# Supernova and Its Scientific Secrets: Postprint

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## Abstract

Supernovae represent the most spectacular cosmic fireworks observable to humanity, releasing energy during outbursts approximately ten billion times the solar luminosity, thereby enabling scientists to probe deeper into the cosmos. Type Ia supernovae function as standard candles, permitting the measurement of intergalactic distances throughout the universe. Supernova explosions also expel substantial quantities of heavy elements into interstellar space, constituting the principal driving mechanism for galactic chemical evolution. Moreover, supernovae are essential to the origin of elements in the Milky Way, the formation of solar system architecture, and the evolution of terrestrial life. Investigations into supernovae contribute to enriching our comprehension of the universe and aid in deciphering the enigmas of cosmic expansion, heavy element nucleosynthesis, and the genesis of life. Presently, scientists anticipate that the next supernova may erupt imminently, with researchers undertaking comprehensive preparations to observe the forthcoming explosion.

## Full Text

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## Supernovae and Their Scientific Secrets

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**Abstract**

Supernovae are the most spectacular fireworks observable in the universe, releasing energy approximately 10 billion times the Sun' s luminosity at peak brightness and enabling scientists to see deeper into the cosmos. Type Ia supernovae serve as standard candles for measuring intergalactic distances. Supernova explosions also eject vast quantities of heavy elements into interstellar space, acting as the primary driver of galactic chemical evolution. Furthermore, supernovae are crucial for understanding the origin of elements in the Milky Way, the formation of the solar system' s structure, and the evolution of life on Earth. Studying supernovae enriches our understanding of the universe and helps unravel mysteries of cosmic expansion, heavy element nucleosynthesis, and the origin of life. Scientists currently predict that the next supernova could explode at any moment, and researchers are making comprehensive preparations to observe this imminent event.

**Keywords:** Supernova, Standard candle, Origin of elements, Origin of life

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Supernovae are immensely powerful stellar explosions in nature, releasing energies up to $10^{46}$ J. During outburst, a star' s luminosity increases suddenly by over ten million times, capable of illuminating an entire galaxy. Supernovae occurring near the Milky Way can be observed with the naked eye from Earth. Their durations vary from several days to several years, appearing and disappearing like transient guests—hence ancient Chinese astronomers called them "guest stars" or "variable stars." For weather prediction and divination purposes, imperial observatories of various dynasties maintained detailed records of these guest stars, which provide valuable historical data for modern supernova research. Table 1 lists supernovae historically observed with the naked eye; astronomers have since identified their remnants and studied them extensively.

**Table 1** Supernovae observed by the naked eye

| Supernova number | Position | Distance from Earth / ly | Duration | Brightness |
|---|---|---|---|---|
| SN185 | Near Alpha Centauri | | 8 months | |

| Supernova number | Position | Distance from Earth / ly | Duration | Brightness |
|---|---|---|---|---|
| SN393 | Scorpio | | Several years | |
| SN1006 | Lupus | | 1 year | |
| SN1054 | Taurus | | Several months | |
| SN1181 | Cassiopeia | | | |
| SN1572 | Cassiopeia | | | |
| SN1604 | Ophiuchus | | | |
| SN1987a | Large Magellanic Cloud | | | |

Supernovae are classified into two major categories based on spectral observations: Type I and Type II. Type I supernovae lack hydrogen lines in their spectra, while Type II supernovae exhibit them. Type I supernovae are further divided into Ia, Ib, and Ic subclasses. Type Ia supernovae show silicon lines, Type Ib lack silicon but display helium lines, and Type Ic supernovae have neither silicon nor helium lines. Type II supernovae can also be categorized as IIL or IIP based on the shape of their light curves.

Type Ia supernovae originate from binary star systems where both components have initial masses below 8 M . The more massive star evolves rapidly through hydrogen and helium burning, forming a carbon-oxygen white dwarf. The companion star, being less massive, evolves more slowly and remains in the red giant or main-sequence phase. According to supernova explosion models, the white dwarf accretes material from its companion, forming a hydrogen-helium envelope. The accreted energy raises the white dwarf' s surface temperature, triggering hydrogen and helium fusion. When the core approaches the Chandrasekhar mass limit (1.4 M ), it reaches carbon ignition temperature and detonates. Type II supernovae represent the inevitable fate of stars exceeding 8 M . Massive stars undergo successive nuclear burning stages—hydrogen, helium, carbon, neon, oxygen, and silicon—forming an iron core. Initially, this core exists in an electron-degenerate state. As the core contracts, gravity intensifies until electron degeneracy pressure can no longer resist collapse. Electrons are forced into iron nuclei, combining with protons to form neutrons, creating a neutron-dominated core where neutron degeneracy pressure replaces electron degeneracy pressure to counteract gravity. The core volume rapidly contracts by a factor of 100,000, releasing enormous gravitational potential energy. Type II supernovae are the most common stellar explosions in nature, comprising about half of all supernovae in the contemporary universe. Approximately one-quarter are Type Ia, with the remaining quarter being Types Ib and Ic. Observations reveal that Type Ia supernovae exhibit higher luminosities and serve as standard candles for cosmic distance measurements.

