Hypernovae

Keiichi Maeda*, Ken'ichi Nomoto† and Hideyuki Umeda†

*Department of Astronomy, School of Science, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, JAPAN
†Department of Astronomy and Research Center for the Early Universe, School of Science, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, JAPAN

Abstract. We discuss the characteristics of nucleosynthesis in 'Hypernovae', i.e., supernovae with very large explosion energies ($\gtrsim 10^{52}$ ergs). The hypernova yields are compared with observations to reveal the nature of hypernova explosions, e.g., asphericity and central remnants. We also suggest that hypernovae have made important contribution to the early Galactic (and Cosmic) chemical evolution.

INTRODUCTION

Type II and Ib/c supernovae (SNe II and SNe Ib/c) are catastrophic explosions which are induced when massive stars (8 to $\sim 100 M_\odot$) reach the core-collapse stage finally at the end of their evolution. Until recently, we have usually considered supernovae with the kinetic energies of explosions $E_{51} = 1$ (where $E_{51} = E/10^{51}$ergs). These values have been estimated from supernovae 1987A, 1993J, and 1994 I, whose progenitors' masses have been modeled to be 13 - 20 $M_\odot$.

SN1998bw called into question if the above energy estimate applies to all core-collapse supernovae. The exceptionally bright Type Ic supernova (SN Ic) SN 1998bw was discovered as the probable optical counterpart of the gamma-ray burst GRB980425. The very broad spectral features and the light curve shape in the early phase have led to the conclusion that SN1998bw was a hyper-energetic explosion (kinetic energy $E_{51} \sim 40$) of a massive C+O star (e.g., Iwamoto et al. 1998).

In this paper the term "hypernova" is used to refer to a SN explosion with $E_{51} \gtrsim 10$, regardless of the nature of the central engine. Recently, other hypernova candidates have been recognized. They include SNeIc 1997ef, 1998ey, 1999cq and 1999as, SNeIIn 1997cy and 1999E, SN II 1998A (see, e.g., Nomoto et al. 2001a).

So far, all the modelings of hypernovae (e.g,, 1998bw, 1997ef, and 1997cy) imply that their progenitors' masses are $M \geq 25 M_\odot$. Such very massive stars are likely to form black holes, while less massive stars form neutron stars.

We investigate the characteristics of nucleosynthesis in hypernovae. Asphericity in a hepernova explosion, the relationship between a hypernova and a stellar mass black hole, and their contributions to the Galactic chemical evolution are discussed.

For details, see the references in each section. More complete sets of references are found there in. Also see Nomoto et al. 2001a,b,c, which give an overview of the field.

NUCLEOSYNTHESIS IN HYPERNOVA EXPLOSIONS

We note the following characteristics of nucleosynthesis with very large explosion energies (Nakamura et al. 2001; Nomoto et al. 2001a,b,c).

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 [(Zn, Co)/Fe], smaller [(Mn, Cr)/Fe], and larger [Fe/O]. The elements synthesized in this region such as ^{56}Ni, ^{59}Cu, ^{63}Zn, and ^{64}Ge (which decay into ^{56}Co, ^{59}Co, ^{63}Cu, and ^{64}Zn, respectively) are ejected more abundantly than in normal supernovae.

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

ASPHERICAL EXPLOSION MODEL FOR SN1998BW

Maeda et al. (2002a) 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 $E = 1 \times 10^{52}$ 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 panel). Figure 2 shows the 2D distribution of ^{56}Ni and ^{16}O in the homologous expansion phase.

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

On the other hand, along the r-direction ^{56}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 (e.g., Si, S).

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 [Zn/Fe] is enhanced irrespective of the mass cut. On the other hand, ^{55}Mn, which is produced by incomplete silicon burning, surrounds ^{56}Fe and located preferentially in the r-direction.

