

Supernova Progenitors: Theory, Observation and Outstanding Questions

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Abstract

Supernovae play a prominent role in current theories of cosmology, galaxy evolution and stellar evolution. Key to understanding supernovae is a characterization of their progenitors. A robust body of theoretical work predicts the nature of these stars, but direct observations are lacking. Current theory and observations to date are summarized, as well as open questions in the field. Interferometric methods are proposed for the resolution of some of these questions.

1 Introduction

Supernovae are the fireworks of the cosmos, so bright that they can light up the Earth's night sky millions of light-years away. The violent and spectacular displays are the dying moments of the most massive stars in the universe. Supernovae have long been a subject of fascination, in part because they are among the few cosmic events that happen on a human time scale, appearing and fading out of sight in only a few months. Supernovae can shine up to a hundred billion times brighter than the sun at their brightest [16]. From Earth, they can appear brighter than the moon and be visible even during the day. Supernovae are among the earliest documented astronomical events: Chinese recordings of supernovae date back to the Han Dynasty, 206 BC [19]. Within the Milky Way, supernovae happen approximately every 40 years [20], and with modern instrumentation, astronomers are able to detect approximately 20 extra-galactic supernovae per decade [3].

Supernovae make important contributions to their host galaxies. Before they go supernova, massive stars take H and He and create heavier elements via fusion in their core. The subsequent expulsion of that material into the inter-stellar medium provides a significant portion of the galaxy's supply of heavy elements. This process, called "chemical enrichment," plays a crucial role in the evolution of the galaxy. Additionally, upon explosion, supernovae release large amounts of kinetic energy into their surroundings. This kinetic energy can cause a new wave of star formation and can later be harnessed as angular momentum in galactic disk formation [17]. Supernovae are also a critical tool for observational astronomers. Though it is a subject of some debate, current theory holds that the specific mechanisms by which Type Ia supernovae are formed require that all have the same intrinsic brightness [2, 7]. This property allows researchers to calculate the distance to these objects based on their observed brightness from Earth. Knowledge of the distance to a particular galaxy or star cluster is the key to understanding a lot of the fundamental physics of the system.

2 Classification

Astronomers have created a classification system for supernovae based on their spectral energy distribution (i.e., how much energy is released at each wavelength), and how it changes with time. This spectral distribution contains the signatures of the atoms or molecules from which the energy was released, so we use this to tell the chemical composition of the star. Generally, they are split into two categories; those without a Hydrogen spectral signature (Type I, including Types Ia, Ib, Ic), and those with Hydrogen present in the spectrum (Type II, including Types IIL, IIP, IIIn). Within those categories, they are further divided by other spectral features (namely Nickel and Helium), and by the rate at which the light from the explosion fades (i.e, Type IIP fades slower than Type IIL).

All supernovae are the result of a breakdown in thermodynamic equilibrium, where the pressure pushing outward on a star is overcome by the inward pull of gravity. The outward pressure can be supplied in two ways: the release of energy due to nuclear fusion happening in the core or “degeneracy pressure,” a quantum mechanical effect. This leads to a second important distinction between supernovae: the first, caused when nuclear fusion fails, are called “iron core collapse supernovae,” and the second, caused when degeneracy pressure is overcome by gravity, are called “degenerate core collapse supernovae.”

2.1 Iron Core Collapse Supernovae

The most common type of supernovae, (iron) core collapse, result from massive stars ($M_* > 8M_\odot$) that run out of nuclear fuel. Typically, stars produce energy by fusing lighter elements into heavier ones. This process releases energy that causes the star to shine. Our sun, for example, processes Hydrogen into Helium. More massive stars will continue stepping up the periodic table, creating Carbon, Nitrogen, Oxygen, and so on. However, there is a limit to this process: energy is only released in a fusion process up to iron. Fusion of iron into heavier elements requires energy input. Thus, once the interior of a star has processed all available nuclear fuel into iron, there is nothing left to burn, and the core furnace shuts down. With no outward force to counteract gravity, the core collapses until it reaches a critical density (a maximum allowable physical density, limited by the nuclear strong force), at which point the collapse halts, sending a shock wave outward through the infalling layers [4]. If the shock wave carries enough energy, it will push all the outer layers away, ejecting them into space in a spectacular explosion. The remaining core will either stabilize as a neutron star, or for a more massive core, a black hole. Core collapse supernovae include Type IIP, forming from Red Supergiant stars with 8–15 M_\odot (most common among the core collapse types), and Types IIL, IIn, Ib, and Ic which form from extremely massive stars (15–40 M_\odot), including Red Supergiants and Wolf-Rayet Stars.

