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Core-collapse supernova diversities

From the weakest to most powerful explosions

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Abstract. Core-collapse supernovae (CC-SNe) show a large variety in their observational properties. Their peak luminosities range from $M_V \sim -14$ mag to ~ -21 mag. The 'faint' and 'bright' SNe show diversities even within the individual luminosity classes. Faint SNe include SNe IIp, peculiar SNe Ib 2005E/2005cz, and even more peculiar SN 2008ha. For this faint class, we propose a scenario that they are outcomes of a low-energy explosion of a star with the main-sequence mass, $M_{\rm ZAMS}$, in the range of $\sim 8-15 M_{\odot}$. Bright SNe also show diversities in their light curves and spectra. SN Ic 2007bi is the most solid case in which a large amount of ^{56}Ni, $\sim 5-10 M_{\odot}$, is ejected. We show that not only a pair-instability SN ($M_{\rm ZAMS} \sim 200-300 M_{\odot}$) but also an Fe-core-collapse SN ($M_{\rm ZAMS} \sim 100 M_{\odot}$) can reproduce its observed behaviors. Finally, the diversity in the luminosity of SNe associated with Gamma-ray bursts is discussed. We suggest that a variety in the jet-induced mechanism (i.e., the duration for which the engine works) as a possible cause of the observed diversity.

Key words. Supernovae – general: Nuclear reactions, Nucleosynthesis, Abundances: Gamma-Ray – bursts

1. Introduction

Evolution of a massive star is characterized by a sequence of nuclear burnings, consumption of the fuel, gravitational contraction of the core leading to the higher temperature, and then the ignition of new species. The structure at the end of their lives thus shows an onion-like structure. A more massive star has the core reached to higher temperature, leading to the core of heavier elements. If the zero-age main-sequence mass (hereafter $M_{\rm ZAMS}$) is in the range of $8-10 M_{\odot}$, the final configuration is a degenerate O-Ne-Mg core (Nomoto 1984). A caveat is that this mass range involves theoretically a large uncertainty. Nucleosynthesis study indicates that the mass range should be as small as $\sim 0.3-0.5 M_{\odot}$, otherwise it results in overproduction of some elements beyond Fe-peaks (Wanajo et al. 2009). Stars with $M_{\rm ZAMS} \gtrsim 10 M_{\odot}$ produce an Fe-core, which an-

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nounces the end of stable hydrostatic nuclear energy generation.

These massive stars are followed by the catastrophic collapse of the core. For stars forming the degenerate O-Ne-Mg core, the core experiences electron captures and collapses to a neutron star (NS) (Nomoto 1987). A shock wave is launched, and then it is energized by neutrinos from the newly born NS. Simulations show that it can result in a weak supernova explosion, by this standard 'delayed neutrino heating mechanism' (Kitaura, Janka, & Hillebrandt 2006). For more massive stars ($M_{\rm ZAMS} \gtrsim 10 M_{\odot}$), the gravitational collapse of the Fe-core also produces a NS. The delayed neutrino heating mechanism is not yet successful to produce an SN in numerical simulations, and it has been suggested that multi-D effects must be appropriately taken into account (e.g., Nordhaus et al. 2010). Despite the requirement for the further theoretical efforts, it has been observationally well developed that a part of these Fe-core collapse events, if not all, trigger an SN explosion. More massive stars, although the critical mass is not yet clarified, may well produce a black-hole (BH), resulting either a whole collapse with no violent optical appearance or a gamma-ray burst (GRB). Another possible route for a SN explosion is a pair-instability SN, theoretically predicted for a star with $M_{\rm ZAMS} \sim 200 - 300 M_{\odot}$ (Barkat, Z., Rakavy, & Sack 1967). In these very massive stars, the high temperature at the O-core contraction stage is in the regime of pair instability, resulting in the total disruption of the star by the explosive O-burning, with no compact remnant left behind the explosion.

