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Principal Characteristics and Theory of Explosion of Thermonuclear Supernovae

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ABSTRACT

The explosive death of a star as a supernova is one of the most dramatic events in the Universe. Supernovae have an outsized impact on many areas of astrophysics: they are major contributors to the chemical enrichment of the cosmos and significantly influence the formation of subsequent generations of stars and the evolution of galaxies. Here we review the observational properties of thermonuclear supernovae exploding white dwarf stars resulting from the stellar evolution of low-mass stars in close binary systems. The best known objects in this class are type-Ia supernovae (SNe Ia), astrophysical important in their application as standardizable candles to measure cosmological distances and the primary source of iron group elements in the Universe. Surprisingly, given their prominent role, SN Ia progenitor systems and explosion mechanisms are not fully understood; the observations we describe here provide constraints on models, not always in consistent ways.

Key words: supernovae, general, white dwarfs, nuclear reactions, nucleosynthesis, abundances etc

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INTRODUCTION

A supernova is a powerful and luminous stellar explosion. This transient astronomical event occurs during the last evolutionary stages of a massive star or when a white dwarf is triggered into runaway nuclear fusion. The original object, called the progenitor, either collapses to a neutron star or black hole, or is completely destroyed. The peak optical luminosity of a supernova can be comparable to that of an entire galaxy before fading over several weeks or months. Supernovae are more energetic than novae. In Latin, nova means "new", referring astronomically to what appears to be a temporary new bright star. Adding the prefix "super-" distinguishes supernovae from ordinary novae, which are far less luminous. The word supernova was coined by Walter Baade and Fritz Zwicky in 1929. The most recent directly observed supernova in the Milky Way was Kepler's Supernova in 1604, but the remnants of more recent supernovae have been found. Observations of supernovae in other galaxies suggest they occur in the Milky Way on average about three times every century. These supernovae would almost certainly be observable with modern astronomical telescopes. The most recent naked-eye supernova was SN 1987A, the explosion of a blue supergiant star in the Large Magellanic Cloud, a satellite of the Milky Way. Theoretical studies indicate that most supernovae are triggered by one of two basic mechanisms: the sudden re-ignition of nuclear fusion in a degenerate star such as a white dwarf, or the sudden gravitational collapse of a massive star's core. In the first class of events, the object's temperature is raised enough to trigger runaway nuclear fusion, completely disrupting the star. Possible causes are an accumulation of material from a binary companion through accretion, or a stellar merger.

Some stars burn out instead of fading. These stars end their evolutions in massive cosmic explosions known as supernovae. When supernovae explode, they jettison matter into space at some 9,000 to 25,000 miles (15,000 to 40,000 kilometres) per second. These blasts produce much of the material in the universe including some elements, like iron, which make up our planet and even ourselves. Heavy elements are only produced in supernovae, so all of us carry the remnants of these distant explosions within our own bodies. Supernovae add enriching elements to space clouds of dust and gas, further interstellar diversity, and produce a shock wave that compresses clouds of gas to aid new star formation. But only a select few stars become supernovae. Many stars cool in later life to end their days as white dwarfs and, later, black dwarfs. Type Ia (thermonuclear-powered) supernovae are among the brightest explosions in the universe. These events are thought to be white dwarf stars in binary systems that explode as a result of a thermonuclear runaway. Observations using them as "cosmic yardsticks" revealed that the expansion rate of the universe is accelerating and led to the discovery of dark energy.The goal of the Flash Center's Type Ia supernova (SN Ia) project is to understand these explosions better, and by doing so, help observers use them to determine the properties of dark energy. The Type Ia supernova research team is using the FLASH computer code and INCITE allocations of computer time on the IBM Blue Gene/P at the ALCF to conduct the first comprehensive, systematic validation of all current SN Ia models.Physically, carbon–oxygen white dwarfs with a low rate of rotation are limited to below 1.44 solar masses ($M_\odot$).Beyond this "critical mass", they reignite and in some cases trigger a supernova explosion. Somewhat confusingly, this critical mass is often referred to as the Chandrasekhar mass, despite being marginally different from the absolute Chandrasekhar limit where electron degeneracy pressure is unable to prevent catastrophic collapse.