2.2 Degenerate Core Collapse Supernovae

The second type of supernova (Type Ia) is born from a type of star called a white dwarf (WD). White dwarfs are the charred remains of stellar cores that have consumed their nuclear fuel. Gravity has forced these stars into an ultra-compressed state. The only thing that prevents complete collapse of the star is “degeneracy pressure,” caused by the unwillingness of the electrons to share space with one another (a result of the Pauli Exclusion Principle). However, this type of pressure will only prevent collapse up to the theoretical “Chandrasekar limit” of 1.4 M_\odot . If a WD grows to this mass, a thermonuclear explosion will ensue. There are two theoretical scenarios by which a white dwarf could reach this limit: two WDs in a binary system could fall into one another and combine, or a WD could be accreting material from a “normal” binary companion. Based on this theoretical limit, all type Ia supernova progenitors should have the same mass upon explosion, and therefore they should all have the same intrinsic brightness. This (unverified) assumption allows us to calculate the distance to that event, based on our knowledge of light dispersion.

2.3 Failed Supernovae

A third core collapse scenario that has received recent attention is that of a failed supernova. Models predict that iron core collapse events could stall out if the shock wave (formed once the critical density is reached) does not carry enough energy to expel the outer layers of the star into space [4]. In this case, the collapse would continue and a black hole would form rather than a supernova [11]. Though some attempts have been made to search for these black holes, they have not been found in the quantity that theorists predict [6].

3 Progenitors

Key to understanding supernovae is a detailed knowledge of their progenitors. This information allows the testing of theoretical models, and helps us to better understand the mechanisms by which the explosion took place. There are several methods by which progenitors are characterized: direct observation prior to explosion, measurements of the interaction between the expanding material and pre-existing stellar winds and study of the spectral signatures contained in the expanding material.

The most obvious method to find a supernova’s progenitor is to look at images of the region from which the material is expanding and extrapolate the exact point in space from which it originated. This method is often employed, but with few positive identifications. The difficulty is that many of the supernovae we observe come from stars that were too distant and faint to be measured (or even seen) prior to the explosion. Additionally, with so many stars in the sky, even a visible star would not necessarily have been studied or characterized in detail unless there was something unusual about it. Thus, astronomers are unable to

identify the sources of the vast majority of supernovae by direct observation.

A less direct method for investigating progenitors is by studying the expansion of the expelled material. As it travels away from the star, it collides with surrounding material that was deposited by the progenitor’s stellar winds. At this interface, a highly luminous shock front forms. The light coming from this shock can be analyzed to determine constituent elements [14], and place limits on certain properties of the progenitors’ winds.

After a supernova happens, the spectral signature of the light emitted will evolve over time. A careful record of these changes and the rate at which the light diminishes can distinguish between different types of progenitors. As an example, Type II-L (linear) supernovae fade linearly with time, while Type II-P (plateau) supernovae show a period of near-constant emission between 30 and 80 days. Spectral studies of the Type II-P events indicate that this plateau is associated with the radioactive decay of Nickel [4]. Additionally, precise measurement of the expanding material can yield a mass estimate for the star. It is from this type of observation that core collapse supernovae are known to come from only the most massive stars in the universe.

