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Published in:
Astronomy & Geophysics

Document Version:
Publisher's PDF, also known as Version of record

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How to blow up a massive star

Bernhard Müller and Stephen Smartt explain how simulations combined with astronomical observations are shaping a more coherent picture of the explosions of massive stars.

Supernovae have a peculiar place in the history of astronomy. They are the only transient phenomena in the sky outside the solar system with a documented history of observations by the naked eye for almost two millennia: prominent examples include the supernova of 1054 that made the Crab Nebula, and those of 1572 and 1604 – now named after Tycho Brahe and Johannes Kepler – which shook the medieval belief in an immutable celestial sphere. Yet it was not until the 20th century that we began to grasp their true nature and realized – starting with the work of Baade & Zwicky (1934b) – that they are violent stellar explosions. The energy budget of supernovae is impressive indeed: they can outshine their host galaxy for weeks and the ejected material reaches several 1000 km s\(^{-1}\), implying an explosion energy of \(\sim 10^{51}\) erg. In view of this enormous energy, Baade & Zwicky (1934a) suggested that some supernovae are associated with gravitational collapse of a massive star to a neutron star – only two years after the discovery of the neutron and more than 30 years before the first neutron star was observed.

As stellar evolution and nuclear astrophysics matured, the details of Baade and Zwicky’s far-sighted idea – what we now call “core-collapse supernovae” – were worked out. They occur in stars that begin their lives with a mass of more than 8 M\(_\odot\) (solar masses). In this mass range, stars can ignite advanced burning stages (carbon, neon, oxygen and silicon burning) after processing hydrogen and then helium in their cores. Eventually, these stars form an onion shell structure with a core composed of...
of iron group nuclei – the ashes of silicon burning – and various outer shells consisting of lighter elements. The iron core is supported against gravity mainly by the pressure of degenerate relativistic electrons, which implies an upper mass limit: the Chandrasekhar mass. As the core grows towards this limit by shell burning, it contracts. Eventually, a new process becomes possible, electron capture burning, it contracts. Eventually, a new core grows towards this limit by shell limit: the Chandrasekhar mass. As the core burns – and various outer shells contract, the ashes of silicon form into a white neutron star.

The most popular idea for shock revival dates back – in a very crude form – to Colgate & White (1966), and is illustrated in its modern guise in figure 2. The gravitational binding energy released during collapse is initially stored as thermal energy in the hot proto-neutron star, whose surface temperature is about 5 × 10^{10} K. The thermal energy is then radiated away over timescales of seconds in the form of neutrinos. If a sufficient fraction of the neutrinos are reabsorbed behind the shock, the concomitant increase of thermal energy and pressure may be enough to drive the shock outward. To verify that this idea works in Nature, we need to model the emission, absorption, scattering and propagation of neutrinos in the core of the supernova using numerical simulations. Because the neutrinos fall out of thermal equilibrium with the stellar matter in the proto-neutron star surface, this is a problem in kinetic theory. Even if we assume the collapse and explosion as perfectly spherical, we are still left with a two-dimensional problem in phase space (radius, neutrino energy and one direction angle). Moreover, there are further technical complications, for example one needs to model the transport of neutrinos in curved spacetime because of the strong gravity of the proto-neutron star.

It therefore took several decades after the original idea of Colgate & White (1966) and the birth of general relativistic kinetic theory (Lindquist 1966) for spherically symmetric (1D) simulations to become sufficiently accurate to model the hydrodynamics and neutrino transport in the core of a supernova. Modern 1D simulations solve the Boltzmann equation for neutrinos and have now convincingly established that the “neutrino-driven mechanism” does not work under the assumption of spherical symmetry (Liebendoerfer et al. 2001, Rampp & Janka 2000) for most massive stars. Only the lightest supernova progenitors form an exception. For stars with initial mass 8–10 M☉, the density declines so rapidly outside the iron core that the pre-shock ram pressure of the infalling shells plummets very quickly and allows neutrino heating to drive a low-energy explosion of ~10^{50} erg (Kitaura et al. 2006). There are several direct detections of the progenitor stars of low-energy supernovae and they are consistent with being red supergiants in the 8–12 M⊙ mass range, such as those for SN 2005cs, SN 2009md and SN 2008bk (Fraser et al. 2011, Maund et al. 2005, 2014).