One of the goals of observing SNe is to clarify how different types of SNe are connected to the theory of the stellar evolution and the supernova explosions. Until the late 1990's, it was naively believed that CC-SNe explode with the kinetic energy ($E_{\rm K}$) of $\sim 10^{51}$ erg, ejecting $\sim 0.07 M_{\odot}$ of newly formed radioactive ^{56}Ni (which decays into ^{56}Co then ^{56}Fe, accounting for a source of the SN luminosity), and that these features are not so different for different SNe. However, progresses in the observations have been revealing that the observed properties of supernovae are much more diverse than expected from this simple picture. In this paper, we present some highlights from such recent efforts. In §2, we show examples of faint and low-energy SNe. The opposite case is presented in §3, where we discuss very luminous, high-energy explosions. In §4, we focus on SNe associated with GRBs, presenting the diversity of such SNe and an idea about the origin of the diversity. The paper is closed in §5 with concluding remarks.

2. Faint and low energy SNe

2.1. Type IIp SNe

One of the recent progresses is a systematic study of the direct detection of a SN in the *HST* (or other telescopes) pre-SN image of the SN site (see Smartt (2009) for a review). So far, the most solid detections have been reported for Type IIp SNe, which are classified by the $\rm H_{\alpha}$ feature in the spectra and by the plateau in the optical light curve lasting for $\sim$ 100 days. They are interpreted to be the explosion of a star with the hydrogen envelope attached at the time of the explosion, constituting an abundant class among CC-SNe. Assuming a single stellar evolution, the range of $M_{\rm ZAMS}$ to explode as SNe IIp has been constrained to be $\sim 8 - 16 M_{\odot}$ (Smartt 2009). This is qualitatively consistent with the idea that they are the result of a relatively less massive star with insignificant mass loss, but quantitatively challenges the stellar evolution model, i.e., (1) the low mass end extends to the mass range in which the O-Ne-Mg core collapse is expected and that (2) the upper mass end is not as large as expected from the single stellar evolution with the standard mass loss prescription.

Aside from the constraints on the stellar evolution, an interesting picture has emerged. It turns out that most of these SNe are faint both in plateau (powered by the thermal energy content after the shock breakout) and subsequent tail phases (powered by the radioactive decay). These features indicate that they are less energetic ($E_{\rm K} \sim 10^{50}$ erg) than canonical, and eject smaller amount of ^{56}Ni ($\sim 0.001 - 0.1 M_{\odot}$) (Smartt 2009).

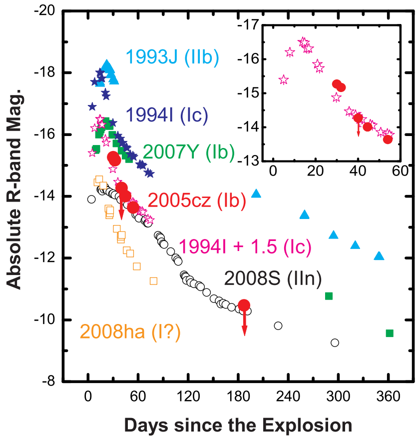

Fig. 1. R-band light curves of SN Ib 2005cz (red-filled circles) and other SNe (Kawabata et al. 2010). The light curve of SN 2008ha is also shown (orange-open squares). The inset shows the comparison between SN 2005cz and SN Ic 1994I dimmed by 1.5 mag, showing that the peak absolute magnitude of SN 2005cz was likely at most -16.5 mag.

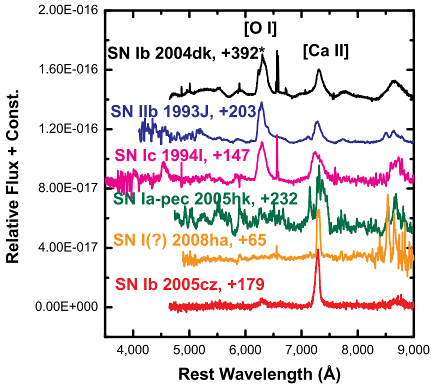

Fig. 2. Late-time nebular spectrum of SN 2005cz as compared to other stripped envelope SNe and SN 2002cx-like objects (also shown is SN 2008ha) (Kawabata et al. 2010).

