Hypermovies and their Nucleosynthesis

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Abstract.

We review the characteristics of nucleosynthesis in ‘Hypernovae’, i.e., core-collapse supernovae with very large explosion energies ($\gtrsim 10^{52}$ ergs). The hypernova yields show the following characteristics: 1) The mass ratio between the complete and incomplete Si burning regions is larger in hypernovae than normal supernovae. As a result, higher energy explosions tend to produce larger $([\text{Zn}, \text{Co}, \text{V}]/\text{Fe})$ and smaller $([\text{Mn}, \text{Cr}]/\text{Fe})$, which could explain the trend observed in very metal-poor stars. 2) Because of enhanced $\alpha$-rich freezeout, $^{44}$Ca, $^{48}$Ti, and $^{64}$Zn are produced more abundantly than in normal supernovae. The large $([\text{Ti}, \text{Zn}]/\text{Fe})$ ratios observed in very metal poor stars strongly suggest a significant contribution of hypernovae. 3) Oxygen burning takes place in more extended regions in hypernovae to synthesize a larger amount of Si, S, Ar, and Ca ("Si"), which makes the "Si"/O ratio larger. The abundance pattern of the starburst galaxy M82 may be attributed to hypernova explosions. We thus suggest that hypernovae make important contribution to the early Galactic (and cosmic) chemical evolution.

1. Introduction

One of the most interesting recent developments in the study of supernovae (SNe) is the discovery of some very energetic Supernovae (SNe), whose kinetic energy (KE) exceeds $10^{52}$ erg, about 10 times the KE of normal core-collapse SNe (hereafter $E_{51} = E/10^{51}$ erg). Type Ic supernova (SN Ic) 1998bw was probably linked to GRB 980425 (Galama et al. 1998), thus establishing for the first time a connection between gamma-ray bursts (GRBs) and the well-studied phenomenon of core-collapse SNe. However, SN 1998bw was exceptional for a SN Ic: it was as luminous at peak as a SN Ia, indicating that it synthesized $\sim 0.5 M_\odot$ of $^{56}$Ni, and its KE was estimated at $E \sim 3 \times 10^{52}$ erg (Iwamoto et al. 1998; Woosley et al. 1999). Because of its large KE, SN 1998bw was called a “Hypernova (HN)”.

Subsequently, other “hypernovae” of Type Ic have been discovered or recognized, such as SN 1997ef (Iwamoto et al. 2000; Mazzali, Iwamoto, & Nomoto 2000), SN 1997dq (Matheson et al. 2001), SN 1999as (Knop et al. 1999; Hatano et al. 2001), and SN 2002ap (Mazzali et al. 2002). Another possible hypernovae,
although of Type IIIn, were SNe 1997cy (Germany et al. 2000; Turatto et al. 2000) and 1999E (Rigon et al. 2002). Figure 1 shows the near-maximum spectra and the absolute $V$-light curves of Type Ic hypernovae. These hypernovae span a wide range of properties, although they all appear to be highly energetic compared to normal core-collapse SNe. SN 1999as is the most luminous supernova ever discovered, reaching a peak magnitude $M_V < -21.5$, while the brightness of SN 2002ap appears to be similar to that of normal core collapse SNe.

In the following sections, we summarize the properties of these hypernovae as derived from optical light curves and spectra. We then show that nucleosynthesis in hypernovae is quite distinct from the case of ordinary supernovae, thus making a unique contribution to galactic chemical evolution.

2. Hypernova Branch and Faint Supernova Branch

Figure 2 shows $E$ and the mass of $^{56}$Ni ejected $M(^{56}$Ni) as a function of the main-sequence mass $M_{\text{ms}}$ of the progenitor star obtained from fitting the optical light curves and spectra. The estimated masses are $M_{\text{ms}} \gtrsim 60 ~ M_\odot$ for SN1999as, $\sim 40 ~ M_\odot$ for SN1998bw, $\sim 35 ~ M_\odot$ for SN1997ef, and $\sim 20 - 25 ~ M_\odot$ for SN2002ap. These mass estimates place hypernovae at the high-mass end of SN progenitors, as they are consistently larger than the mass of the progenitors of normal core-collapse SNe ($\sim 10 - 20 ~ M_\odot$). Our analysis of these objects suggests that the KE may be related to $M_{\text{ms}}$. $M(^{56}$Ni) also appears to increase with increasing $M_{\text{ms}}$, which is important to know for the study of the chemical evolution of galaxies.