Simulating the mechanism

Tapping the gravitational energy directly after collapse might appear to be the simplest solution. Once the inner part of the iron core of the progenitor reaches then overshoots nuclear density, it becomes highly incompressible and “rebounds” almost elastically, launching a shock wave into the surrounding shells. But this “bounce” does not deliver enough energy to eject the envelope. Instead, the shock quickly “stalls” as it uses up about 1.7 × 10^{51} erg per 0.1 M⊙, as it propagates through the infalling shells. Hydrodynamic simulations show that the shock winds up hovering some 100–200 km above the newly formed “proto-neutron star”, kept in place by the ram pressure of the infalling outer shells. For the star to explode, there must be some mechanism for depositing energy to “revive” the shock front and power the flow of matter out of the gravitational potential well of the proto-neutron star. The most popular idea for shock revival is the “neutrino-driven mechanism” as it does not work under the assumption of spherical symmetry. Graceful acceleration by the ram pressure of the infalling shells plummets very quickly and allows neutrino heating to drive a low-energy explosion of ~10^{50} erg (Kitaura et al. 2006). There are several direct detections of the progenitor stars of low-energy supernovae and they are consistent with being red supergiants in the 8–12 M⊙ mass range, such as those for SN 2005cs, SN 2009md and SN 2008bk (Fraser et al. 2011, Maund et al. 2005, 2014).

Multidimensional models

The solution for the supernova explosion problem for more massive stars lies in breaking spherical symmetry. As was pointed out by several authors in the 1990s (e.g. Herant et al. 1992, Burrows et al. 1995), multidimensional effects facilitate neutrino-powered explosions in various ways. Convective overturn, driven by strong neutrino heating close to the proto-neutron star, transports hot material outwards.
The life cycle of a massive star ends with a supernova explosion, which releases a vast amount of energy and material into the interstellar medium. While the process is well understood in principle, numerical simulations have played a crucial role in advancing our understanding of the details of supernova explosions.

One of the key challenges in simulating supernovae is the transition from two-dimensional (2D) to three-dimensional (3D) models. Early 2D simulations showed that certain phenomena were not captured accurately in 2D, leading to a lack of confidence in the results. This prompted a move to 3D simulations, which offered a more realistic representation of the multidimensional flows and shock dynamics.

However, 3D simulations posed new challenges, such as increased computational resources required and the potential for a different outcome due to the altered geometry. An example of this is the silicon-rich plume observed in the 3D simulations, which was not seen in 2D models. This led to the question of whether 3D simulations were more accurate and whether they could better predict the behavior of supernovae.

To address these issues, researchers have employed perturbation-aided methods, which involve adding small disturbances to the initial conditions to drive the shock revival. This approach has been successful in some cases, but not all, highlighting the need for further refinement.

The efficiency of shock revival in 3D simulations is influenced by factors such as neutrino heating, which can help propell shock waves and drive the explosion. However, the presence of neutrino-heated matter can also reduce the likelihood of explosion.

Overall, the transition to 3D simulations has been a significant step forward in our understanding of supernova explosions. Further refinements and improvements are needed to ensure that these simulations can accurately predict the behavior of supernovae across a range of progenitor masses and conditions.
course, be unthinkable without modern methods for neutrino transport, which build on decades of code development.