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

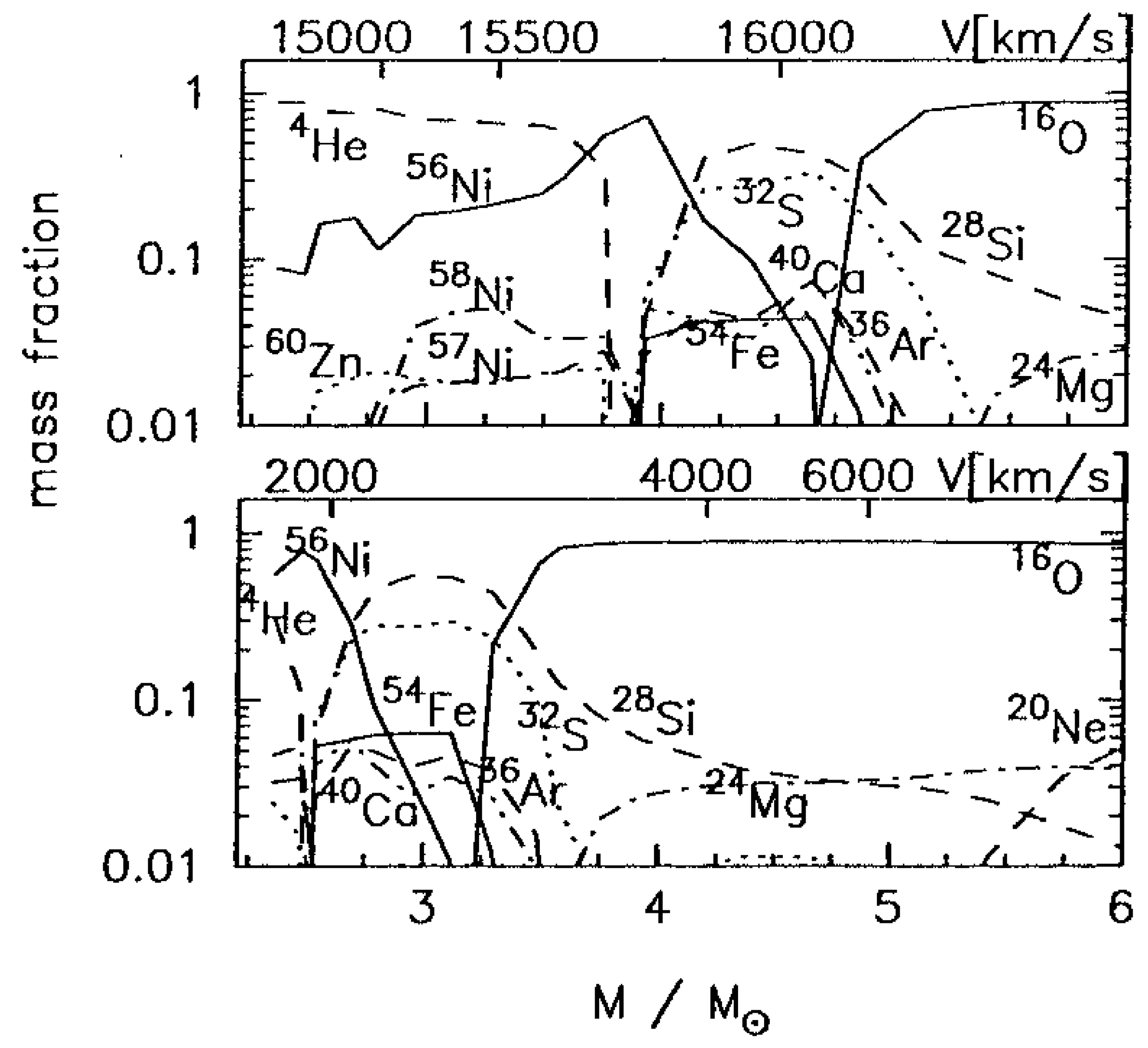

FIGURE 1. The isotopic composition of the ejecta of an aspherical explosion in the direction of the jet (z; upper panel) and perpendicular to the jet (r; lower panel). The ordinate indicates the initial spherical Lagrangian coordinate (M_r) of the test particles (lower scale), and the final expansion velocities (V) of those particles (upper scale).

