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MMA SAG: Thermonuclear Supernovae

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☑ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☑ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☑ Multi-Messenger Astronomy and Astrophysics

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Abstract: A Type Ia supernova (SN Ia) is an extremely energetic thermonuclear explosion, the brightness of which approaches that of its host galaxy. This immense luminosity has made them important cosmological distance probes, leading to the discovery of the acceleration of the expansion of the Universe. SN Ia are also important sites of nucleosynthesis and chemical enrichment of galaxies. Despite their importance to the field of astronomy, it is remarkable that today there is still no consensus on what is the underlying progenitor of SN Ia. Simulations have done a tremendous job in understanding the progenitors and their evolution and connecting to observations. With new surveys and space missions, the multimessenger observations of SN Ia will paint a clearer picture of the origin and mechanism of these events.

1 Introduction

Type Ia supernovae (SN Ia) are unique among supernovae in that these events play a critical role in cosmological studies because their observational properties (e.g. the light curve) allow calibration of events for use as "standard candles," i.e. objects of known brightness that may be used as distance indicators (Phillips, 1993; Howell et al., 2009). Using thermonuclear supernovae in this capacity resulted in the discovery of the accelerating expansion of the Universe and thus the mysterious dark energy driving the acceleration (Riess et al., 1998; Perlmutter et al., 1999; Leibundgut, 2001).

Despite accepted use of these events as distance indicators, the setting and mechanism of the explosion is incompletely understood. The broad consensus is that SN Ia result from the thermonuclear explosion of approximately one solar mass of a mixture of carbon and oxygen under degenerate conditions. However, there is considerable uncertainty in the exact form of the progenitor system: a single white dwarf in the binary system or a system of two white dwarfs. For these systems, there are a variety of ways that the explosion can be initiated: a single massive white dwarf accreting to the Chandrasekhar mass, collisions or merges of white dwarfs, or the detonation of a helium in a white dwarf system, to name a few. The recent review by Maoz et al., 2014 discusses these different systems.

Unlike core-collapse supernovae, the pre-explosion system is faint, and we have no direct observations of a pre-SN Ia system. This means we must infer the nature of the progenitor system from the observables, including light curves, spectra, and polarization measurements, all as a function of time, or by studying supernovae remnants or presolar grains. Whatever the basic mechanism, in a typical brightness event, the thermonuclear energy release is enough to unbind the white dwarf, leaving no compact remnant behind. The nucleosynthesis during the explosion produces iron-group and intermediate mass elements. This tells us important information about the conditions where the burning took place; a stellar progenitor which is too dense overproduces iron-group elements without making the intermediate mass elements seen in the SNe Ia spectra.

The capability of modern computing allows the development of models with a vast amount of included physics, and thus unprecedented realism. Accordingly, simulation plays a central role in understanding the feasibility of the different proposed progenitor scenarios. As simulations have progressed in complexity over the last decade, observational campaigns have also dramatically become more advanced. These observations have increased both the number of SNe Ia observed in a year, and also the breadth of information from any single event, pushing across the electromagnetic spectrum, and also capturing the events earlier in time, closer to the explosion itself. Together these advances create a synthesis of observation and theory that allows study of the connections between progenitors and the observed light curves and spectra (Höflich et al., 2013; Hillebrandt et al., 2013). This combined approach allows study of the efficacy of proposed progenitor systems, and within a given progenitor system, it also enables the study of systematic effects on the brightness of an event due to age and composition (Jackson et al., 2010; Krueger et al., 2010; Bravo et al., 2011; Seitenzahl et al., 2011; Bravo et al., 2011; Krueger et al., 2012; Ohlmann et al., 2014; Miles et al., 2016; Leung & Nomoto, 2018).

Over the next decade, new surveys and instruments will further contribute to the breadth of observations. Computation will also continue to play a large role in testing different mechanisms and predicting multimessenger observables through detailed multiscale and multiphysics simulation. Both computational resources and sustained funding for code development, maintenance, and porting to novel architectures will be needed to continue the success that simulation has had in unveiling the mechanism behind SNe Ia. Additionally, a better theoretical understanding will increase the fidelity of studies using Type Ia supernovae as distance indicators. Good progress has been made with controlling systematic effects in surveys due to calibration (Conley et al., 2011), and astrophysical uncertainties, such as the intrinsic scatter of Type Ia supernova brightness, are becoming relatively important sources of uncertainty. Efforts at controlling astrophysical uncertainty are underway (e.g. Silverman et al., 2012), and a robust theoretical understand will further increase the precision of cosmological studies.