Predicting explosion properties by means of multidimensional simulations remains a bigger challenge. The reason for this is that the neutrino-driven engine can operate for a second or more, as long as accretion downflows funnel fresh matter onto the proto-neutron star surface; this keeps the neutrino luminosity and hence the mass outflow rate in neutrino-heated bubbles high. Few simulations can be extended to well above a second after core bounce, and therefore the final explosion energies and the amount and composition of the ejecta remain uncertain. 3D simulation can make firm predictions only for progenitors at the low-mass end, where Melson et al. (2015b) predict an explosion energy of $\sim10^{50}$ erg for a 9.6 M$_\odot$ progenitor. Self-consistent 2D simulations can be taken well beyond the first second (Müller 2015, Bruenn et al. 2016) and are cheap enough to scan a wide range of progenitor models (Nakamura 2015), but cannot be trusted to predict the energetics of the explosion correctly (Müller 2015).

**The explosion landscape**

We are therefore relegated to following other approaches to obtain predictions that can actually be confronted with observations of the explosions themselves, of their progenitors and their compact and gaseous remnants.

To this end, various authors have developed more phenomenological models for predicting supernova explosion properties. Early works from around 2000 (e.g. Fryer & Kalogera 2001, Heger et al. 2003) that studied the “explodability” of supernova progenitors as a function of their initial mass were based on a simple comparison of the binding energy of the envelope and the explosion energy provided by the neutrino-driven engine, which could not be reliably predicted at that time.

In recent years, several groups have developed better phenomenological supernova models that take the physics of the neutrino-driven mechanism into account, in a simplified form. Various authors have used 1D simulations with artificially enhanced neutrino heating to study the “explodability” of supernova progenitors (O’Connor & Ott 2011, Ugliano et al. 2012, Ertl et al. 2016, Perego et al. 2015). These studies have estimated the compact remnant mass function and potential observables that can be inferred from light curves and spectra, such as the explosion energy and the amount of $^{56}$Ni.

The radioactive isotope $^{56}$Ni is one of the most important isotopes in astrophysics and is key to understanding supernovae and nucleosynthesis. As the shock from core-collapse shoots through the inner silicon and oxygen layers of the progenitor star, high entropy causes the quasi-equilibrium and burning of the alpha-rich gas predominantly to $^{56}$Ni. The decay of this to stable $^{56}$Fe (via $^{56}$Co) powers Type I supernovae and the later phases of Type II supernovae. The mass of $^{56}$Ni produced is a direct probe of the explosion just seconds after core collapse and this mass can be measured from the luminosity of supernovae at different stages.

The most advanced and comprehensive study of a population of supernova progenitor and explosion models is that of Sukhbold et al. (2016). These authors tuned their model for the neutrino-driven engine to fit the explosion properties of SN 1987A (figure 1), which had an explosion energy of $\sim1.3 \times 10^{50}$ erg and produced 0.07 M$_\odot$ of $^{56}$Ni, and those of the Crab supernova SN 1054 at the low-mass end with an explosion energy $\sim10^{50}$ erg. Based on the results of their 1D simulations, they also compute supernova light curves and study the detailed population-integrated nucleosynthesis from progenitors in the range 9–120 M$_\odot$.

Other studies have opted for an analytic framework to study the systematics of neutrino-driven explosions (Fryer et al. 2012, Müller et al. 2016a and, to some extent, Pejcha & Thompson 2015). Such analytic approaches need to simplify the physics of the neutrino-driven mechanism even more than calibrated 1D simulations, but have two important advantages. First, exploring parameter variations to test the robustness of the predictions is cheap. Secondly, analytic models can approximately account for effects that are missing in 1D simulations, such as convective overturn. Guided by 3D simulations, Müller et al. (2016a), for example, use semi-empirical scaling laws for the neutrino emission and mass outflow rate in neutrino-heated bubbles (compare to figure 3) to estimate how the explosion energy grows due to a cycle of accretion and mass ejection over timescales of seconds, something which is beyond 1D models by construction.

Reassuringly, the different phenomenological approaches to the supernova explosion model complement each other well. There is broad qualitative agreement about trends in the explodability of supernova progenitors of solar metallicity. Despite variations in detail, recent theoretical studies typically predict a rugged landscape of interlaced islands of black hole and neutron star formation (figure 4). Massive stars are expected to blow up quite robustly, up to an initial mass of about 15 M$_\odot$. The fate of stars in the region 15–20 M$_\odot$ is highly uncertain; between 20 M$_\odot$ and 23 M$_\odot$, and above 28 M$_\odot$, explosions are particularly hard to achieve. Around 24 M$_\odot$ and 26 M$_\odot$, theory predicts “islands of explodability”. Core-collapse supernova explosions may be possible for very massive progenitors that suffer from extreme mass loss during and after the main sequence.

