Hyernova Nucleosynthesis and Early Chemical Evolution

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

1. Introduction

Massive stars in the range of 8 to \( \sim 100M_\odot \) undergo core-collapse at the end of their evolution and become Type II and Ib/c supernovae (SNe II and SNe Ib/c). Until recently, we have considered supernovae with the explosion energies of \( E = 1 - 1.5 \times 10^{51} \) ergs. These energies have been best estimated from SNe 1987A, 1993J, and 1994I, whose progenitors’ masses have been estimated to be 13 - 20 \( M_\odot \) (e.g., Nomoto et al. 1993, 1994; Blinnikov et al. 2000).

Recently, SN Ic 1998bw, which was associated with GRB980425 (Iwamoto et al. 1998; Woosley et al. 1999), and SN Ic 1997ef (Iwamoto et al. 2000; Mazzali et al. 2000) have been found to have such a large kinetic explosion energy as \( E \gtrsim 10^{52} \) erg. This is more than one order of magnitude larger than typical SNe, so that these objects may be called “Hypernovae”. These SNe produced more
$^{56}\text{Ni}$ than the average core collapse SN. Their progenitors’ masses are estimated to be $M \gtrsim 25 M_\odot$. These massive stars are likely to form black holes, while less massive stars form neutron stars (see, however, Wheeler et al. 2000).

We investigate the characteristics of nucleosynthesis in such energetic core-collapse hypernovae, the systematic study of which has not yet been done. We examine both spherical and aspherical explosion models and discuss their contributions to the Galactic chemical evolution.

2. Nucleosynthesis in Hypernova Explosions

2.1. Silicon and Oxygen Burning

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 et al. 1989; Woosley, & Weaver 1995; Thielemann et al. 1996).

We note the following characteristics of nucleosynthesis with very large explosion energies (Nomoto et al. 2001):

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 $[(\text{Zn, Co})/\text{Fe}]$, smaller $[(\text{Mn, Cr})/\text{Fe}]$, and larger $[\text{Fe}/\text{O}]$. The elements synthesized in this region such as $^{56}\text{Ni}$, $^{59}\text{Cu}$, $^{63}\text{Zn}$, and $^{64}\text{Ge}$ (which decay into $^{56}\text{Co}$, $^{59}\text{Co}$, $^{63}\text{Cu}$, 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, lower density regions for the larger explosion energy. Therefore, 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 $[\text{Si}/\text{O}]$, $[\text{S}/\text{O}]$, $[\text{Ti}/\text{O}]$, and $[\text{Ca}/\text{O}]$.

2.2. Aspherical Explosions

Nakamura et al. (2001a) and Mazzali et al. (2001) have identified some signatures of asymmetric explosion in the late light curve and spectra of SN 1998bw. Maeda et al. (2002) have examined the effect of aspherical (jet-like) explosions on nucleosynthesis in hypernovae. The progenitor model is the $16 M_\odot$ He core of the $40 M_\odot$ star and the explosion energy is $E = 1 \times 10^{52} \text{ergs}$.

Figure 1 shows the isotopic composition of the ejecta of asymmetric explosion model in the direction of the jet (upper panel) and perpendicular to it (lower
Figure 1. The isotopic composition of the ejecta in the direction of the jet (upper panel) and perpendicular to it (lower panel). The ordinate indicates the initial spherical Lagrangian coordinate ($M_r$) of the test particles (lower scale), and the final expansion velocities ($V$) of those particles (upper scale) (Maeda et al. 2002).
Figure 2. Left: The distribution of $^{56}\text{Ni}$ (open circles) and $^{16}\text{O}$ (dots). The open circles and the dots denote test particles in which the mass fraction of $^{56}\text{Ni}$ and $^{16}\text{O}$, respectively, exceeds 0.1. The lines are density contours at the level of 0.5 (solid), 0.3 (dashed), 0.1 (dash-dotted), and 0.01 (dotted) of the max density, respectively (Maeda et al. 2002). Right: The profiles of the Fe-blend (left panels) and of $\text{O I}$ 6300, 6363 Å (right panels) viewed at 15° from the jet direction (Maeda et al. 2002). The top panels show the profiles of the spherically symmetric model. The observed lines at a SN rest-frame epoch of 139 days are also plotted for comparison (dotted lines, Patat et al. 2001).

panel). Figure 2 shows the 2D distribution of $^{56}\text{Ni}$ and $^{16}\text{O}$ in the homologous expansion phase.

In the $z$-direction, where the ejecta carry more kinetic energy, the shock is stronger and post-shock temperatures are higher. Therefore, larger amounts of $\alpha$-rich freeze-out elements, such as $^4\text{He}$, $^{44}\text{Ti}$, and $^{56}\text{Ni}$ are produced in the $z$-direction than in the $r$-direction.

