Supernova explosions in the Universe

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During the lifetime of our Milky Way galaxy, there have been something like 100 million supernova explosions, which have enriched the Galaxy with the oxygen we breathe, the iron in our cars, the calcium in our bones and the silicon in the rocks beneath our feet. These exploding stars also influence the birth of new stars and are the source of the energetic cosmic rays that irradiate us on the Earth. The prodigious amount of energy ($\sim 10^{51}$, or $\sim 2.5 \times 10^{28}$ megatonnes of TNT equivalent) and momentum associated with each supernova may even have helped to shape galaxies as they formed in the early Universe. Supernovae are now being used to measure the geometry of the Universe, and have recently been implicated in the decades-old mystery of the origin of the γ-ray bursts. Together with major conceptual advances in our theoretical understanding of supernovae, these developments have made supernovae the centre of attention in astrophysics.

Supernovae are crucial to the dynamical and morphological development of the Universe. They are also at the nexus of many of the great debates now raging among astronomers. One subtype of supernovae, the so-called type Ias, is now arguably astronomy's most accurate probe of the scale and geometry of the Universe. An unknown fraction of another subtype, the core-collapse supernovae, may be the source of γ-ray bursts. As major sources of the elements of existence, supernovae themselves are primary agents of stellar and galactic evolution. Supernovae and γ-ray bursts share the distinction of being the most powerful explosions in the cosmos, and recent observational and theoretical breakthroughs and a renewed appreciation of the manifold roles of supernovae have inaugurated a new era in their study. Here I attempt to summarize, from one theorist's perspective, these new developments. In particular, I survey the context of supernova theory, then delve into the physics of core-collapse supernova explosions, continue by summarizing the emerging connection between supernovae and γ-ray bursts, and finally highlight the role of type Ia supernovae as 'standard candles' with which to measure the geometry and dynamics of the Universe. A clear and inescapable subtext of this review is the centrality of supernovae and their aftermaths to the fundamental questions of astrophysics and cosmology.

About supernovae

It is by its death that the purpose of a massive star is most clearly revealed. All stars are born, have thermonuclear lives, and die, leaving behind tiny fossils. For most stars, including our Sun, these fossils are or will be carbon/oxygen white dwarfs with radii near that of the Earth, masses near 0.5–1.0 solar masses ($M_\odot$), and central densities $\sim 10^7$ times that of tungsten. Low-mass stars die and white dwarfs are born slowly over hundreds to thousands of years through the ejection of the dying star's heavy outer mantle. There is no explosion. The dense white-dwarf residue, if in isolation, then cools into obscurity.

In contrast, a star more massive than $\sim 8 M_\odot$ does not go with a whimper. Without the quietus of gentle mantle ejection, the white dwarf that such a star creates in its core during its last thermonuclear stages continues to evolve in composition and grow in mass and density until it achieves the so-called "Chandrasekhar" mass near $1.4 M_\odot$ (refs 1,2). At this mass, an iron or oxygen–neon–magnesium white dwarf, normally supported against gravity by electron degeneracy pressure, becomes sufficiently unstable to collapse. Owing to the Pauli exclusion principle, at the high densities achieved by massive white dwarfs, their electrons are relativistic. Unlike a non-relativistic gas, a relativistic gas has a soft equation of state and is easily compressed by the ineluctable forces of persistent gravity. Within one second, the core of a star that may have lived for ten million years, cooking its hydrogen into progressively heavier elements, implodes from something the size of our planet to something the size of a city, achieving densities in excess of that of the atomic nucleus and velocities one-fourth the speed of light. At nuclear densities ($\sim 10^{13}$ times that of tungsten), matter is barely compressible and the core bounces[3], rebounding into the infalling inner mantle and, like a piston, generating a strong shock front that with effort and a short delay overcomes the confining tamp of imploding mantle mass in order to launch a supernova explosion. The violent explosion disassembles the massive star, litters the interstellar medium with freshly synthesized heavy elements (such as oxygen, carbon, magnesium, silicon, calcium, sulphur, and radioactive ^{56}Ni), blows a many-parsec-sized hole in the surrounding galactic gas, and announces itself with a luminous display that can rival that of its parent galaxy for months. Its fossil is most often a neutron star, twenty kilometres wide, with an average density near that of an atomic nucleus, spinning with a period of milliseconds to seconds, and possessing a surface magnetic field of $\sim 10^{12}$ gauss. With the right combination of period and field, this object is a radio pulsar. Astronomers have discovered more than 1,000 such radio beacons in the galaxy, each of which was born in a supernova explosion[4]. The famous Crab pulsar is one such result, now pulsing in the radio, optical, and X-ray frequencies with a period of ~ 30 milliseconds and surrounded by an X-ray emitting remnant of the supernova explosion, that itself was witnessed by humans in AD 1054 to be as bright as Venus in the night sky. Figure 1 depicts the various stages of core collapse and neutron star formation.