Supernovae harbor numerous profound scientific secrets, and deciphering them can significantly advance scientific progress while deepening our understanding of the universe' s fundamental nature. This paper describes how supernovae can be used to investigate the age and composition of the universe, the chemical evolution history of the Milky Way, the formation of the solar system, and the mystery of life' s origin.

## Age and Composition of the Universe

Observations of supernovae yield the relationship between galactic redshift and distance, as shown in Figure 1 [Figure 1: see original paper]. To quantitatively interpret this distance-redshift relation, cosmological evolution models must be established to explain the universe' s shape, size, composition, characteristics, and evolution laws. According to the Friedmann cosmological equations, the relationship between cosmic expansion rate and matter density can be expressed as:

$$H^2 = \langle MATH_0 \rangle$$

Defining the critical density of the universe as $\rho_c = \langle MATH_1 \rangle$ and the cosmological parameters for each component as $\Omega_i = \langle MATH_2 \rangle$, we obtain the relationship between luminosity distance and cosmological parameters:

$$d_L = \frac{1+z}{H_0} \int_0^z \frac{dz'}{[\Omega_\Lambda + \Omega_k(1+z')^2 + \Omega_m(1+z')^3 + \Omega_r(1+z')^4]^{1/2}}$$

By adjusting cosmological parameters, we can fit the distance-redshift relation to match astronomical observations and further derive the universe' s age and scale. Based on the latest observational data, the current cosmic composition is fitted as 68.3% dark energy, 26.8% dark matter, and approximately 4.9% baryonic matter. These results also imply a universe age of 13.8 billion years and a radius of about 46.5 billion light-years.

Many factors affect the relationship between intergalactic distance and redshift. For instance, the peak luminosity of Type Ia supernovae depends on host galaxy morphology, mass, age, star formation rate, and cosmic mean metallicity. Physical causes such as variations in fundamental constants can also alter cosmological parameters, leading to significant uncertainties in analysis. Recently, we investigated the effects of varying fine-structure constants and cosmic mean metallicity on cosmological parameters, revealing deeper physical connections between microscopic and cosmic scales and concluding that the universe is expanding at an accelerating rate.

## Chemical Evolution of the Milky Way

Supernova explosions not only release enormous energy but also eject matter into interstellar space, driving galactic chemical evolution. Throughout their lives, massive stars undergo various nuclear burning stages, gradually increasing heavy element abundances and stellar metallicity. Supernova explosions expel these synthesized elements into the interstellar medium, progressively enriching its metallicity. The interstellar medium can subsequently form nebulae that condense into the next generation of stars, continuing this cyclical process. Therefore, the metallicity of interstellar medium or stellar surface material can be used to trace the history of galactic chemical evolution.

Radioactive elements serve as chronometers for studying supernova explosion frequencies and galactic chemical evolution patterns. Supernovae produce pure r-process nuclides whose time evolution follows:

$$\frac{dN_i(t)}{dt} = -\lambda_i N_i(t) + P_i \Psi(t)$$

where $N_i(t)$ is the number of radioactive nuclide $i$ at time $t$, $\Psi(t)$ is the rate of supernova ejecta accretion or matter production, and $P_i$ is the abundance of nuclide $i$ produced by the r-process, calculable through r-process models. Assuming the first supernova in the Milky Way exploded at $t = 0$ and the solar system formed at $t = \tau$, we have $N_i(0) = 0$ and $N_i(\tau)$ as the primordial solar system nuclide abundance. To determine $\tau$ and the average galactic matter production rate, we can solve equation (3) graphically using four pure r-process nuclides: $^{187}$Re, $^{232}$Th, $^{235}$U, and $^{238}$U, with results shown in Figure 2 [Figure 2: see original paper]. Except for $^{232}$Th, which yields less ideal solutions, the curves for $^{187}$Re, $^{235}$U, and $^{238}$U intersect perfectly at a single point. This yields a Milky Way age of 7.8 billion years at solar system formation. Adding the solar system' s age of 4.6 billion years indicates that approximately 12.4 billion years have elapsed since the first supernova in the Milky Way, consistent with dynamical simulations of galaxy formation epochs after the Big Bang.