If a white dwarf gradually accretes mass from a binary companion, or merges with a second white dwarf, the general hypothesis is that its core will reach the ignition temperature for carbon fusion as it approaches the Chandrasekhar mass. Within a few seconds of initiation of nuclear fusion, a substantial fraction of the matter in the white dwarf undergoes a runaway reaction, releasing enough energy ($1\text{–}2\times10^{44}$ J)to unbind the star in a supernova explosion. The type Ia category of supernova produces a fairly consistent peak luminosity because of this fixed critical mass at which a white dwarf will explode. Their consistent peak luminosity allows these explosions to be used as standard candles to measure the distance to their host galaxies: the visual magnitude of a type Ia supernova, as observed from Earth, indicates its distance from Earth. In May 2015, NASA reported that the Kepler space observatory observed KSN 2011b, a type Ia supernova in the process of exploding. Details of the pre-nova moments may help scientist's better judge the quality of Type Ia supernovae as standard candles, which is an important link in the argument for dark energy.Iron cannot release energy by fusion because it requires a larger input of energy than it releases. So the iron core continues to be subjected to gravity, which pushes the electrons closer to the nuclei than the quantum limit allows, and they disappear by combining with protons to form neutrons, giving off neutrinos in the process.

Once this process starts, in a fraction of a second, an iron core the size of the earth and with a mass like our Sun, collapses into a ball of neutrons a few kilometers across. This gravitational collapse releases an enormous amount of energy, more than 100 times what our Sun will radiate over its entire 10 billion year lifetime. This energy blows the outer layers of the star off into space in a giant explosion called a supernova. The ball of neutrons left behind is called a neutron star and is incredibly dense. In some cases the remaining mass is large enough that gravity continues to collapse the core until it becomes a black hole. The explosion sends a shock wave of the star's former surface zooming out at a speed of 10,000 km/s, and heating it so it shines brilliantly for about a week. This shock wave compresses the material it passes through and is the only place where many elements such as zinc, silver, tin, gold, mercury, lead and uranium are produced. Over several months the gases cool and fade in brightness and join the debris of interstellar space. This debris has in it all of the elements that were created in the star's core. Millions or billions of years later, this debris may be incorporated into new stars.

The fact that the Earth contains elements that are produced only in supernovae is evidence that our solar system, planet and bodies contain material that was produced long ago by a supernova. Thermonuclear Supernovae, stellar explosions of White Dwarf Stars (WD)/the degenerate C/O cores of low mass stars are important for understanding the Universe. As well as being one of the building blocks and drivers of modern cosmology, they are also important for understanding the origin of elements, and are laboratories for the explosion physics of WDs in close binary systems. Here, we focus on new developments. For a general discussion from our perspective. Recently advances in observations and theory have caused new problems to emerge. One of these is the discrepancy in the Hubble constant Ho obtained using the Microwave background (66.93 ± 0.62km/s/M pc,and that obtained using the empirical SNe Ia-based methods (73.24 ±1.74, . This discrepancy may have direct consequences for: the interpretation of the Big bang nucleosynthesis (Li-problem), high precision cosmology, early Black Hole formation, and new physics beyond the high-energy standard model. The majority of Type Ia supernovae appear to be rather homogeneous with a well-defined luminosity decline relation of light curves Δm15 and similar spectra. However, there is in fact some diversity in their observations which has been hypothesized to be due to various progenitor channels and explosion scenarios. Potential progenitor systems may either consist of two WDs, called a double degenerate (DD) system, or a single WD with a donor which may be main sequence, red giant, or Helium (He) star, called a single degenerate (SD) system. The various explosion scenarios can be distinguished by three possible triggering mechanisms: a) Compressional heat in a slow accretion triggers the explosion when the WD approaches (!) the Chandrasekhar mass MCh in either SD or DD systems.

The flame propagates as a detonation (Det.), a deflagration (Defl.) or, more likely, starts as deflagration and transitions to a detonation with or without a pulsation phase (DDT,PDDT); b) Heat released on dynamical time scales triggers a detonation of a DD-system (dynamical mergers); c) in Helium detonations (HeDs,) a surface He-detonation triggers a detonation in a C/O core of a sub-MCh WD with a He-star companion. Core-degenerates (CD) are explosions within a Red-Supergiant by a) or b). From theory, the empirical SNe Ia relations dm15 and CMAGIC for cosmology are stable because basic nuclear physics determines: the structure of the progenitor WD, the explosion physics, and the average expansion velocities. This ’Stellar amnesia‘leads to similar light curve shapes and spectral evolution. All scenarios may contribute to the SNe Ia population but there is observationalevidence that one scenario dominates. However which one dominates is heavily discussed in the community. Dynamical mergers are not likely as they predict high continuum polarization and aspherical explosions, this is not seen in the data. The DDT (MCh) seems to explain most of the observed properties of SNe Ia , and DDT model-based, δ − Ceph.- independent distances give an Ho = 68 ± 4km/M pc/s [8, 9]. However, HeDs have recently become a serious contender because their main-flaw, the need for a large He-layers on the surface of the WD, can be migrated by a mixing of the He and C, as long as the MWD > 1.1M. In this scenario the optical spectra and LCs become similar to DDTs. However, these HeDs result in systematically larger Ho when analyzing observations.