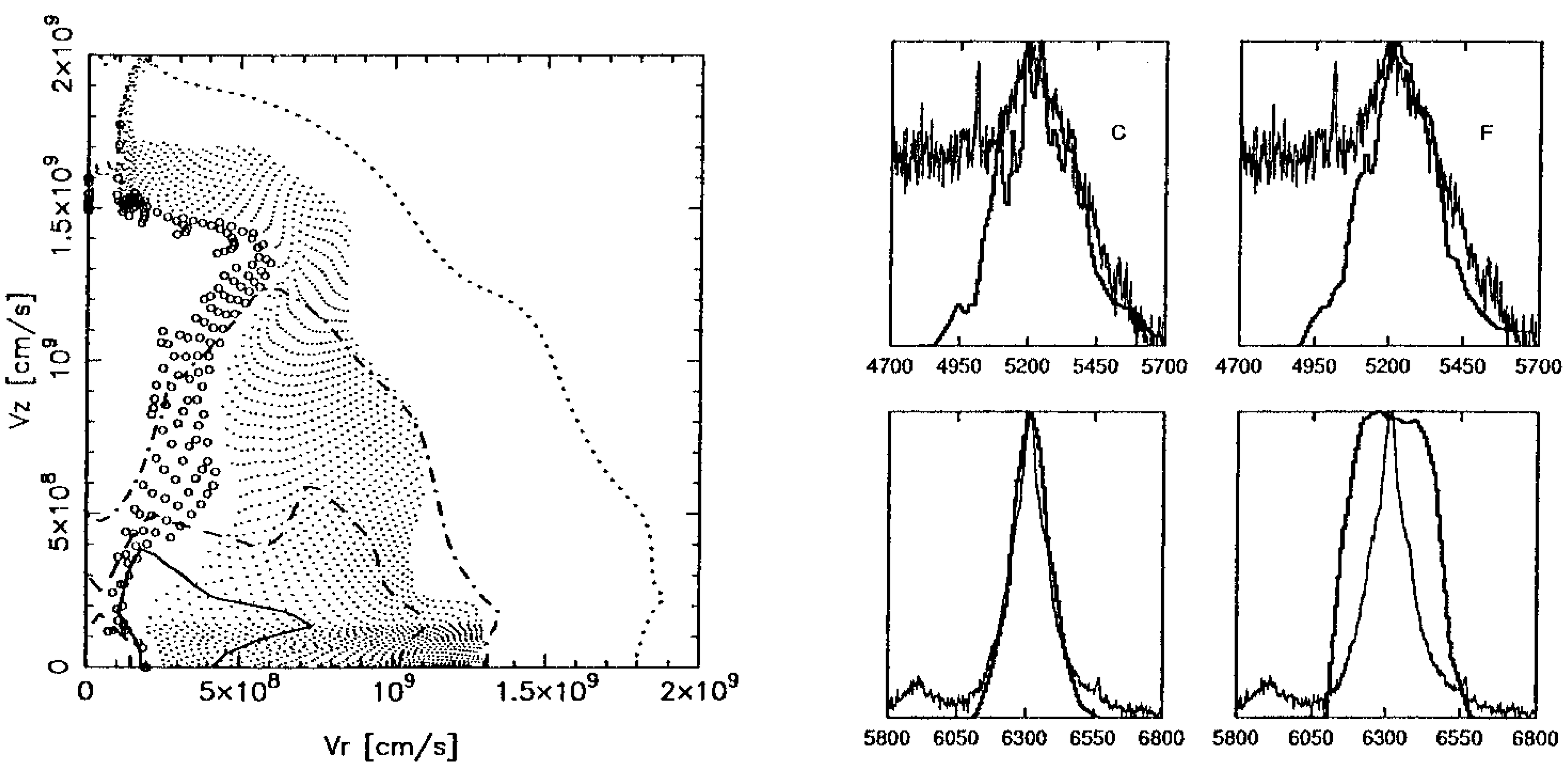

FIGURE 2. Left: The 2D distribution of ^{56}Ni (open circles) and ^{16}O (dots) in the homologous expansion phase. The lines are density contours at the level of 0.5 (solid), 0.3 (dashed), 0.1 (dash-dotted), and 0.01 (dotted) of the max density, respectively. Right: The profiles of the [Fe II] feature (upper panels) and of [O I] 6300, 6363 Å (lower panels) viewed at 15° from the jet direction (left panels; thick lines) and for a spherical model (right panels).