2.2. SN Ib 2005cz and faint SNe Ib

Type Ib/c SNe are classified by the absence of H features in their maximum spectra, with Ib showing He features and Ic no He features (Filippenko 1997). In the stellar evolution scenario, they are interpreted to be an explosion of a massive star having lost H-rich envelope (Ib) or even He-rich envelope (Ic), due to strong stellar wind or binary interaction (Nomoto, Iwamoto, & Suzuki 1995). SNe IIb share similar properties, with the difference being a temporal existence of H features in their spectra, interpreted to be coming from a thin hydrogen envelope, being placed as the intermediate case between SNe IIp and Ib. These SNe with at most a small amount of H-rich envelope are called ‘stripped-envelope SNe’.

A class of faint SNe Ib have been discovered. Prototypical cases are SNe Ib 2005E (Perets et al. 2010) and 2005cz (Kawabata et al. 2010). They seem to be related to a relatively older stellar population than other SNe Ib, as they are discovered either in the outskirt of host galaxies (e.g., SN 2005E) or in elliptical galaxies (e.g., SN 2005cz).

Emission from these SNe evolves rapidly leading to the optically thin phase (Fig. 1), indicating a small amount of the ejecta in which only $\lesssim 0.1 M_{\odot}$ is C, O and heavier elements. Their peak luminosities indicate that the mass of ejected ^{56}Ni is at most $\sim 0.01 M_{\odot}$. These properties are different from the classical examples of stripped envelope SNe (e.g., SN Ib 1993J, SN Ic 1994I; see e.g., Nomoto et al. 1993). The most striking difference, however, has been found in their late-time, nebular spectra (Fig. 2). They show strong [Ca II] λ7300 line and extremely weak [O I] λ6300, in contrast with other canonical SNe Ib/c in which [O I] λ6300 is always the strongest feature.

There are two scenarios proposed for this class of objects. Perets et al. (2010) proposed a ‘.Ia’ model (e.g., Bildsten et al. 2007). In this scenario, a WD accretes He-rich materials from a companion donor, and He is detonated in the envelope. The envelope is ejected while the WD is left in this interpretation.

The other scenario, as we have proposed in Kawabata et al. (2010), is an explosion of a star with $M_{\rm ZAMS} \sim 8 - 12 M_{\odot}$ having lost a large part of H-rich envelope. It is either the O-Ne-Mg or Fe core-collapse (or less likely, a collapse of an O-Ne-Mg WD accreting He-rich

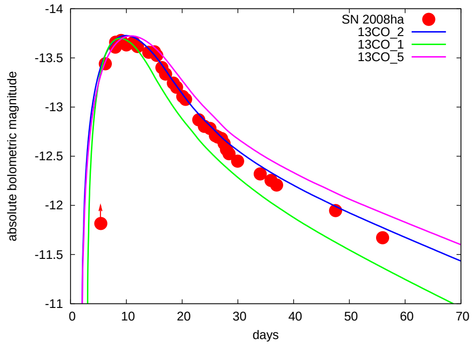

Fig. 3. The bolometric light curve of SN 2008ha as compared to the synthetic curves calculated for a set of the fall-back models (Moriya et al. 2010a).

materials from a donor companion). This scenario is an analog of the faint SNe IIp, with the difference only in the existence or absence of the H-rich envelope. In this scenario, the weak [O I] is a result of the small O-core materials being ejected. For example, a star with $M_{\rm ZAMS} \sim 10 M_\odot$ will end up with the He star with $\sim 2.5 M_\odot$, with the mass of O-core being $\sim 1.5 M_\odot$. Following the core-collapse, it will leave a NS ($\sim 1.4 M_\odot$), with only $\lesssim 0.1 M_\odot$ of O-rich materials being ejected. This will lead to the weak [O I] in its late-time spectra, resulting in the large ratio of [Ca II]/[O I].

It has not been clarified which of these two scenario is the case. It will require more detailed studies on their observed appearance, as well as population synthesis study to explain their rate and the environment properties.