In contrast, SNe II 1997D and 1999br were very faint SNe with very low KE (Turatto et al. 1998; Hamuy 2002; Zampieri et al. 2002). In Figure 2,
Figure 2. The explosion energy and the ejected $^{56}$Ni mass as a function of the main sequence mass of the progenitors for several supernovae/hypernovae.

therefore, we propose that SNe from stars with $M_{\text{ms}} \gtrsim 20-25 \, M_\odot$ have different $E$ and $M(^{56}\text{Ni})$ with a bright, energetic “hypernova branch” at one extreme and a faint, low-energy SN branch at the other. For the faint SNe, the explosion energy was so small that most $^{56}$Ni fell back onto the compact remnant. Thus the faint SN branch may become a “failed” SN branch at larger $M_{\text{ms}}$. Between the two branches, there may be a variety of SNe (Hamuy 2002).

This trend might be interpreted as follows. Stars with $M_{\text{ms}} \lesssim 20-25 \, M_\odot$ form a neutron star, producing $\sim 0.08 \pm 0.03 \, M_\odot$ $^{56}$Ni as in SNe 1993J, 1994I, and 1987A (SN 1987A may be a borderline case between the neutron star and black hole formation). Stars with $M_{\text{ms}} \gtrsim 20-25 \, M_\odot$ form a black hole; whether they become hypernovae or faint SNe may depend on the angular momentum in the collapsing core, which in turn depends on the stellar winds, metallicity, magnetic fields, and binarity. Hypernovae might have rapidly rotating cores owing possibly to the spiraling-in of a companion star in a binary system.
3. Aspherical Hypernova Models

Although all modeling presented above was performed assuming spherical symmetry, the data show evidence for significant deviations from sphericity. In particular, some polarization was detected in both SNe 1998bw (Iwamoto et al. 1998; Patat et al. 2001) and 2002ap (Kawabata et al. 2002; Leonard et al. 2002; Wang et al. 2002). Furthermore, in the case of SN 1998bw, the late time spectra showed peculiar nebular line profiles, where the OI $\lambda$ 6300Å line is significantly narrower than the FeII blend near 5200Å (Patat et al. 2001).

In spherically symmetric models this is not expected, as O should always be located above Fe in velocity space. Moreover, the OI line declines more slowly than the FeII ones, possibly signalling deposition of $\gamma$-rays in a slowly-moving, O-dominated region (Mazzali et al. 2001). Another peculiarity is observed in SN 1997ef, where the photosphere persists to advanced epochs, showing line absorption at velocities of $\sim$ 2000 km s$^{-1}$, which is well below the expected position of the mass-cut in spherically symmetric models (Mazzali et al. 2000). Finally, all three hypernovae show a late decline of the light curve at epochs of a few months.

Maeda et al. (2002) calculated the nucleosynthesis in aspherical explosions. In such a model, $^{56}$Ni is synthesized preferentially along the polar axis, where the KE is larger, while a lot of unburned material, dominated by O, is left at low velocity in the equatorial region, where burning is much less efficient. A model where the ratio of the polar-to-equatorial kinetic energy is about 8 yields an asymmetric explosion whose properties at late times are consistent with the observed lines of SN 1998bw if it is viewed at an angle of about 15 degrees from the polar axis. At such an angle one might expect that the GRB is weaker than it would be if observed along the jet axis. The actual aspect ratio of the ejecta is much smaller than 8:1, however, as the jet expands laterally, and this may be consistent with the observed polarization.

The asymmetric model has a smaller total kinetic energy than the corresponding symmetric model, as the KE away from the line of sight is significantly reduced. The estimate, however, is still large, $E_{51} \sim 10$. The estimate of $M(^{56}\text{Ni}) \sim 0.6M_\odot$ from the nebula spectra does not much depend on the asphericity either.

4. Nucleosynthesis in Hypernova Explosions

In core-collapse supernovae/hypernovae, stellar material undergoes shock heating and subsequent explosive nucleosynthesis. Iron-peak elements are produced in two distinct regions, which are characterized by the peak temperature, $T_{\text{peak}}$, of the shocked material. For $T_{\text{peak}} > 5 \times 10^9\text{K}$, material undergoes complete Si burning whose products include Co, Zn, V, and some Cr after radioactive decays. For $4 \times 10^9\text{K} < T_{\text{peak}} < 5 \times 10^9\text{K}$, incomplete Si burning takes place and its after decay products include Cr and Mn (e.g., Hashimoto, Nomoto, & Shigeyama 1989; Thielemann, Nomoto, & Hashimoto 1996).