In order to verify the observable consequences of an axisymmetric explosion, Maeda et al. (2002a) 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 216 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.

BLACK HOLE BINARY GRO J1655-40 (X-RAY NOVA SCO)

X-ray Nova Sco (GRO J1655-40), which consists of a stellar mass black hole and a low mass companion, also exhibits what could be the nucleosynthesis signature of a hypernova explosion. The companion star is enriched with Ti, S, Si, Mg, and O but not much Fe. This is compatible with heavy element ejection from a black hole progenitor. In order to eject large amount of Ti, S, and Si and to have at least $\sim 4\ M_\odot$ below mass cut and thus form a massive black hole, the explosion would need to be highly energetic. A hypernova explosion with the mass cut at large M_r ejects a relatively small mass Fe and would be consistent with these observed abundance features.

Podsiadlowski et al. (2002) modeled the pollution of the secondary. Their model handles the binary evolution, which follows the changes in binary parameters (i.e., the primary's mass, the secondary's mass, and the orbital separation) in different evolutional stages (i.e., the pre-supernova mass lose, the supernova explosion, and the post-supernova mass transfer) as well as the pollution of the secondary by the supernova explosion using several supernova models. The progenitor models are helium stars of 6 to 16 $M_\odot$ (which correspond to main sequence stars of 20 to 40 $M_\odot$) and the explosion energies range from $E_{51} = 1$ to 30.

The main results are summarized as follows (see Podsiadlowski et al. 2002 for details),

1) Helium star models of 10 and 16 $M_\odot$ (whose main sequence masses are 30 and 40 $M_\odot$, respectively) are most probable.

2) Hypernova models are preferred over standard supernova models, which tend not to produce enough S and Si. These results 1) and 2) strengthen the connection among a massive star, a supernova which leaves a black hole as a compact remnant, and a hypernova.

3) The overabundance of Ti in the secondary star is difficult to explain in current models (at least by spherical models). Aspherical explosion models can reproduce the observed abundance of Ti when we assume that there is complete lateral mixing between the ejecta in the equatorial plane and in the polar direction. If such extreme mixing, however, can be realized or not needs further numerical studies.