2.3. Peculiar and faint SN 2008ha

Even more peculiar SNe have been discovered. SN 2008ha was found to show an extremely low peak luminosity ($M_V \sim -14$ mag) (Fig. 3) and a low expansion velocity in their spectra ($\sim 2,000$ km s^{-1}) (Valenti et al. 2009; Foley et al. 2009, 2010). The luminosity indicates that $M(^{56}{\rm Ni}) \sim 0.001 - 0.005 M_\odot$. Its spectra showed copious Fe lines, thus tentatively classified as SN Ia, but other spectral features are totally different from SNe Ia. The standard scenario for SNe Ia (i.e., a thermonuclear explosion of a WD) would not apply to this object.

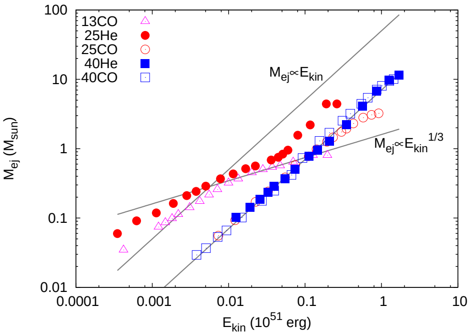

Fig. 4. The relation between the explosion energy and the ejecta mass predicted for a set of the fall-back model. A sequence of the C+O star progenitor explosion with $M_{\rm ZAMS} = 13 M_\odot$, with different $E_{\rm K}$ and the resulting amount of the fall back, are shown by open triangles. The model explains $E_{\rm K} \sim 10^{48}$ erg and $M_{\rm ej} \sim 0.1 M_\odot$ as inferred from the observational properties of SN 2008ha. See Moriya et al. (2010a) for details.

SN 2008ha seems to be an extreme case of a class of the peculiar SN 2002cx-like objects (Li et al. 2003). They share similar spectra, with the variation in the expansion velocity (with SN 2008ha showing the lowest velocity). They also form a sequence with a possible relation between the velocity and the luminosity (Narayan et al. 2011), while the sample size is not yet sufficiently large.

There are several scenarios proposed for this class of objects, especially for SN 2008ha. The scenario we have proposed for SN 2008ha is the following (Moriya et al. 2010a). Given the range of the explosion energy found for CC-SNe (§2.1), we considered the case in which the energy created by the core-collapse is small, just comparable to the binding energy of the progenitor C+O star. Under this condition, the shock wave leads to the ejection of only the surface layer, with the rest of the star eventually collapse to the central remnant by fall back (hypothetically producing a BH). A similar scenario has been proposed to explain the early Galactic chemical evolution (Umeda & Nomoto 2002; Iwamoto et al. 2005; Tominaga, Umeda, & Nomoto 2007).

Moriya et al. (2010a) showed that a C+O star with $M_{\rm ZAMS} \sim 13 M_\odot$ results in $M_{\rm ej} \sim$

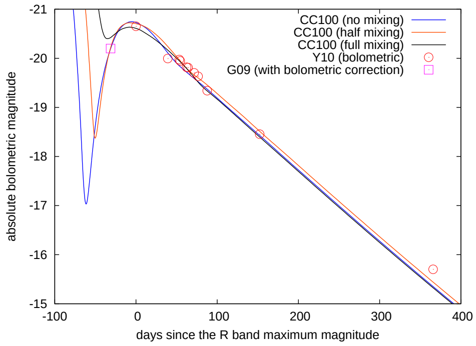

Fig. 5. The light curve of SN 2007bi as compared to the synthetic curves calculated for the Fe-core collapse model with $M_{\rm ZAMS} = 100 M_{\odot}$. See Moriya et al. (2010b) for details.

