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A century of supernovae

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Supernovae were first recognized a hundred years ago, and despite much progress in understanding these catastrophic cosmic explosions, several fundamental properties remain to be determined. A deluge of high-cadence observations from new facilities and the availability of fast computers will accelerate the field into the next century.

In 1925, Swedish astronomer Knud Lundmark, using Edwin Hubble's recently calculated distance to Andromeda, determined that the 1885 'nova' S Andromedae had reached a peak absolute magnitude of −16. "One may hesitate to accept such a luminosity", he wrote (K. Lundmark *Mon. Not. R. Astron. Soc.* **85**, 865–894; 1925), knowing that a standard nova would have a peak absolute magnitude of −9 or so. He recalled also, "an analogous case in the famous Nova B Cassiopeiae of 1572", now known as Tycho's supernova (after Tycho Brahe), and with these two cases suggested a distinct class of much more energetic novae. Last month, a conference near Stockholm Observatory was convened to commemorate Knud Lundmark's realization, and the hundred years of supernova science that have ensued.

Lundmark did not coin the term 'supernova' (SN), which instead became popular following a paper almost a decade later, where Walter Baade and Fritz Zwicky linked the energetics of these objects to the creation of neutron stars. This association was remarkable given that the neutron had only been discovered two years earlier. Ironically, the SNe studied by Zwicky and Baade at the time were thermonuclear (so-called type Ia), which do not leave behind a neutron star remnant. Lundmark made another important contribution to the field in 1939, when he proposed that SNe originate from two different sources: massive stars and white dwarfs (WDs).

Initially, SNe were not classified by their progenitors, but by their spectral appearance at optical wavelengths. In 1941, Rudolph Minkowski suggested 'type I SNe' for those without strong hydrogen features in their spectra, and 'type II SNe' for those with. This simple classification became progressively modified with the increase in SN diversity brought about by observations and time, creating subclasses linked to specific spectral lines (such as the type Ib SNe that lack hydrogen but exhibit helium absorption features). It also has become clear that the appearance of SNe changes over time, both in luminosity and spectral features, complicating any classification solely based on spectra. Thus, there have been attempts from the community to propose alternatives more centred around the physical nature of the SN progenitor rather than their appearance (for example, A. Gal-Yam in *Handbook of Supernovae* (eds Alsabti, A. W. & Murdin, P.) 195–197; Springer, 2017).

The physical nature of SN progenitors, however, is also still up for debate. Take type Ia SNe as an example: they are thought to arise from the thermonuclear explosion of a carbon–oxygen WD in a binary system, but does that system contain just one WD, or are there two involved? The single WD case (called the 'single degenerate' scenario) now seems disfavoured by the community because it does not match the observations, at least for the majority of SNe Ia. However, the alternative 'double degenerate' scenario also has complications: the classical merger picture, which produces a super-Chandrasekhar-mass WD that collapses, has been shown in simulations not to work. Two close WDs can engage in mass transfer, leading to the explosion of one of them and the ejection at high velocity of the other, but while there is observational support for this explosion mechanism, observational searches for the high-velocity WDs find surprisingly few. The latest thinking for the origin of the majority of type Ia SNe involves the initial explosion triggering a similar explosion in the second WD. Observational confirmation of this scenario is needed.

Core-collapse SNe have similar progenitor-related uncertainties. There is, for example, a debate about whether an apparent lack of the most massive red supergiant stars is a physical diagnostic of their end-of-life fate (explosion as type II-P SNe or collapse to a black hole) or simply due to systematics. Recent research by Eva Laplace and colleagues (V. A. Bronner et al. *Astron. Astrophys.* (in the press); preprint at https://arxiv.org/abs/2508.11077) has highlighted the need to consider even the pulsational phase of such massive stars prior to explosion, since simulations of red supergiants in a compressed state produce type II-P SNe, while explosions of the same star in an expanded state generate type II-L-like SNe!

Perhaps the most prominent implication of unresolved issues in SN studies lies in the use of type Ia SNe as markers on the local distance ladder. Type Ia SNe are 'standardizable candles', in that they have an intrinsic peak luminosity that can be calibrated and used to measure distances. This makes them suitable for quantifying the Hubble constant, H_0. However, they join a set of local-Universe probes which yield a significantly higher value for H_0 relative to that constrained by the Cosmic Microwave Background and other early-Universe phenomena. Though it is not yet clear if this is driven by unaccounted-for systematic measurement errors — or, on the other hand, new physics — it is likely that a better understanding of observational factors (such as the extinction parameter, R_V) and distance calibrations for SNe could help clarify where solutions to the Hubble tension might best be sought.

While 100 years of SN studies have accumulated and the topic is now clearly mature, there are still many unknowns and unresolved questions in the field that will keep astronomers occupied for some time to come. Nowadays, more than 17,500 SNe have been catalogued, with the majority coming from observations of the Zwicky Transient Facility, and several million are expected to be delivered over the course of the Legacy Survey of Space and Time. Combined with the neighbouring Dark Energy Camera, images of SN progenitors will be captured at a daily cadence, and SNe will be routinely caught minutes and hours after explosion, revealing the intricacies of the detonations and deflagrations. The future looks bright for our understanding of supernovae.

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