But massive stars, many times larger than our own sun, may create a supernova when their core's fusion process runs out of fuel. Star fusion provides a constant outward pressure, which exists in balance with the star's own mass-driven, inward gravitational pull. When fusion slows, outbound pressure drops and the star's core begins to condense under gravity—becoming ever denser and hotter. To outward appearances, such stars begin growing, swelling into bodies known as red supergiants. But at their cores, shrinking continues, making a supernova imminent. When a star's core contracts to a critical point, a series of nuclear reactions is unleashed. This fusion staves off core collapse for a time but only until the core is composed largely of iron, which can no longer sustain star fusion. In a microsecond, the core may reach temperatures of billions of degrees Celsius. Iron atoms become crushed so closely together that the repulsive forces of their nuclei create a recoil of the squeezed core a bounce that causes the star to explode as a supernova and give birth to an enormous, superheated, shock wave.Gravitational waves provide an ideal probe of the white dwarf systems the are believed to be progenitors of thermonuclear supernovae and the gravitational-wave signal of these systems lies right in the frequency band of space-based gravitational-wave missions such as LISA. The gravitational wave chirp mass coupled with electromagnetic observations of white dwarfs will allow astronomers to probe the effects of tides on the orbital evolution, one of the key uncertainties in theoretical models of SN Ia progenitors. In addition, with accurate chirp masses, gravitational wave observations are ideally suited to observing the mass distribution of white dwarf binaries, determining the fraction of systems whose combined mass exceeds the Chandrasekhar limit. Finally, if a Galactic supernova occurs, gravitational waves will definitively distinguish between double white dwarf and accreting white dwarf progenitors.

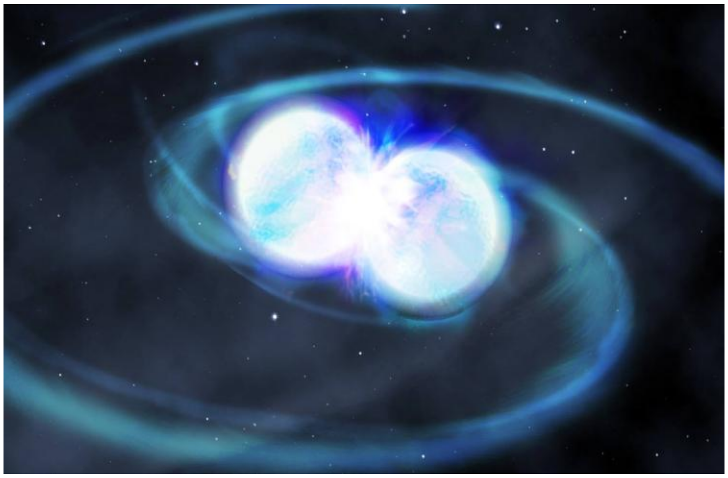

Fig. 1: Thermonuclear Supernovae

PRINCIPAL OBSERVED CHARACTERISTICS

A type Ia supernova reaches its peak brightness about 20 days after the explosion, with an absolute visual magnitude of about, or almost 10 billion time the luminosity of the Sun. After peaking, the supernova declines in brightness by 3 magnitudes over a month and then by 1 magnitude every subsequent month until it fades from sight. The features that mark a supernova as type Ia are the absence of hydrogen lines and the presence of silicon lines in the spectrum. The spectrum also shows the lines of intermediate mass elements such as oxygen, calcium, magnesium, and sulfur. Two weeks after the supernova reaches its peak magnitude, its spectrum shows the lines of iron and other elements of similar mass such as cobalt. The debris emitting this light moves at a very high velocity away from the explosion site.

The highest velocities are about 10% of the speed of light.The type Ia supernovae behave as though a single variable determines all of their characteristics; the shape of the spectrum, the change in luminosity with time, and the velocity of the debris are all set by the total amount of energy released in the explosion. Most supernovae differ from the average peak visual absolute magnitude by less than 0.3 magnitudes. Low-luminosity supernovae are redder and shorter-lived, with debris moving at a lower velocity, than high-luminosity supernovae. A consequence of this behavior is that if one knows the spectrum of a type Ia supernova at the peak apparent magnitude, one can infer the peak absolute magnitude. This property permits astronomers to use the type Ia supernovae as a standard candle for deriving the distances to the farthest galaxies and for studying the expansion of the universe.