$0.1 M_{\odot}$ and $E_{\rm K} \sim 10^{48}$ ergs, as consistent with the estimate for SN 2008ha (Figs. 3 & 4). They showed that the resulting light curve is consistent with that of SN 2008ha, assuming that $0.003 M_{\odot}$ of ^{56}Ni is ejected. One problem in the model is that no ^{56}Ni is ejected in their 1D explosion calculations, since the inner part eventually falls back to the central remnant. This, however, could be overcome in real explosions. During the explosion there may be significant mixing within the ejecta, as was invoked in the 'maxing-fall back' process to explain the Galactic chemical evolution (Umeda & Nomoto 2002). Another possibility is that a highly asymmetric explosion, e.g., a jet-driven explosion (Maeda & Nomoto (2003); Tominaga et al. (2007); §4.1). These mechanisms are able to bring the inner materials toward the surface while the rest of materials experience fall back.

3. Luminous and powerful SNe

3.1. Luminous SNe Ic

Not only the faint SNe, but also extremely bright SNe reaching to $M_V \sim -21$ mag, seemingly powerful explosions, have been discovered recently (Ofek et al. 2007; Smith et al. 2007; Gal-Yam et al. 2009; Quimby, et al. 2011). They show diversities in the light curve evolution and spectra, perhaps partly related to different energy sources. There are two possibilities to produce such huge luminosities: a large amount of ^{56}Ni and the interaction between the energetic SN ejecta and dense CSM.

Here we focus on SN Ic 2007bi, which was very likely powered by the decay of ^{56}Ni (Gal-Yam et al. 2009). It showed spectra of SNe Ic. Also the light curve was similar to other SNe Ic, with the difference in its large peak luminosity and slow evolution. This behavior is well consistent with the expectation for an SN powered by a large amount of ^{56}Ni ($\sim 5 - 10 M_{\odot}$) with massive ejecta. Its late-time spectra were also typical of SNe Ic, with [Fe II] possibly stronger than others, again consistent with the expectation. In sum, it is the first solid example in which a large amount of ^{56}Ni ($\gtrsim 5 - 10 M_{\odot}$) is ejected in CC-SNe.

Important questions are how such a large amount of ^{56}Ni was produced in the explosion and what was the progenitor star. An interesting possibility is a pair-instability SN as proposed by Gal-Yam et al. (2009). This, however, is not a unique solution. It has been shown that an Fe-core collapse SN scenario can also explain its observed properties (Moriya et al. 2010b). If a star with $M_{\rm ZAMS} \sim 100 M_{\odot}$ explode with $E_{\rm K} \gtrsim 10^{52}$ ergs (as observed for energetic SNe sometimes associated with GRBs: §4), the required amount of ^{56}Ni ($5 - 10 M_{\odot}$) can be synthesized and ejected (Umeda & Nomoto 2008), and the resulting light curve is consistent with observed (Moriya et al. 2010b). Indeed, both the pair-instability and Fe-core collapse scenarios predict similar outcome – $M(^{56}{\rm Ni}) \sim 5 - 10 M_{\odot}$, $M_{\rm O} \sim 10 - 30 M_{\odot}$, and $E_{\rm K} \sim 10^{52} - 10^{53}$ erg – and it is difficult to distinguish these two models. There is small difference, however, e.g., $M_{\rm Si} \sim 20 M_{\odot}$ and $\sim 5 M_{\odot}$ is the two models, and more detailed study of the explosion and radiation transfer models will hopefully resolve this issue.

4. GRB-SNe

It has been widely accepted that at least a part of long-soft Gamma-ray bursts (GRBs) are associated with an SN explosion. Well-studied spectroscopically confirmed GRB-SNe include SNe Ic 1998bw (GRB980425) (Galama et al. 1998), 2003dh (GRB030329) (Hjorth et

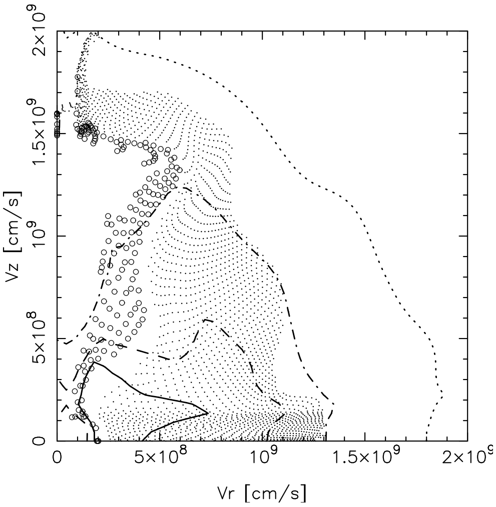

Fig. 6. An example of the 'jet-like' model (Maeda et al. 2002). The distributions of ^{56}Ni (which decays into ^{56}Fe) and ^{16}O are shown by open circles and dots, respectively. The contour is for the density structure.