Below we discuss the connection of different multimessenger observables to SN Ia.

2 Light-Curves and Spectra from Infra-red to Ultraviolet

Transient observations are undergoing a revolution and the number of telescopes designed to discover and obtain detailed spectroscopic information about thermonuclear supernovae is expected to grow considerably over the next decade. For most type Ia supernovae, the light curves depend on only a few parameters: the ^{56}Ni mass, the total ejected mass, the distribution of the ^{56}Ni in the ejected mass, the initial white dwarf radius, the opacity, and the explosion energy. As the number of transient observatories increases, more and more thermonuclear supernovae are discovered at the early rise (e.g. Scolnic et al., 2018). Combined with UV observations from Swift (e.g. Pan et al., 2018), our understanding of the initial rise of the emission has increased dramatically, allowing astronomers to not only probe the nickel distribution but also the atomic physics (Arnett et al., 2017). The early-time light curve can also be used to probe shock interactions with a possible white dwarf companion expected in some channels (Hosseinzadeh et al., 2017). At later times, the shape and late-time decay of the light-curve probes the ^{56}Ni production. The spectral features in the supernovae are sensitive to the nature of the explosion mechanism and the progenitors behind thermonuclear supernovae and astronomers are actively comparing these spectra to increasingly detailed models of the supernova engine (van Rossum et al., 2016; Mazzali et al., 2018; Blondin et al., 2018). Current comparisons suggest a broad range of progenitors and explosion mechanisms may be at play, but, over the next decade, improved models coupled with a much more extensive set of data will allow astronomers to pinpoint the exact role each proposed progenitor plays in the population of thermonuclear supernovae.

3 Gamma-Rays

Thermonuclear supernovae are the dominant source of iron in the Galaxy, produced in the decay of the α-rich isotope ^{56}Ni. The gamma-rays emitted in the decay chain from ^{56}Ni through ^{56}Co to ^{56}Fe are an ideal probe of the burning in the supernova. Different engines predict different distributions of the ^{56}Ni and gamma-rays can probe this distribution. Gamma-ray detections of the nearby supernova SN2014J has demonstrated the power of gamma-ray observations to probe the distribution of ^{56}Ni and, ultimately, the explosive engine itself (Diehl et al., 2014, 2015; Churazov et al., 2015). Figure 1 shows three different light-curves for models with the same explosion energy and nickel mass, but with the nickel distributed slightly differently. The variation in the nickel can be probed by the gamma-ray measurements and these studies can then be used to understand the

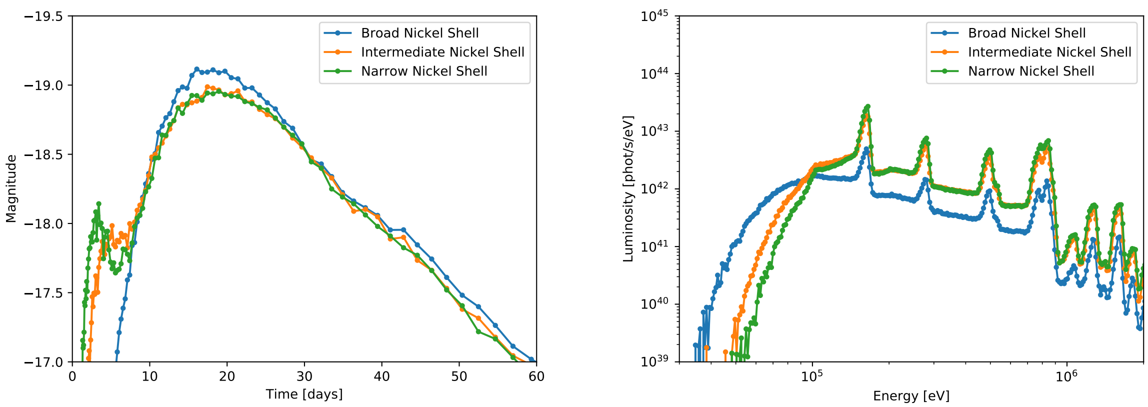

Figure 1: Bolometric light curve (left) and gamma-ray spectra (right) near peak gamma-ray emission for 3 different thermonuclear supernova models. In these models, the explosion energy and nickel production are the same, but the distribution of nickel is altered. Changes in the distribution can significantly alter the gamma-ray signal, ultimately affecting the peak brightness. To truly use thermonuclear supernovae as cosmological tools, we must understand the distribution of nickel production and how it might vary with redshift.

uncertainties in the light-curve observations. Next-generation telescopes will be able to increase the sample of gamma-ray observed thermonuclear supernova tenfold, providing unprecedented information on the mixing and clumpiness of ^{56}Ni production in thermonuclear supernovae.