## The "Trigger" for Solar System Formation and the Origin of Life

Supernova explosions may have served as the trigger for solar system formation. One hypothesis proposes that the primordial solar nebula, after accumulating for billions of years, suddenly encountered a supernova explosion. The ejected supernova material was absorbed by the solar nebula, causing it to condense and contract. Constrained by momentum conservation, the nebula' s rotation accelerated as it contracted, becoming increasingly flattened into a disk shape with a slightly bulging center. The central region gradually formed the Sun under gravitational collapse, while the surrounding thinner regions formed the eight planets. Dynamical simulations suggest this process lasted approximately 2 million years. Consequently, nuclides with half-lives ranging from hundreds of thousands to millions of years can be used to trace solar system formation history.

Banerjee et al. studied the evolution curves of several radioactive nuclides ($^{10}$Be, $^{41}$Ca, $^{107}$Pd) in the early solar system (Figure 3 [Figure 3: see original paper]). They found that assuming these nuclides originated from a low-mass supernova explosion yields isotopic abundances consistent with observational data. Boss and Keiser developed a two-dimensional model whose evolution suggests that $^{60}$Fe in primitive solar system meteorites may have come from a supernova. Additionally, scientists discovered $^{26}$Mg isotopic excess in the Allende meteorite. This excess is attributed to substantial $^{26}$Al injection during solar system formation. The decay of these $^{26}$Al nuclides explains the $^{26}$Mg excess and accounts for numerous microscopic grains in meteorites. Investigating the production mechanisms of these radioactive nuclides and analyzing them in primitive meteorites can reconstruct solar system formation history and help solve its formation mysteries.

Elements essential for life—including carbon, nitrogen, and oxygen—are synthesized in stars and ejected via supernova explosions, eventually reaching Earth to become fundamental building blocks of our bodies. Without supernovae, life would not exist. Recent research reveals that human survival requires 20 amino acids, half of which can be synthesized internally while the rest must be obtained from food. Among these 20 vital amino acids, 19 exhibit left-handed chirality (except glycine, which is achiral). Miller and Urey's spark discharge experiments produced 22 amino acids with roughly equal left- and right-handed proportions. Why, then, does life exclusively select left-handed amino acids? Boyd et al.' s supernova neutrino amino acid processing model suggests that following supernova explosions, newly formed neutron stars or black holes generate extremely strong magnetic fields. As neutrino fluxes and dust grains traverse these fields, organic molecules moving opposite to neutrinos are destroyed, while co-moving molecules are preserved due to momentum conservation constraints, resulting in left-handed amino acid selection. Life likely emerged and propagated throughout the Milky Way and Earth through this mechanism.

Supernovae are also crucial for life evolution beyond amino acid chirality. Nearby supernova explosions can extinguish some Earth species while simultaneously providing impetus for new species emergence. American scientists have linked the Ordovician mass extinction 440 million years ago to a supernova explosion and identified its remnant. Radioactive nuclides produced during supernova explosions (such as $^{60}$Fe) can be used to study the history of near-Earth supernova events.

In summary, supernova research is profoundly significant for understanding the universe, the solar system, and life' s emergence. As standard candles for measuring cosmic distances, supernovae help determine intergalactic distances, revealing the universe' s composition and expansion dynamics. Supernovae drive galactic chemical evolution, triggered solar system formation, and nurtured life throughout the cosmos. They contain numerous scientific secrets whose investigation will undoubtedly enrich our cosmic understanding and resolve many natural mysteries.

Predictions indicate that approximately two supernova explosions occur in the Milky Way each century. The last nearby supernova event (SN 1987A) occurred 35 years ago, suggesting the next naked-eye supernova may appear soon. Scientists worldwide are preparing extensively: the James Webb Space Telescope launched in 2021 and began operations in July 2022, capturing images of the earliest known galaxies. The Super-Kamiokande neutrino detector is ready, equipped with a supernova early warning system. Italy' s Virgo gravitational wave detector is improving interferometer sensitivity to better measure distant supernovae. The Five-hundred-meter Aperture Spherical radio Telescope (FAST) is also searching for supernova remnants, with observations contributing to future supernova research. Amateur astronomers are likewise attempting to detect supernovae by photographing evening skies with modest telescopes.

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*Note: Figure translations are in progress. See original paper for figures.*