al. 2003; Stanek et al. 2003), and 2003lw (GRB031203) (Malesani et al. 2004). Other examples have been reported, and we refer Hjorth & Bloom (2011) for a recent review. The above three SNe share similar properties. They show high expansion velocity in their maximum spectra, and peak luminosity is somewhat larger than normal. From radiation transfer study, it has been shown that they are energetic ($\gtrsim 10^{52}$ ergs) explosions of a massive star ($\sim 30-50 M_{\odot}$), ejecting a larger amount of ^{56}Ni ($\sim 0.4 M_{\odot}$) than canonical SNe (Iwamoto et al. 1998; Mazzali et al. 2003). They are also all SNe Ic, indicating that the small amount of the H- and He-envelops is critical for the relativistic jet being able to penetrate into the stellar materials to produce the observed GRB appearance, as proposed e.g., by the collapser model (Woosley 1993). The large progenitor mass also indicates that it is likely a result of the formation of a BH, rather than a NS.

4.1. Asymmetry in the explosion

The popular model for GRBs (and GRB-SNe) is the jet-driven explosion following a BH formation (e.g., Woosley 1993; MacFadyen et al. 1999). The most striking difference between this scenario and canonical SNe is the expected geometry, i.e., large deviation from spherically symmetric ejecta (e.g., Maeda & Nomoto (2003): Fig. 6). Thus, deriving a geometry of the explosion gives a strong diagnostics to explore the explosion mechanism.

The issue has been intensively addressed for SN 1998bw, a prototypical SN associated with a GRB. It has been shown that spherical symmetric models are unable to explain multi-epoch observations consistently (Maeda et al. 2003), and that a jet-like explosion can reproduce the observations without fine-tuning assuming that it was viewed from the direction close to the jet-axis (Maeda et al. 2006; Maeda, Mazzali, & Nomoto 2006; Tanaka et al. 2007). Especially, a spherical model predicts too broad [O I] $\lambda 6300$ in the late-time, optically-thin spectra, contrary to the observed profile (Maeda et al. 2002, 2006). This can be explained if O is distributed mainly in equatorial directions (as the jet pushes the progenitor materials laterally; Fig. 6): the narrow and peaked profile is predicted for an on-axis observer while doubly-peaked profile for an observer close to the equatorial direction.

Indeed, it was suggested that this behavior in the late-phase [O I] profile can be a strong diagnostics of the explosion geometry and viewing angle (Maeda et al. 2002, 2006). Another energetic SN 2003jd without an associated GRB showed the predicted doubly-peaked profile, leading to the suggestion that this was similar to SN 1998bw but viewed from the side (thus no GRB as well) (Mazzali et al. 2005). The idea was pushed further by observing a number of ('normal') SNe Ib/c in late phases (Maeda et al. 2008). Indeed, about one-thirds of SNe Ib/c show the doubly-peaked [OI] profile, leading to the conclusion that asymmetry is a generic feature of them. Based on the observational data, Maeda et al. (2008) argued that the degree of asymmetry is larger for GRB-SNe than other SNe Ib/c, suggesting different explosion mechanisms for GRB-SNe and other SNe, perhaps related to the formation of different compact objects (i.e., a NS versus a BH).