4 Gravitational Waves and Neutrinos

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 (Kupfer, 2019).

5 Supernova Remnants as Probes of the chemical elements and explosion mechanism in thermonuclear SNe

The nature of SN Ia explosions is one of the most debated and important questions in astrophysics. These explosions are important for cosmology, for the chemical enrichment and evolution of galaxies, for being major contributors to cosmic iron, and for the acceleration of cosmic rays up to the knee of the cosmic ray spectrum. While SN Ia are believed to result from the thermonuclear disruption of a white dwarf (WD) in a binary system, the progenitor and explosion mechanism are still debated; namely are they single degenerate (SD) or double degenerate (DD) explosions? In the SD scenario, the WD accretes matter from a non-degenerate companion until its mass becomes comparable to the Chandrasekhar mass (M_{ch}); while in the DD scenario, the explosion results from the merger of two sub-Chandrasekhar mass (sub-M_{ch}) WDs. Furthermore, it has been recently suggested that near-M_{ch} systems may be the primary nucleosynthesis sites of ^{48}Ca and other neutron-rich isotopes (Seitenzahl & Townsley, 2017; Jones et al., 2019).

Observations of Supernova Remnants (SNRs), the diffuse remnants of these explosions, provide nearby laboratories to directly probe the heavy elements synthesized in Ia explosions, as well as address the mechanism of the explosion. Imaging and spectroscopy allow measurements of proper motions, Doppler shifts, emission line diagnostics and ejecta distribution (Fesen et al., 2017; Williams et al., 2017). Optical and UV observations provide crucial insights into the SN type, physics of shocks as well as the physics of the SN explosions, their progenitors, and evolution (Blair & Raymond, 2017).

X-ray spectroscopy is a particularly a powerful tool that probes the Fe-peak elements which can then be compared to nucleosynthesis model yields (Seitenzahl et al., 2013). Furthermore, the Mn-to-Cr mass ratio in Type Ia explosion models correlates with the initial metallicity of the white dwarf's progenitor (Badenes et al., 2008). The detection of Cr, Mn and Ni in the X-ray band has emerged recently as a powerful tool to directly probe the WD mass (M_{ch} vs sub-M_{ch}); production of substantial Mn and Ni requires neutronized material which necessitates an exploding near-M_{ch} WD (Yamaguchi et al., 2017). Studies of one remnant, SNR 3C 397, have demonstrated that the complex and uncertain physics of nuclear ignition and detonation, as well as the structure of the progenitor white dwarf, may be meaningfully constrained through observations and modeling (Dave et al., 2017). Lastly, X-ray and gamma-ray emission from radioactive species probe the youngest SNRs and the mechanism for the explosion. ^{44}Ti decay produces nuclear gamma-ray lines at 67.9, 78.4 and 1157 keV, its decay through electron-capture to ^{44}Sc produces the ^{44}Sc line at 4.1 keV, and the distribution of these elements sheds light on the asymmetry in the explosion which has been suggested as the origin of the spectral evolution diversity in Ia explosions (Maeda et al., 2010).

Making further advances in this area requires multi-wavelength spectroscopy from the optical to the gamma-ray band (particularly high-resolution X-ray spectroscopy) as well as improved modelling and numerical 3D simulations taking into account the metallicity dependence, asymmetries, instabilities and different regimes of burning, and connecting to observations via radiation transfer. Furthermore, high-imaging resolution is needed to map the distribution of ejecta across the SNR and infer the reverse shock structure to tie to the SN models.

6 Stardust

In addition to observational constraints, presolar stardust grains have proven to be invaluable samples for constraining their parent star's astrophysical history (see, e.g., Nittler & Ciesla, 2016). Recently, the first presolar grains from thermonuclear supernovae were discovered by Nittler et al. (2018). In addition to gamma-rays and supernova remnants, the analyses of such stardust grains for their isotopic composition yield information on the nucleosynthesis yields and mixing processes that led to the formation of these dust grains. New instruments to measure the isotopic composition of these stardust grains (e.g., Stephan et al., 2016) recently started allowing us to simultaneously measure trace-elemental isotopic abundances of multiple elements in individual, μm-sized grains (Stephan et al., 2018; Trappitsch et al., 2018).

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