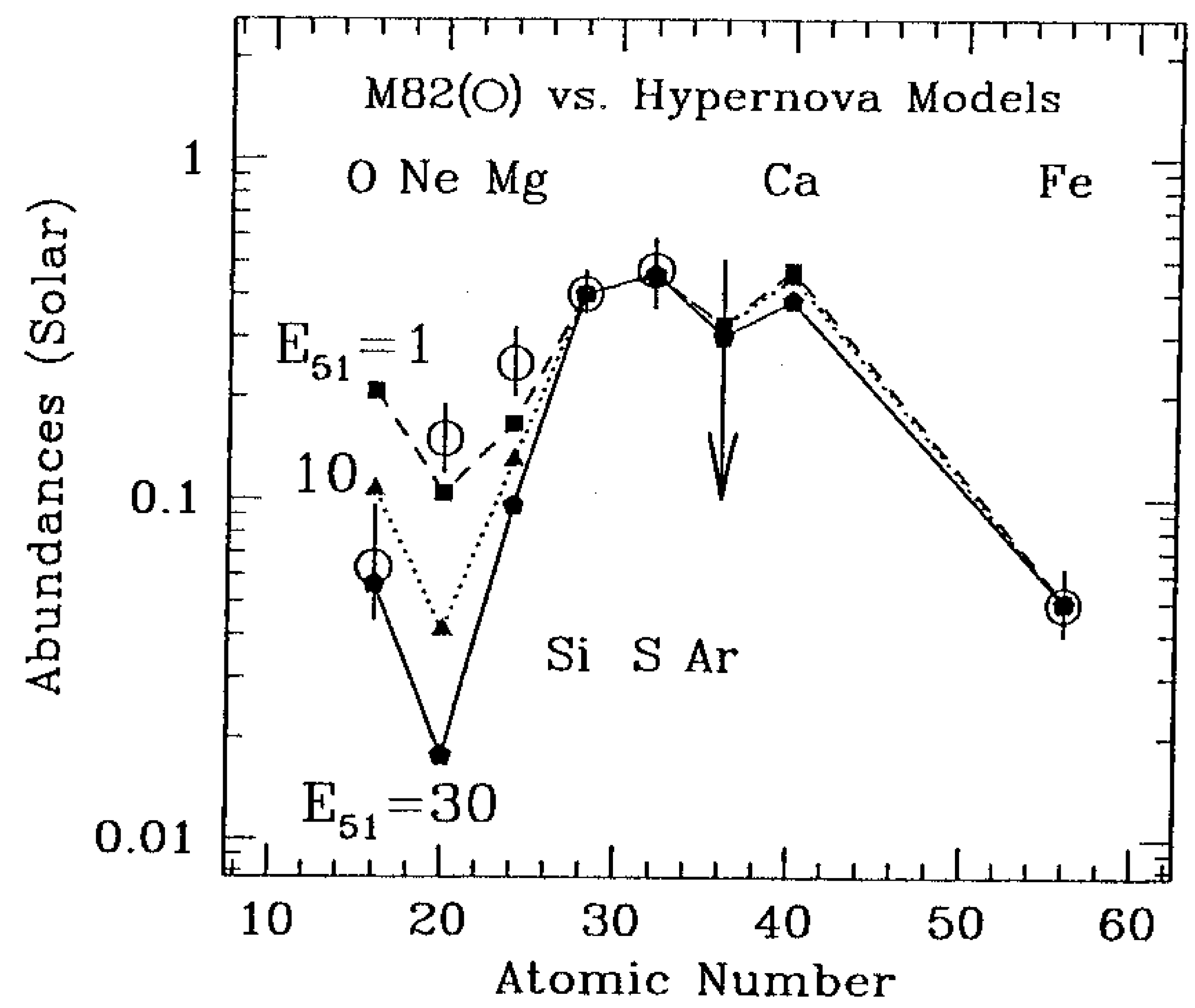

FIGURE 3. Abundance patterns in the ejecta of $25M_\odot$ metal-free SN II and hypernova models compared with abundances (relative to the solar values) of M82 observed with ASCA (Tsuru et al. 1997). Here, the open circles with error bars show the M82 data. The filled square, triangle, and pentagons represent E_{51} ($= E/10^{51}$ergs) =1, 10, and 30 models, respectively (Umeda et al. 2002).

CONTRIBUTION OF HYPERNOVAE TO CHEMICAL EVOLUTIONS OF GALAXIES

Starburst Galaxy M82

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 metalicity 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 3 shows the good agreement between the hypernova model ($E_{51} = 30$) and the observed abundances in M82 (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 $\lesssim 10^7$ years, which is so young that only massive stars ($M > 25\ M_\odot$) contributed to nucleosynthesis in M82.