Strictly speaking, not all type Ia supernovae behave in the same way. About 85% of these supernovae behave according to the single-variable pattern just described. The remaining nonconforming type Ia supernovae can differ in a variety of ways, including being several magnitudes less luminous than the conforming 85%. They are believed to have a different origin than the conforming 85%. They may be produced by the thermonuclear explosion of white dwarfs under different conditions than the conforming supernovae, or they may be from massive stars undergoing core collapse.

BASIC BOMB THEORY

Theorists uniformly believe that the conforming 85% of type Ia supernovae are white-dwarf thermonuclear explosions. Most of the theoretical effort has been directed at the explosion of carbon-oxygen white dwarfs, although some theorists believe that the detonation of oxygen-neon-magnesium white dwarfs may be responsible for some other supernova subclass. The basic theory is that a white dwarf composed of carbon and oxygen releases most of its thermonuclear energy in a sudden burst. Thermonuclear burning in the outer parts of the star convert the carbon and oxygen into intermediate-mass elements, such as sulfur. The burning in the white-dwarf interior converts the carbon and oxygen into nickel, which is the lowest-energy atomic nucleus that can be rapidly created through fusion. This sudden release of energy heats the interior to energies far above the white dwarf's gravitational binding energy, so the star expands outward at a very high velocity, leaving nothing behind. As the stellar debris expands and dissipates, it is heated by the radioactive decay of nickel into cobalt and then iron.

The expanding photosphere drifts to deeper, hotter regions within the debris. This combination of increasing surface area and increasing temperature of the photosphere causes the debris to emit more power over time, causing the brightening that we see in a supernova. The lines we see in the spectrum of a type Ia supernova is the progression of thermonuclear products created in the supernova, starting with the intermediate elements created in the outer layers of the expanding debris, and ending with cobalt and iron. When the debris has expanded enough for light to escape from the center of the explosion, it cools, and the supernova fades from sight.All of these properties fit in nicely with the view that the type Ia supernova is the explosion of a degenerate dwarf star. Computer simulations show that the detonation of a white dwarf fits the rise and fall of the supernova's luminosity very nicely, and the elements generated in the detonation of a white dwarf matches the elements portrayed by the supernova's spectrum. For these reasons, astrophysicists working on this problem accept the theory that a degenerate dwarf creates the supernova. The only real disagreement is over the detonator for the explosion**.**

Astronomers see numerous supernovae every year, but these are usually in very distant galaxies. Supernovae are rare, occurring in any one galaxy once every fifty years or so. This means that to see large numbers of supernovae, one must search numerous galaxies every day, which means looking far out into space. On occasion, however, a supernova occurs in a nearby galaxy, providing astronomers with a close-up view of an exploding star.The most important of the nearby supernovae is a supernova seen in February of 1987, named SN 1987A. It occurred in the Large Magellanic Cloud, which is 50 kpc away from Earth, so it occurred only (!) 163,000 years ago. No other supernova observed since the start of the space age has occurred closer to Earth. SN 1987A was observed with ground-based and space-based instruments, as well as with neutrino detectors buried deep under the Earth. It occurred in a highly-visible region of the Southern Hemisphere sky, unobscured by dust. It's source was a star that had been studied before the supernova occurred, with the final observation of the star occurring just hours before the explosion. This supernova proved the theory that the core-collapse of a massive star produces a supernova, but it also showed that, contrary expectation, not all stars that explode in a supernova are red supergiants sometimes blue supergiants also explode.

The blue supergiant star Sk -69 202, which is a type B3 I star, created SN 1987A. Like all blue supergiants, it was extremely luminous, with an absolute visual magnitude of -6.3, but it was too faint to see with the unaided eye, having at 50 kpc distance an apparent visual magnitude of 12.2, which is at the limit of the largest portable telescopes. Because of its high luminosity, it was regularly observed, with the last observation occurring about 5 hours before a neutrino burst released by the supernova arrived at Earth. Three more observations were made in the following 6 hours. Subsequent observations, made less than 24 hours after the neutrino burst, finally alerted the astronomical community that a supernova had occurred. The blue supergiant brightening from 12th magnitude to 6th magnitude, a factor of 250 increase in power radiated as visible light, in the first-three hours after the neutrino burst. This brightening accounts for most of the brightening of the supernova. Once the supernova faded, and the supernova shell expanded sufficiently to become transparent, astronomers found that Sk -69 202 no longer exists.