On the other hand, along the $r$-direction $^{56}\text{Ni}$ is produced only in the deepest layers, and the elements ejected in this direction are mostly the products of hydrostatic nuclear burning stages (O) with some explosive oxygen-burning products (Si, S, etc).

In the spherical case, Zn is produced only in the deepest layer, while in the aspherical model, the complete silicon burning region is elongated to the $z$ (jet) direction, so that $[\text{Zn/Fe}]$ is enhanced irrespective of the mass cut. On the other hand, $^{55}\text{Mn}$, which is produced by incomplete silicon burning, surrounds $^{56}\text{Fe}$ and located preferentially in the $r$-direction.

In this way, larger asphericity in the explosion leads to larger $[\text{Zn/Fe}]$ and $[\text{Co/Fe}]$, but to smaller $[\text{Mn/Fe}]$ and $[\text{Cr/Fe}]$. Then, if the degree of the asphericity tends to be larger for lower $[\text{Fe/H}]$, the trends of $[\text{Zn, Co, Mn, Cr/Fe}]$ follow the ones observed in metal-poor stars, as discussed later.

2.3. Nebula Spectra of SN 1998bw

In order to verify the observable consequences of an axisymmetric explosion, Maeda et al. (2002) calculated the profiles of the Fe-dominated blend near
5200Å, and of O I] 6300, 6363Å. These are the lines that deviate most from the expectations from a spherically symmetric explosion (Mazzali et al. 2001).

The iron and oxygen profiles viewed at an angle of 15° from the jet direction are found to be most consistent with the observed spectrum on day 139 in Figure 2. When the degree of asphericity is high and the viewing angle is close to the jet direction, the component iron lines in the blend have double-peaked profiles, the blue- and red-shifted peaks corresponding to Fe-dominated matter moving towards and away from us, respectively. Because of the high velocity of Fe, the peaks are widely separated, making the blend wide. This is the case for the synthetic Fe-blend shown in Figure 2. In contrast, the oxygen line is narrower and has a sharper peak, because O is produced mostly in the r-direction, at lower velocities and with a less aspherical distribution.

3. Signatures of Hypernova Nucleosynthesis in Chemical Evolution

The abundance pattern of metal-poor stars with [Fe/H] < −2 provides us with very important information on the formation, evolution, and explosions of massive stars in the early evolution of the galaxy.

In the early galactic epoch when the galaxy is not yet chemically well-mixed, [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 [Fe/H] is determined by the ejected Fe mass and the amount of circumstellar hydrogen swept-up by the shock wave (Ryan, Norris, & Beers 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 canonical supernovae.

3.1. Zn, Co, Mn, Cr

The observed abundances of metal-poor halo stars show quite interesting pattern. There are significant differences between the abundance patterns in the iron-peak elements below and above [Fe/H] ~ −2.5 - −3.

1) For [Fe/H] < −2.5, the mean values of [Cr/Fe] and [Mn/Fe] decrease toward smaller metallicity, while [Co/Fe] increases (McWilliam et al. 1995; Ryan et al. 1996).

2) [Zn/Fe] ~ 0 for [Fe/H] < −3 to 0 (Sneden, Gratton, & Crocker 1991), while at [Fe/H] < −3.3, [Zn/Fe] increases toward smaller metallicity (Figure 3; 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 [(Zn, Co)/Fe] and smaller [(Mn, Cr)/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 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 collapsed star 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. 2001b), or (3) asphericity in the explosion is larger.

Also a large explosion energy $E$ results in the enhancement of the local mass fractions of Zn and Co, while Cr and Mn are not enhanced (Umeda & Nomoto 2001). 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.

The dependence of [Zn/Fe] on $M$ and $E$ is summarized in Figure 3. Models with $E_{51} = E/10^{51}\text{ergs}$ do not produce sufficiently large [Zn/Fe]. To be compatible with the observations of [Zn/Fe] $\sim 0.5$, the explosion energy must be much larger, i.e., $E_{51} \gtrsim 20$ 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.

3.2. Ni

The observed trend of another iron-peak element, Ni, is also interesting. Unlike the elements we have focused on, [Ni/Fe] of metal-poor stars shows no clear trend (see e.g., Ryan et al. 1996; Nakamura et al. 1999). Theoretically, this is understood as the fact that Ni is produced abundantly by both complete and incomplete Si-burning. Recently, Ellison et al. (2001) observed DLA abundance and found [Co/Fe] > 0, which is similar to the metal-poor halo stars. They, on the other hand, did not find oversolar [Ni/Fe]. Similar results have also been found by Norris et al. (2001), who observed abundances of five halo stars with
[Fe/H] \lesssim -3.5. They discussed that the results are inconsistent with the predictions of Nakamura et al. (1999), where the enhancement of [Co/Fe] appears to be accompanied by the enhancement of [Ni/Fe].