The right panel of Figure 3 shows the composition in the ejecta of a 25 $M_\odot$ HN model ($E_{51} = 10$). The nucleosynthesis in a normal 25 $M_\odot$ SN model ($E_{51} = 1$) is also shown for comparison in the left panel of Figure 3.
We note the following characteristics of nucleosynthesis with very large explosion energies (Nomoto et al. 2001a,b):

1. Both complete and incomplete Si-burning regions shift outward in mass compared with normal supernovae, so that the mass ratio between the complete and incomplete Si-burning regions becomes larger. As a result, higher energy explosions tend to produce larger \([\text{Zn, Co, V}]/\text{Fe}\) and smaller \([\text{Mn, Cr}]/\text{Fe}\). The elements synthesized in this region such as \(^{56}\text{Ni}, \^{59}\text{Cu}, \^{63}\text{Zn},\) and \(^{64}\text{Ge}\) (which decay into \(^{56}\text{Fe}, \^{59}\text{Co}, \^{63}\text{Cu},\) and \(^{64}\text{Zn},\) respectively) are ejected more abundantly than in normal supernovae.

2. In the complete Si-burning region of hypernovae, elements produced by \(\alpha\)-rich freezeout are enhanced because nucleosynthesis proceeds at lower densities (i.e., higher entropy) and thus a larger amount of \(^4\text{He}\) is left. Hence, elements synthesized through capturing of \(\alpha\)-particles, such as \(^{44}\text{Ti}, \^{48}\text{Cr},\) and \(^{64}\text{Ge}\) (decaying into \(^{44}\text{Ca}, \^{48}\text{Ti},\) and \(^{64}\text{Zn},\) respectively) are more abundant.

3. Oxygen burning takes place in more extended regions for the larger KE. Then more O, C, Al are burned to produce a larger amount of burning products such as Si, S, and Ar. Therefore, hypernova nucleosynthesis is characterized by large abundance ratios of \([\text{Si/O}], [\text{S/O}], [\text{Ti/O}],\) and \([\text{Ca/O}],\)

5. Hypernovae and Galactic Chemical Evolution

Hypernova nucleosynthesis may have made an important contribution to Galactic chemical evolution. In the early galactic epoch when the galaxy was not yet chemically well-mixed, \([\text{Fe/H}],\) may well be determined by mostly a single SN event (Audouze & Silk 1995). The formation of metal-poor stars is supposed to be driven by a supernova shock, so that \([\text{Fe/H}],\) is determined by the ejected Fe mass and the amount of circumstellar hydrogen swept-up by the shock wave.
Nomoto et al. (Ryan et al. 1996). Then, hypernovae with larger $E$ are likely to induce the formation of stars with smaller [Fe/H], because the mass of interstellar hydrogen swept up by a hypernova is roughly proportional to $E$ (Ryan et al. 1996; Shigeyama & Tsujimoto 1998) and the ratio of the ejected iron mass to $E$ is smaller for hypernovae than for normal supernovae.

5.1. Zn, Co, Mn, Cr

The observed abundances of metal-poor halo stars show quite interesting patterns. There are significant differences between the abundance patterns in the iron-peak elements below and above $[\text{Fe/H}] \sim -2.5 - -3$.

(1) For $[\text{Fe/H}] \leq -2.5$, the mean values of $[\text{Cr/Fe}]$ and $[\text{Mn/Fe}]$ decrease toward smaller metallicity, while $[\text{Co/Fe}]$ increases (Fig. 4; McWilliam et al. 1995; Ryan et al. 1996).

(2) $[\text{Zn/Fe}] \sim 0$ for $[\text{Fe/H}] \approx -3$ to 0 (Sneden et al. 1991), while at $[\text{Fe/H}] < -3.3$, $[\text{Zn/Fe}]$ increases toward smaller metallicity (Fig. 4; Primas et al. 2000; Blake et al. 2001).

These trends cannot be explained with the conventional chemical evolution model that uses previous nucleosynthesis yields.

The larger $[(\text{Zn, Co})/\text{Fe}]$ and smaller $[(\text{Mn, Cr})/\text{Fe}]$ in the supernova ejecta can be realized if the mass ratio between the complete Si burning region and the incomplete Si burning region is larger, or equivalently if deep material from the complete Si-burning region is ejected by mixing or aspherical effects. This can be realized if (1) the mass cut between the ejecta and the compact remnant is located at smaller $M_r$ (Nakamura et al. 1999), (2) $E$ is larger to move the outer edge of the complete Si burning region to larger $M_r$ (Nakamura et al. 2001), or (3) asphericity in the explosion is larger.