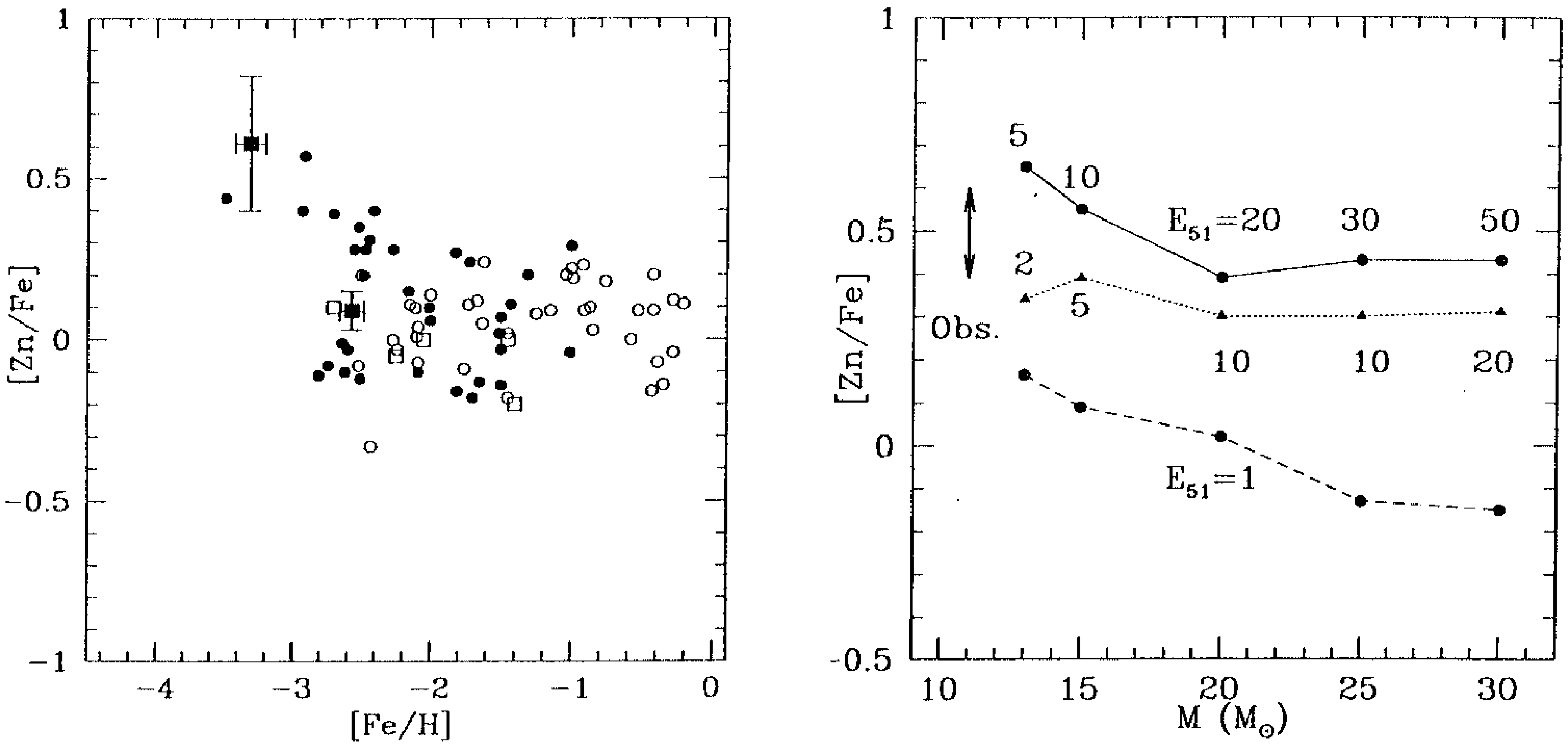

FIGURE 4. Left: Observed abundance ratios of [Zn/Fe]. These data are taken from Primas et al. (2000) (filled circles), Blake et al. (2001) (filled square) and from Sneden et al. (1991) (others) (Umeda & Nomoto 2002).
Right: The maximum [Zn/Fe] ratios as a function of M and $E_{51} = E/10^{51}$ergs (Umeda & Nomoto 2002). The observed large [Zn/Fe] ratio in very low-metal stars ([Fe/H] < -2.6; see references in Umeda & Nomoto 2002 for the observation) are represented by a thick arrow.

Early Galactic 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.

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]$\lesssim -2.5$, the mean values of [Cr/Fe] and [Mn/Fe] decrease toward smaller metalicity, while [Co/Fe] increases.

2) [Zn/Fe]~ 0 for [Fe/H] $\simeq -3$ to 0, while at [Fe/H] < -3.3, [Zn/Fe] increases toward smaller metalicity (Figure 4).

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. 2001), or (3) asphericity in the explosion is larger (Maeda et al. 2002b).

Also a large explosion energy E and a large asphericity result in the enhancement of the local mass fractions of Zn and Co, while Cr and Mn are not enhanced (Umeda &

Nomoto 2002; maeda et al 2002b). Therefore, if (aspherical) 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.

SUMMARY

We investigated explosive nucleosynthesis in hypernovae. The characteristics of hypernova yields compared to those of ordinary core-collapse supernovae are summarized in section 2 and 3.

Then we investigated the nature of hypernova explosions and suggested 1) aspherical explosion models for hypernovae, and 2) the connection among hypernovae, stellar mass black holes, and massive progenitors, through the modelings of individual objects (SN1998bw and Nova Sco).

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 metalicity phase.

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