We note that the increase in [Ni/Fe] along with the increase in [Co/Fe] is not significant in the hypernova models by Umeda & Nomoto (2001); for example, Co/Fe in the hypernova is larger by a factor of 17 than a normal SN II, while Ni is larger only by a factor of 1.8.

The apparent difference from the results in Nakamura et al. (1999) can be understood as follows. In Nakamura et al. (1999), the explosion energy was fixed to be $E_{51} = 1$. They obtained the larger Co/Fe ratio for more massive SNe II by assuming “deeper” mass-cuts so that $Y_e$ in the explosive burning region is smaller ($Y_e \simeq 0.495$). For smaller $Y_e$, the Co abundance is larger, but the abundance of Ni (especially $^{58}$Ni) is enhanced by a larger factor than Co. Therefore, the increase in [Ni/Fe] with [Co/Fe] was unavoidable, unless neutrinos substantially enhance $Y_e$ in the deep complete Si burning region.

In Umeda & Nomoto models, mass-cuts of the larger Co (and Zn) models are not deeper in $M_r$, and $Y_e$ in the complete Si burning region is not small. This is because they assume larger explosion energies for more massive stars, which shifts the mass-cut outwards in $M_r$. As a result, the dominant Ni isotope is $^{60}$Ni. In our model, with increasing $E$, the abundances of Co and Zn increase more than $^{60}$Ni. Therefore, Co and Zn abundances can be enhanced without appreciable increase in the Ni abundance. In this sense, the abundance trends of very metal-poor stars is better explained with hypernova models rather than the simple “deep” mass-cut models (Nakamura et al. 1999).

### 3.3. Pair Instability Supernovae

One may wonder whether the abundance anomaly of iron-peak elements may be related to the peculiar IMF of Pop III stars. It is quite likely that the IMF of Pop III stars is different from that of Pop I and II stars, and that more massive stars are abundant for Pop III. Nakamura & Umemura (1999) discussed that the IMF of Pop III and very low metal stars may have a peak at even larger masses, around $\sim (1\text{-} few) \times 100 M_\odot$. If $M \lesssim 130 M_\odot$, then these stars are likely to form black holes either without explosion or with energetic explosions. The nucleosynthesis of the latter case may not be so different from the models considered here. This might favor the scenario that invokes the hypernova-like explosions for large [Zn/Fe].

If stars are even more massive than $\sim 150 M_\odot$, these stars become pair-instability SNe (PISNe) and their nucleosynthesis is different from core-collapse SNe. In particular, PISNe produce $[Zn/Fe] < -1.5$, because in PISNe, iron peak elements are mostly produced by incomplete Si burning so that the mass fraction of complete Si burning elements is much smaller than SNe II (Umeda & Nomoto 2001). We thus conclude that PISNe are unlikely to produce a large enough Zn/Fe ratio to explain the observations.

### 4. 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. Figure 4 shows the good agreement between the hypernova model \((E_{51}=30)\) and the observed abundances in M82.

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 \(< 10^7\) years (Stickland 2001), which is so young that only massive stars \((M > 25 M_\odot)\) contributed to nucleosynthesis in M82.

5. Hypernovae vs. Type Ia Supernovae

The large [Fe/O] observed in some metal-poor stars and galaxies might possibly be the indication of Hypernovae rather than Type Ia supernovae (SNe Ia).

To distinguish between Hypernova (Nakamura et al. 2001b; Umeda & Nomoto) and SN Ia (Iwamoto et al. 1999; Nomoto et al. 1997b) nucleosynthesis, following abundance ratios are useful:
[Ti/Fe] $\sim$ 0.3 - 0.5 in Hypernovae; < 0 in SNe Ia.
[Mn/Fe] < 0 in Hypernovae; > 0 in SNe Ia.
[Ni/Fe] $\sim$ 0 - 0.3 in Hypernovae; $\sim$ 0 - 0.5 in SNe Ia.
[Zn/Fe] $\sim$ 0.3 - 0.5 in Hypernovae; < 0 in SNe Ia.

To reproduce the solar abundance ratios with the combination of SN II and SN I products, there exist certain constraints on the model abundances of SNe Ia. For example, [Si/Fe] $\sim$ 0.3 in SNe II (Nomoto et al. 1997a) so that [Si/Fe] $< -0.2$ in SNe Ia (Iwamoto et al. 1999). For a system with a non-solar abundance pattern, this constraint would be weaker.

6. Concluding Remarks

We have shown that signatures of hypernova nucleosynthesis are seen in the large [(Ti, Zn)/Fe] ratios in very metal poor stars and the large Si/O and Fe/O ratios in the starburst galaxy M82. (See also the abundance pattern in X-ray Nova Sco;Israeli et al. 1999; Podsiałdowski et al. 2001). These properties of hypernova nucleosynthesis suggest that hypernovae of massive stars may make important contributions to the Galactic (and cosmic) chemical evolution, especially in the early low metallicity phase. This may be consistent with the suggestion that the IMF of Pop III stars is different from that of Pop I and II stars, and that more massive stars are abundant for Pop III.

