in the spectra of the HII regions at the explosion sites?

MODJAZ (A): For some of them, yes, and a current student of mine, David Fierroz, is analyzing the data – the published spectra, as well as other ones we obtained from Keck.