Among these possibilities, a large explosion energy $E$ enhances $\alpha$-rich freeze-out, which results in an increase of the local mass fractions of Zn and Co, while Cr and Mn are not enhanced (Umeda & Nomoto 2002a,b). Models with $E_{51} = 1$ do not produce sufficiently large $[\text{Zn/Fe}]$. To be compatible with the observations of $[\text{Zn/Fe}] \sim 0.5$, the explosion energy must be much larger, i.e., $E_{51} > 20$ for $M \gtrsim 20M_\odot$, i.e., hypernova-like explosions of massive stars ($M \gtrsim 25M_\odot$) with $E_{51} > 10$ are responsible for the production of Zn.

In the hypernova models, the overproduction of Ni, as found in the simple “deep” mass-cut model, can be avoided. Therefore, if hypernovae made significant contributions to the early Galactic chemical evolution, it could explain the large Zn and Co abundances and the small Mn and Cr abundances observed in very metal-poor stars as seen in Figure 4.

5.2. Fe, Ti

The Fe mass observed in hypernovae show a trend with the progenitor mass, ranging from $\sim 5 M_\odot$ in SN 1999as to 0.07 $M_\odot$ in SN 2002ap. Thus $[\text{O/Fe}]$ in the ejecta of most hypernovae may be larger than the solar ratio (see Umeda & Nomoto 2002a). The small $[\text{O/Fe}]$ observed in some metal-poor stars and galaxies might be the results of SNe from 13 - 15 $M_\odot$ stars (Nomoto et al. 1997) or possibly very massive hypernovae rather than Type Ia supernovae. In contrast, $[\text{O/Fe}]$ must be very large in the faint SN branch. Therefore, the
scatter of [O/Fe] in metal-poor stars might provide constraints on the fraction of these branches (e.g., Argast et al. 2002).

It has been pointed out that Ti is deficient in Galactic chemical evolution models using supernova yields currently available (e.g., Timmes et al. 1996; Thielemann et al. 1996), especially at [Fe/H] \( \lesssim -1 \) when SNe Ia have not contributed to the chemical evolution. However, if the contribution from hypernovae to Galactic chemical evolution is relatively large (or supernovae are more energetic than the typical value of \( E_{51} = 1 \)), this problem could be relaxed. The \( \alpha \)-rich freezeout is enhanced in hypernovae, so that \( ^{48}\text{Ti} \) could be ejected more abundantly.

6. Starburst Galaxy M82 and Hypernovae

X-ray emissions from the starburst galaxy M82 were observed with ASCA and the abundances of several heavy elements were obtained (Tsuru et al. 1997). Tsuru et al. (1997) found that the overall metallicity of M82 is quite low, i.e., O/H and Fe/H are only 0.06 - 0.05 times solar, while Si/H and S/H are \( \sim 0.40 \) - 0.47 times solar. This implies that the abundance ratios are peculiar, i.e., the ratio O/Fe is about solar, while the ratios of Si and S relative to O and Fe are as high as \( \sim 6 - 8 \). These ratios are very different from those ratios in SNe II. Compared with normal SNe II, the important characteristic of hypernova nucleosynthesis is the large Si/O, S/O, and Fe/O ratios. The good agreement between the hypernova model (\( E_{51} = 30 \)) and the observed abundances in M82 is seen in Umeda et al. (2002).

Hypernovae could also produce larger \( E \) per oxygen mass than normal SNe II, as required for M82. We therefore suggest that hypernova explosions may make important contributions to the metal enrichment and energy input to
the interstellar matter in M82. The age of starburst activity is estimated to be \( t \sim 10^7 \) years (Strickland 2002), which is so young that only massive stars \((M > 25 M_\odot)\) contributed to nucleosynthesis in M82.

7. Concluding Remarks

We have shown that signatures of hypernova nucleosynthesis are seen in the abundance patterns in very metal poor stars and the starburst galaxy M82. (See also the abundance pattern in X-ray Nova Sco; Israelian et al. 1999; Podsiadlowski et al. 2002). We suggest that hypernovae of massive stars may make important contributions to the Galactic (and cosmic) chemical evolution, especially in the early low metallicity phase. The IMF of Pop III stars might be different from that of Pop I and II stars, and that more massive stars are abundant for Pop III.

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