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References

Audouze, J., & Silk, J. 1995, ApJ, 451, L49
Blake, L.A.J., Ryan, S.G., Norris, J.E., & Beers, T.C. 2001, Nucl.Phys.A.
Blinnikov, S., Lundqvist, P, Bartunov, O., Nomoto, K., & Iwamoto, K. 2000, ApJ, 532, 1132
Ellison, S. L., Ryan, S. G., & Prochaska, J. X. 2001, MNRAS, in press (astro-ph/0104466)
Hashimoto, M., Nomoto, K., & Shigeyama, T. 1989, A&A, 210, L5
Israeli, G., Rebolo, R., Basri, G., Casas, J., & Martin, E.L., 1999, Nat, 401, 142
Iwamoto, K., Mazzali, P.A., Nomoto, K., et al. 1998, Nature, 395, 672
Iwamoto, K., Brachwitz, F., Nomoto, K., et al. 1999, ApJS, 125, 439
Iwamoto, K., Nakamura, T., Nomoto, K., et al. 2000, ApJ, 534, 660
Maeda, K., Nakamura, T., Nomoto, K., Mazzali, P.A., & Hachisu, I. 2002, ApJ, 565, in press (astro-ph/0011003)
Maeda, K. 2001, Master Thesis, University of Tokyo
Mazzali, P.A., Iwamoto, K., & Nomoto, K. 2000, ApJ, 545, 407
Mazzali, P.A., Nomoto, K., Patat, F., & Maeda, K. 2001, ApJ, 559, in press (astro-ph/0106095)
McWilliam, A., Preston, G.W., Sneden, C., & Searle, L. 1995, AJ, 109, 2757
Nakamura, F., & Unemura, M. 1999, ApJ, 515, 239
Nakamura, T., Umeda, H., Nomoto, K., Thielemann, F.-K., & Burrows, A. 1999, ApJ, 517, 193
Nakamura, T., Mazzali, P. A., Nomoto, K., & Iwamoto, K. 2001a, ApJ, 550, 991
Nakamura, T., Umeda, H., Iwamoto, K., Nomoto, K., Hashimoto, M., Hix, R.W., Thielemann, F.-K. 2001b, ApJ, 555, 880
Nomoto, K., Suzuki, T., Shigeyama, T., Kumagai, S., Yamaoka, H., Saio, H. 1993, Nature, 364, 507
Nomoto, K., Yamaoka, H., Pols, O. R., van den Heuvel, E. P. J., Iwamoto, K., Kumagai, S., & Shigeyama, T. 1994, Nature, 371, 227
Nomoto, K., et al. 1997, Nucl. Phys. A616, 79c
Nomoto, K., et al. 1997b, Nucl. Phys. A621, 467c
Nomoto, K., et al. 2001a, in Supernovae and Gamma Ray Bursts, eds. M. Livio, et al. (Cambridge Univ. Press) 144 (astro-ph/0003077)
Nomoto, K., Maeda, K., Umada, H., & Nakamura, T. 2001b, in The Influence of Binaries on Stellar Populations Studies, ed. D. Vanbeveren (Kluwer) 507 (astro-ph/0105127)
Norris, J.E., Ryan S.G., & Beers, T.C. 2001, ApJ, in press (astro-ph/0107304)
Patat, F., et al. 2001, ApJ, 555, 900
Podsiadlowski, Ph., Nomoto, K., Maeda, K., Nakamura, T., Mazzali, P.A., & Schmidt, B. 2001, ApJ, submitted (astro-ph/0109244)
Primas, F., Reimers, D., Wisotzki, L., Reetz, J., Gehren, T., & Beers, T.C. 2000, in The First Stars, ed. A. Weiss, et al. (Springer), 51
Ryan, S.G., Norris, J.E. & Beers, T.C. 1996, ApJ, 471, 254
Shigeyama. T., & Tsujimoto, T. 1998, ApJ, 507, L135
Sneden, C., Gratton, R.G., & Crocker, D.A. 1991, A&A, 246, 354
Stickland, D. 2001, this volume
Thielemann, F.-K., Nomoto, K., & Hashimoto, M. 1996, ApJ, 460, 408
Tsuru, T. G., Awaki, H., Koyama K., Ptak, A. 1997, PASJ, 49, 619
Umeda, H., & Nomoto, K. 2001, ApJ, 563, in press (astro-ph/0103241)
Wheeler, J. C., Yi, I., Höflich, P. A., & Wang, L. 2000, ApJ, 537, 810
Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181
Woosley, S.E., Eastman, R.G., & Schmidt, B.P. 1999, ApJ, 516, 788