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Nucleosynthesis yields of core-collapse supernovae and hypernovae, and galactic chemical evolution

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Abstract

We present new nucleosynthesis yields as functions of the stellar mass, metallicity, and explosion energy (corresponding to normal supernovae and hypernovae). We apply the results to the chemical evolution of the solar neighborhood. Our new yields are based on the new developments in the observational/theoretical studies of supernovae (SNe) and extremely metal-poor (EMP) stars in the halo, which have provided excellent opportunities to test the explosion models and their nucleosynthesis. We use the light curve and spectra fitting of individual SN to estimate the mass of the progenitor, explosion energy, and produced ^{56}Ni mass. Comparison with the abundance patterns of EMP stars has made it possible to determine the model parameters of core-collapse SNe, such as mixing-fallback parameters. More specifically, we take into account the two distinct new classes of massive SNe: (1) very energetic hypernovae, whose kinetic energy (KE) is more than 10 times the KE of normal core-collapse SNe, and (2) very faint and low energy SNe (faint SNe). These two new classes of SNe are likely to be "black-hole-forming" SNe with rotating or non-rotating black holes. Nucleosynthesis in hypernovae is characterized by larger abundance ratios (Zn, Co, V, Ti)/Fe and smaller (Mn, Cr)/Fe than normal SNe, which can explain the observed trends of these ratios in EMP stars. Nucleosynthesis in faint SNe is characterized by a large amount of fall-back, which explains the abundance pattern of the most Fe-poor stars. These comparisons suggest that black-hole-forming SNe made important contributions to the early galactic (and cosmic) chemical evolution.

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1. Introduction

Massive stars in the range of 8 to $\sim 130 M_\odot$ undergo core-collapse at the end of their evolution and become type II and Ib/c supernovae (SNe) unless the entire star collapses into a black hole with no mass ejection (e.g., [1–3]). Here, supernovae are classified based on the maximum light spectra as follows (e.g., [4]). Type II supernovae (SNe II) are defined by the presence of hydrogen, which implies that the progenitors are red (or blue) supergiants keeping their hydrogen-rich envelope. Type Ib supernovae (SNe Ib) are characterized by the lack of hydrogen but the presence of prominent He lines, so that their progenitors are Wolf–Rayet (WN) or He stars losing their H-rich envelope in a stellar wind or by Roche lobe overflow in binary systems. Type Ic supernovae (SNe Ic) do not show prominent He lines as well as H, which implies that their progenitors have lost even most of He layers to become WC/WO Wolf–Rayet stars or C + O stars in binary systems (e.g., [5]). (In contrast, type Ia SNe are the thermonuclear explosions of mass accreting white dwarfs in binary systems and spectroscopically characterized by the lack of H and He and the presence of strong Si lines (e.g., [6]).)

These supernovae release large explosion energies and eject explosive nucleosynthesis materials, thus having strong dynamical, thermal, and chemical influences on the evolution of interstellar, intergalactic, and intracluster matter (e.g., [7]) as well as galaxies and galaxy clusters. Therefore, the explosion energies of core-collapse supernovae are fundamentally important quantities, and an estimate of $E \sim 1 \times 10^{51}$ ergs has often been used in calculating nucleosynthesis and the impact on the interstellar medium. (In the present paper, we use the explosion energy E for the final kinetic energy of explosion, and $E_{51} = E/10^{51}$ erg.) A good example is SN1987A in the Large Magellanic Cloud, whose energy is estimated to be $E_{51} = 1.0$–1.5 from its early light curve (e.g., [1,8]).

One of the most interesting recent developments in the study of supernovae is the discovery of some very energetic supernovae, whose kinetic energy (KE) exceeds 10^{52} erg, more than 10 times the KE of normal core-collapse SNe. The most luminous and powerful of these objects, the type Ic supernova (SN Ic) 1998bw, was linked to the gamma-ray burst GRB 980425 [9], thus establishing for the first time a connection between gamma-ray bursts (GRBs) and the well-studied phenomenon of core-collapse SNe [10–12]. 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 $E_{51} \sim 30$ [13].

In the present paper, we use the term "hypernova (HN)" to describe such a hyper-energetic supernova with $E \gtrsim 10^{52}$ ergs without specifying the explosion mechanism [14]. Following SN 1998bw, other "hypernovae" of type Ic have been discovered or recognized [15].

Nucleosynthesis features in such hyper-energetic (and hyper-aspherical) supernovae must show some important differences from normal supernova explosions. This might be related to the unpredicted abundance patterns observed in the extremely metal-poor (EMP) halo stars (e.g., [16,17]). This approach leads to identifying the first stars in the universe, i.e., metal-free, population III (Pop III) stars which were born in a primordial hydrogen–helium gas cloud. This is one of the important challenges of the current astronomy (e.g., [18–20]).

More generally, the enrichment by a single SN can dominate the preexisting metal contents in the early universe (e.g., [21–24]). Therefore, the comparison between the SN model and the abundance patterns of EMP stars can provide a new way to find out the individual SN nucleosynthesis.