SN 1987A is classified as an unusual type II supernova. It is type II because it has hydrogen lines in its spectrum. It is unusual because the doppler shift of those lines suggests an expansion of around one-tenth the speed of light (twice the expansion speed of a typical type II supernova) and because it is much less luminous than a typical type II supernova, although the total amount of energy released in the explosion is similar to that released in a typical type II supernova. SN 1987A is also unusual in brightening in only 3 hours, rather than over the several days that is more typical of type II supernovae. These unusual features are directly tied to the small radius of the exploding star.

The rapid brightening of the star directly reflects this small radius; more time is required for the energy released by the collapse of a star's core to travel to the photosphere of a red supergiant than to that of a blue supergiant, because the red supergiant is physically much larger than the blue supergiant. The remaining-two characteristicsthe high velocity and the low luminosityare set by the star's radius through the thermodynamics of a supernova.Like an internal combustion engine, a supernova explosion is a heat engine that converts heat into kinetic energy. Just as the motion of an engine's pistons convert the heat released when fuel is burned into the kinetic energy that propels a car, the expansion of a star during a supernova explosion converts the heat released by the collapse of the star's core into kinetic motion of the outer regions of the star, and as with an internal combustion engine, the efficiency of this conversion depends on the compression ratio of the system.

The higher the compression ratio in an internal combustion engine, meaning the higher the ratio of the final volume in a piston cylinder to the initial volume in the cylinder, the more efficient the conversion of heat into kinetic energy. For an exploding star, a high compression ratio is achieved by making the radius of the star that explodes as small as possible, because the point at which the supernova shell becomes transparent and releases its remaining heat is independent of the initial radius of the star. This means that the supernova of a blue supergiant converts much more of the supernova energy into kinetic energy than does the supernova of a red supergiant of equivalent mass; the former is a more efficient heat engine than the latter, because a blue supergiant has a much smaller radius than does a red supergiant. The consequence of this efficiency is that the velocity of the supernova shell is higher, and the temperature of the shell is lower, in a blue supergiant supernova than in a red supergiant supernova.

Fig. 2: Supernova Explosion

Explosion models

3D vs 1D Numerical calculations of thermonuclear supernova explosions in one dimension have become a commonplace benchmark for the analysis of Type Ia SNe, but their validity is questionable because the subsonic combustion fronts (deflagrations) that play a fundamental role in all of them are subject to instabilities, and therefore cannot be simulated with 1D codes in a self-consistent way. In recent times, the first three dimensional (3D) calculations of Type Ia explosions have begun to appear in the literature and the paper by Bravo & Garc´ia-Senz in these proceedings. A common feature of all these calculations, and the most remarkable difference between 1D and 3D models, is the uniform mixing of unburnt C and O material with 56Ni and other elements throughout the eject. This mixing should have an impact on the optical spectra of the supernovae and on the thermal X-ray spectra from the shocked eject in the SNRs, but neither of these signatures has been confirmed so far pointed out that no evidence for low-velocity C and O was found in optical spectra of Type Ia SNe, but this assertion is being revised. Spatially resolved spectroscopy of Type Ia SNRs also provides indirect evidence for some kind of composition stratification in the shocked eject. The absorbed UV spectrum of the Schweizer-Middleditch star, which is placed behind the remnant of SN1006, poses an alternative observational constraint for the presence of mixing in Type Ia SN eject. No evidence has been found for C or O absorption lines in HST observations of this star, implying that these elements, if present, would have to be in ionization states very different from those of the observed Si and Fe.

CONCLUSION

In the massive star case, the core of a massive star may undergo sudden collapse, releasing gravitational potential energy as a supernova. While some observed supernovae are more complex than these two simplified theories, the astrophysical mechanics have been established and accepted by most astronomers for some time. Supernovae can expel several solar masses of material at speeds up to several percent of the speed of light. This drives an expanding shock wave into the surrounding interstellar medium, sweeping up an expanding shell of gas and dust observed as a supernova remnant. Supernovae are a major source of elements in the interstellar medium from oxygen to rubidium. The expanding shock waves of supernovae can trigger the formation of new stars. Supernova remnants might be a major source of cosmic rays. Supernovae might produce gravitational waves, though thus far, gravitational waves have been detected only from the mergers of black holes and neutron stars.

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