The origin of this pattern of explodability has been traced to the core structure of supernova progenitors; quantitative measures for the explodability of massive stars have been proposed, such as the “compactness parameter” of O’Connor & Ott (2011) and the two-parameter explosion criterion of Ertl et al. (2016). Qualitatively, the following structural features appear to determine the explodability:

- The onset of the explosion probably occurs when the oxygen burning shell is accreted. This shell interface is typically associated with a drop in density, so that the ram pressure onto the shock drops as the interface falls through the shock.
- If the oxygen shell is dense, the accretion does not drop significantly upon infall, and an explosion is less likely.
- The mass of the silicon core plays an ambiguous role. On the one hand, a proto-neutron star from a massive silicon core leads to higher neutrino luminosities and mean energies and more heating. On the other hand, a massive silicon core typically comes with a denser oxygen shell around it, which tends to decrease explodability.
- No explosions are expected if the silicon core mass approaches the (unknown) maximum neutron star mass.

Predicting explosion properties—and not only “explodability”—is more challenging because such predictions depend more sensitively on how the neutrino-driven engine is approximated in a 1D simulation or an analytic framework. Explosion energies of the order of 10$^{50}$ erg can be obtained through phenomenological models (Ugliano et al. 2012, Pejcha & Thompson 2015, Ertl et al. 2016, Sukhbold et al. 2016, Perego et al. 2015), but is the good match with observed explosion energies merely a result of the explicit or implicit calibration of model parameters? For example, Ertl et al. (2016) and Sukhbold et al. (2016) tune their model such as to reproduce the explosion energy of the SN 1987A and the Crab supernova with progenitors of 15–20 M$_\odot$ and 9.6 M$_\odot$, respectively. Will self-consistent multidimensional supernova explosion models also reach these energies once we can extend them to sufficiently late times?

The approach of Müller et al. (2016a) sheds some light on this, because it seeks to extrapolate the findings from
multidimensional simulations to predict explosion properties, instead of using observed supernovae as calibration points. This is accomplished by incorporating empirical scaling laws obtained from 3D simulations for the mass outflow rate of neutrino-heated matter and the growth of the explosion energy. Although this approach still has to deal with uncertainties in various parameters, it suggests that a reasonable distribution of explosion energies can be obtained with parameters that are roughly compatible with current 3D simulations.

For their standard set of parameters, Müller et al. (2016a) obtain a distribution of explosion energies peaking around $5 \times 10^{50}$ erg with a tail reaching up to $2 \times 10^{51}$ erg, and masses of radioactive $^{56}$Ni of a few $0.01 M_\odot$. Kasen & Woosley (2009) report that the typical observed value for explosions of Type II supernovae is around $9 \times 10^{50}$ erg. However, that is based on an observed magnitude limited sample (effectively the bright supernovae) and is not a complete, volume-limited sample. Hence a careful observational estimate of the true distribution of explosion energies is now required for a quantitative comparison. In line with long-time 2D simulations (Nakamura et al. 2015, Bruenn et al. 2016), they also find a weak trend for more massive progenitors to explode more energetically, which appears to be compatible with observations (Poznanski 2013).

The quantitative accuracy of phenomological predictions is, of course, somewhat limited. By exploring parameter variations, Pejcha & Prieto (2015) and Müller et al. (2016a) showed that there is considerable leeway in shifting the limit for the “explodability” of supernova progenitors without sacrificing decent overall agreement with observations in the typical explosion energy. By the same token, the explosion energy and the mass of radioactive $^{56}$Ni can easily be shifted up or down by a factor of two by tweaking parameters within reasonable bounds. What proves robust, however, is the general shape of the landscape of explosion properties and the location (as opposed to the width) of the islands of neutron star and black hole formation.