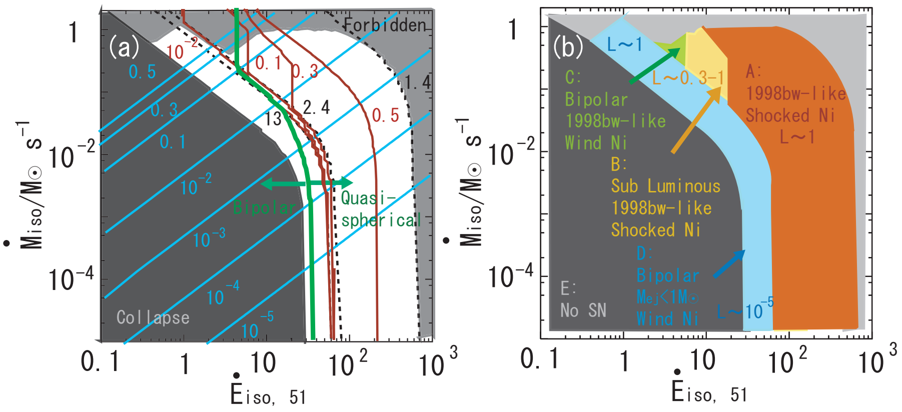

Fig. 7. Theoretical expectations about how the ‘duration’ time of the jet-explosion (i.e., the energy injection ‘rate’) affects the resulting SNe. (a) shows $M(^{56}\mathrm{Ni})$ and (b) shows the expected properties of SNe, as a function of the energy injection rate (horizontal axis) and the mass injection rate (vertical axis). See Maeda & Tominaga (2009) for details.

4.2. A diversity and possible origin

Although the well-studied GRB-SNe share the similar properties in their explosion energy, ejecta mass, and the mass of ^{56}Ni, recent studies indicate that there is indeed a large variety in properties of GRB-SNe. In addition to the spectroscopic confirmation, GRB-SN associations have been proposed for GRBs showing a bump at 10 - 30 days (rest frame) after the GRB. A diversity in GRB-SNe has been indicated from such studies. For example, the bump of GRB040924 is consistent with the light curve of SN 1998bw but dimmer by a factor of 5 (Soderberg et al. 2006). More striking observations were reported for GRBs 060505 and 060614 which did not show any sign of the SN bump (Della Valle et al. 2006; Fynbo et al. 2006; Gal-Yam et al. 2006). Their light curves rejected the existence of associated SNe with the luminosity brighter than 1% of SN 1998bw, showing that either an SN was lacking or very faint (i.e., small amount of ^{56}Ni).

The possibility of very faint SNe in the context of the jet-induced explosion was indeed mentioned before these observations. Maeda & Nomoto (2003) pointed out that the jet-driven explosion does not necessarily result in a bright SN (see also Nagataki et al. 2003). They showed that the ejected amount of ^{56}Ni is sensitive to the mass of the central remnant and the time scale of the energy generation. The larger initial remnant mass reduces the Ni production and the longer time scale for given E_{K} (i.e., smaller energy generation ‘rate’) reduces the Ni production as well. Tominaga et al. (2007) provided a detailed study, suggesting that a jet-driven explosion with the ‘long’ energy generation (or ‘small’ energy generation rate) as a scenario for the missing SNe in GRB 060505 and 060614. Maeda & Tominaga (2009) generalized these arguments, and discussed that the diversity in the energy generation rate can account for the observed diversity in properties of GRB-SNe (and non-detection of SNe in some GRBs) (Fig. 7).

5. Concluding remarks

In this paper, we have presented diverse properties of CC-SNe, ranging from very faint to bright SNe. The diversities should reflect different progenitors and explosion mechanism, providing a good test for the stellar evolution theory. Also discussed was properties of SNe associated with GRBs.

For the faint class, we have presented a scenario that they are outcomes of a low-energy explosion of a star with the main-sequence mass, $M_{\rm ZAMS}$, in the range of $\sim 8 - 15 M_{\odot}$. For the bright class, we have discussed possible models for SN Ic 2007bi, either a pair-instability SN ($M_{\rm ZAMS} \sim 200 - 300 M_{\odot}$) or an Fe core-collapse ($M_{\rm ZAMS} \sim 100 M_{\odot}$). For GRB-SNe, we have presented an idea that a variety in the jet-induced mechanism (i.e., the duration for which the engine works) could account for the observed diversity in their luminosities.

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