3.1 Theory

Stars massive enough to produce the amount of material observed in supernovae are rare, so this places a strong constraint on what types of stars could be responsible. Theoretical models predict that stars with more than 10 solar masses live very short lives, quickly burning through their nuclear fuel. They begin as Main-Sequence stars, rapidly fusing Hydrogen into Helium. When the Hydrogen in the core is burned up, they begin the Helium burning phase and are called Red Supergiant stars. If the stars are less than 15 solar masses, they will eventually burn through all of the fuel at their core and become iron core collapse Type II supernovae. The more massive stars will leave the Red Supergiant phase and become Wolf-Rayet stars, expelling their outer layers (made of Hydrogen) into space in a fast, dense stellar wind. When they collapse, they become core collapse Type Ib and Ic supernovae. Because these stars have blown off their outer envelopes (composed mostly of Hydrogen), we do not see a Hydrogen signature in the spectrum, distinguishing them from Type II core collapse events.

3.2 Observation

There is some observational evidence supporting the above scenario for Type II supernovae. Since this type is most common, they comprise the majority of progenitors that have been directly identified from pre-explosion images. A list of directly observed progenitors that have also been spectrally identified can be found in Table 1. Though searches have been done for dozens more, most supernovae originate from locations where no source was ever detected prior to explosion [12]. Notably absent from this list are Type I supernovae: not a single progenitor has been detected to date. The theory of supernova origins is robust, but lacking in observational verification. Since we cannot predict exactly which stars will go supernova (candidates number in the thousands), the only way to ensure direct identification of future supernova progenitors is to image the entire sky. Ideally, this would be done in a range of wavelengths to provide rudimentary spectral information. With the breadth of all-sky surveys now available in many wavelengths, identification of future supernova should be forthcoming.

Table 1. Supernova progenitors identified from pre-collapse images

Type	Supernova	Progenitor	Mass (1)	Reference
II pec	1987A	Blue Supergiant	20M _⊙	[5]
IIb	1993J	Red Supergiant (2)	17M _⊙	[1], [13]
IIP	2003gd	Red Supergiant	6–12M _⊙	[18]
IIP	2004et	Yellow Supergiant	13–20M _⊙	[8]
IIP	2005cs	Red Supergiant	7–13M _⊙	[9]
IIP	2006my	Red Supergiant	7–15M _⊙	[10]
IIP	2006ov	Red Supergiant	12–20M _⊙	[10]
IIn	2008S	Red Supergiant	10M _⊙	[15]

(1) Zero Age Main Sequence Mass

(2) with massive binary companion

4 Research Plan

To help identify new supernova progenitors, interferometric studies offer a terrific opportunity to directly measure physical properties of candidate stars. Generally, the diffraction-limited angular resolution of a telescope at wavelength λ with aperture diameter d is given by the formula:

$$\Theta = 1.22\lambda/d$$

However, due to turbulence in the atmosphere, any telescope with an aperture larger than approximately 10 cm will see a blurred image. Techniques have been developed to cope with this blurring, but the larger the telescope is, the more dramatic, and thus the more expensive and complex, the corrections must be. Interferometry circumvents this issue by combining the light from a series of smaller telescopes, which need only rudimentary atmospheric corrections. This gives an effective aperture (d in the above equation) the size of the separation between the telescopes. With this dramatic increase in resolution, interferometers are able to actually resolve the surfaces of stars. This allows the measurement of the physical size and shape of the star. By making the same measurement in a range of wavelengths, it is also possible to resolve specific layers in the stellar winds. This information will play a crucial role in testing the current theory of supernova progenitors.

To that end, I have obtained measurements of a large body of core collapse supernova progenitor candidates, including a large sample of Supergiants and several Wolf-Rayet stars with the Palomar Testbed Interferometer (PTI) [21]. PTI combines near infra-red light from three 40 cm aperture telescopes (in pairwise combination) to exploit the enhanced resolution provided by baselines of up to 110 meters. For future work, I have applied for more PTI observing time in the coming year to get a closer look at a subset of the Supergiants mentioned above. Additionally, I will be attending the Very Large Telescope Interferometer Summer School in June to learn more about the use of that instrument, with the intention of applying for observing time on that instrument.

5 Conclusion

Supernovae play a prominent role in the evolution of the universe. They are the primary manufacturers of heavy elements, the ingredients for the next generation of stars and rocky planets such as earth. A clear understanding of their progenitors will unlock many mysteries about how our universe grew to be what it is today. Supernovae are more than just spectacular fireworks: they are key to understanding the past, present and future of the cosmos.

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