Taken together, the various phenomenological approaches nonetheless suggest that the neutrino-driven mechanism may indeed be able to explain adequately the explosion properties of most core-collapse supernovae. This does not imply, of course, that the systematics of core-collapse supernova explosion properties are yet fully understood. The phenomenological approach is a shortcut through uncharted territory, and a range of 3D long-time simulations with detailed neutrino transport will be needed to back it up eventually.

4 Fraction of massive stars exploding as supernova in bins of $0.25 M_\odot$ as predicted by the analytic supernova model of Müller et al. 2016a. A sizable fraction of massive stars is expected to form black holes already at moderate masses (at $15–16 M_\odot$ and $18–19 M_\odot$), while there are also two islands of explosability at $23–25 M_\odot$ and $26–27 M_\odot$.

Even then, much of the input physics in supernova simulations – from the neutron star equation of state to the precise core structure of the progenitors – will remain subject to uncertainties that can only be eliminated by confronting the theoretical predictions with observations.

Observing supernovae and progenitors

The direct ways of testing the explosion models are to determine the mass ejected and energy of the explosion together with the amount of $^{56}$Ni produced. The mass of the isotopes synthesized during hydrostatic burning during the last stages of stellar evolution (such as $^{56}$O, $^{26}$Ne, $^{24}$Mg) are also key tests (Jerkstrand et al. 2012). Determining ejecta masses and explosion energies require hydrodynamic models of the explosion and radiative transfer calculations to compare with supernova light curves and spectra. This, of course, introduces another model dependency on the results and depends on a reliable physical description of the hydrodynamic explosion (Pumo & Zampieri 2011).

An even more fundamental test is to compare the explosion properties with progenitor star detections. For more than a decade, teams have been searching for direct detections of progenitor stars for the closest supernovae in the local universe (those closer than about 20 Mpc), with results summarized in Smartt (2009, 2015). The progenitors of Type II supernovae (the most common subtypes are called II-plateau) have been confirmed to be red supergiants. The Type IIn supernovae show evidence of lower hydrogen and greater helium content in their ejecta and these have been confirmed to be yellow supergiants within binary systems (Van Dyk et al. 2011). Only one progenitor from a stripped envelope Ibc has been found, which is likely to be the explosion of a He star in a binary system. There are now about 20 detections of progenitor stars of core-collapse supernovae and around 30 upper limits within a volume-limited sample.

Perhaps the most interesting result is that the stellar masses inferred from the luminosities (based on stellar evolution models) do not follow the expected initial mass function from $8 M_\odot$ up to $50–100 M_\odot$. It’s remarkable that there is a complete deficit of progenitors with luminosities greater than $\log L/L_\odot \approx 5.1$ dex, which would correspond to an initial mass of $M < 18 M_\odot$. This lack of massive progenitors was first pointed out by Kuchanek et al. (2008) and Smartt et al. (2009) and has grown in statistical significance since. With the sample of 50 progenitor sites of nearby core-collapse, the initial mass function would imply that we should have 13 high-mass progenitors above the luminosity limit of $\log L/L_\odot \approx 5.1$ dex, but we have found none – or possibly one. The one case is SN2009ip, the nature of which is still debated (Mauerhan et al. 2013, Pastorello et al. 2013).

While there are arguments that the high-mass progenitors may be giving Type Ibc supernovae and are not detected because they are hot and faint Wolf–Rayet stars, this appears unlikely (Eldridge et al. 2013). The observational constraints are in good qualitative agreement with the theoretical results of islands of explosibility. Figure 5 shows a plot of the cumulative frequency distribution (CDF) of the progenitor masses and mass limits to date from Smartt (2015) and supplemented with more recent measurements of ASASSN-16dq (Kochanek et al. 2016) and SN2016kgg (Tartaglia et al. 2016). These include all Type II, Ibc and Ib detections and upper limits, representing an extension of the volume- and time-limited sample compiled by Smartt (2015), with references therein. The CFD for the successfully exploded models of Müller et al.
(2016a) is plotted for comparison and shows good agreement between the theory and data. The differences between the curves between about 12 and 14 M⊙ are probably not significant given the uncertainty in the mass estimates of each progenitor detection of at least 2–4 M⊙. (Smartt 2015, Smartt et al. 2009). In addition, many of the data points in this mass range (8 out of 20) are upper limits and hence a simple Kolmogorov–Smirnov (KS) test would not be quantitatively reflective. Smartt (2015) used the maximum likelihood approach to circumvent these two problems of the KS test, finding that a Salpeter IMF with minimum and maximum masses of \( m_{\text{min}} = 9.5 \pm 0.9 \) and \( m_{\text{max}} = 16.5 \pm 2.5 \) described the data well.

Hence the major difference between the data and explosion models is the prediction of the high mass explodability islands in the region 23–27 M⊙. It seems that some Type Ibc supernovae could come from progenitors both in lower mass binaries (Eldridge et al. 2015) and in this higher mass range (Anderson et al. 2012) and that their progenitors have evaded discovery to date because of the low numbers and relative faintness of Wolf–Rayet star progenitors.

### The most energetic explosions

Theory and observations are thus on the way to converging on the question of which massive stars explode in the local universe. But the fact that our understanding of core-collapse supernova explosions is far from complete is clear when we consider the diversity of observed explosion properties. The observed explosion energies, for example, vary by two orders of magnitude from about \( 10^{50} \) erg for low-energy events to \( 2 \times 10^{52} \) erg. The most energetic explosions span a range of types, from the “hypernova” explosions associated with gamma-ray bursts (Iwamoto et al. 1998) to supernovae—like so-called pair-instability supernovae—65–100 in energy. The standard paradigm of neutrino-driven explosions seems unable to explain the upper end of the supernova energy distribution because neutrino heating is a rather inefficient mechanism for tapping the neutron star binding energy of \( \sim 10^{53} \) erg. Less than 10% of the emitted neutrino energy is reabsorbed in the heating region, and a large fraction of the energy input is spent merely to lift the ejecta out of the gravitational well of the neutron star. Phenomenological models of the neutrino-driven mechanism suggest that this leads to an upper limit of about \( 2 \times 10^{53} \) erg for neutrino-driven explosions.

The most energetic core-collapse supernovae therefore require a different mechanism that operates only in a small subset of massive stars. The most likely contender is some kind of magnetorotational mechanism that taps the rotational energy of a rapidly rotating neutron star or, alternatively, a massive accretion disc around a nascent black hole (Kasen & Bildsten 2010, Woosley 2010, Dexter & Kasen 2013, Akiyama et al. 2003). While the available energy reservoir (a few \( 10^{52} \) erg) is smaller than the binding energy of a neutron star that feeds the neutrino emission, sufficiently strong magnetic fields may be able to transfer it efficiently to the ejecta. Magnetohydrodynamic effects also provide a plausible explanation for collimated jet outflows in the gamma-ray bursts (Woosley & Bloom 2016) associated with some hypernovae.

Especially from the viewpoint of supernova and stellar evolution theory, this scenario remains subject to many more imponderables than the vast majority of “ordinary” core-collapse supernovae. Other scenarios for extremely powerful explosions—like so-called pair-instability supernovae—are well-rooted in theory, but prove more elusive for observers. Nonetheless, our emerging picture of the connection between supernovae and their progenitors remains incomplete without them.

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**ACKNOWLEDGMENTS**

SJR acknowledges funding from the (FP7/2007–2013) European Research Council Grant agreement no. 241822 and Science and Technology Facilities Council (grants ST/G508131/1 and ST/I000709/1). Figure 3 is based on work supported by the STFC DiRAC HPC Facility (DiRAC Data Centric system, ICC Durham), the National Computational Infrastructure (Australia) and the Pawsey Supercomputing Centre (University of Western Australia).

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