The gravitational collapse of the core of a massive star is not the only context in which a supernova explosion is thought to occur. The smaller carbon–oxygen white dwarfs produced by low-mass stars at their death might be situated in tight binaries with a stellar companion. In a small subset of these systems, matter is stripped from this companion by the white dwarf's gravitational pull and accreted at a rate sufficient to reach the Chandrasekhar mass. As with the core of a dying massive star, collapse ensues. However, since these white dwarfs consist predominantly of carbon and oxygen, not heavier elements such as iron near the peak of the nuclear binding energy curve, compression and heating soon lead, not to continued implosion, but to the thermonuclear incineration of the white dwarf. As much as a solar mass burns to iron-peak and intermediate-mass (such as Ca, Si, S, Ne, Mg) elements and the entire star explosively disassembles, leaving nothing behind but its violently disturbed donor[5]. In some models, the donor is another white dwarf, in which case nothing at all remains. In either case, the ejecta are rich in heavy elements, in particular ^{56}Ni, which by its radioactive decay to ^{56}Co (in a mean time of 8.8 days) and then to stable ^{56}Fe (in a mean time of 111.3 days) powers its optical light curve (luminosity versus time) for the months during which it can be seen across the Universe[6,7]. Astronomers believe these to be the so-called type Ia supernovae. If it were not for radioactive heating, adiabatic expansion of the debris would cool it to near invisibility in less than an hour. Type Ia supernovae are about ten times less prevalent than core-collapse supernovae, but yield about ten times as much iron, are often more than ten times brighter at peak light, and are spectacular sources of nuclear γ-ray lines and continuum[8]. It is with these bright supernovae that observers are now obtaining the best and, perhaps, the most provocative information about the geometry of the Universe.

Astronomers use observational, not theoretical, criteria to type supernovae. A type I supernova (such as a type Ia) is one with no hydrogen in its spectrum, while the spectrum of a type II supernova has prominent hydrogen lines. The epochal supernova in the Large Magellanic Cloud (LMC), SN1987A, was a core-collapse supernova, because it exploded as a $\sim$15–20$M_\odot$ blue supergiant with a radius of $\sim 4 \times 10^7$ km (ref. 9) and not as the canonical red supergiant with a radius of $\sim 10^9$ km; however, it was dimmer than a typical type II and early relied on ^{56}Ni to power its muted optical light curve. Yet there is no reason to suspect that the explosion itself was not of the common core-collapse variety. The light curve and spectrum of a supernova reflect more its progenitor's radius, chemical makeup, and expansion velocities than the mechanism by which it exploded. To the theorist, the achievement of the critical Chandrasekhar mass unites the types; the supernova mechanism is either by implosion to nuclear densities and subsequent hydrodynamic ejection, or by thermonuclear runaway and explosive incineration.

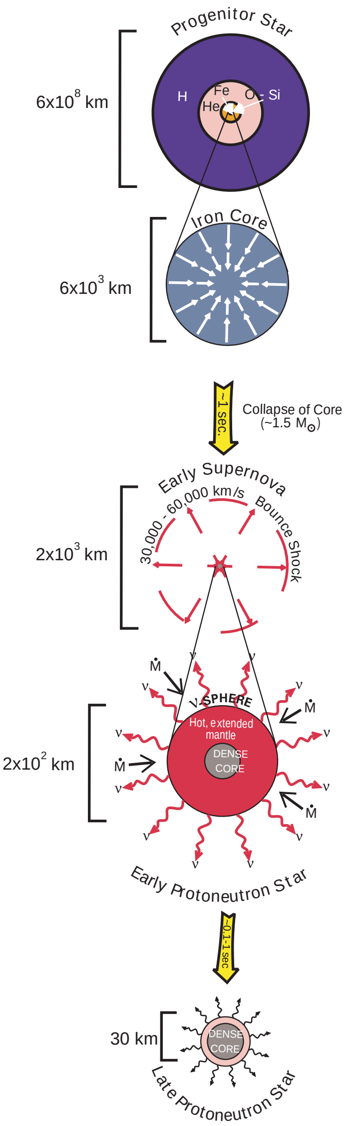

Figure 1 The sequence of events in the collapse of a stellar core to a nascent neutron star. It begins with a massive star with an 'onion-skin' structure, goes through white-dwarf core implosion, to core bounce and shock-wave formation, to the protoneutron-star stage before explosion, and finally to the cooling and isolated-neutron-star stage after explosion. This figure is not to scale. The wavy arrows depict escaping neutrinos and the straight arrows depict mass motion.

There is approximately one supernova explosion in the Universe every second. In our galaxy, there is one supernova every $\sim$30–50 years and one type Ia supernova every $\sim$300 years. Supernova hunters, peering deeply with only modest-aperture telescopes, can now capture a dozen or so extragalactic supernovae per night, mostly the bright type Ias. Approximately 200 supernova remnant shells are known in the Milky Way and these are radio, optical, and X-ray echoes of only the most recent galactic supernova explosions. Within the last millennium, humans have witnessed and recorded six supernovae in our galaxy (Table 1).

Supernovae from massive stars

A star's first thermonuclear stage is the fusion of hydrogen into helium in its hot core. With the exhaustion of core hydrogen, most stars then proceed to shell hydrogen burning, and then to core helium burning. The ashes of the latter are predominantly carbon and oxygen and low-mass stars do not proceed beyond this stage. However, stars with masses from $\sim 8M_\odot$ to $\sim$60–100$M_\odot$ (the upper limit depending upon the heavy-element fraction at birth) proceed to carbon burning, with mostly oxygen, neon, and magnesium as ashes[1,2]. For stars more massive than $\sim$9–10$M_\odot$, the ashes of carbon burning achieve sufficient temperatures to ignite and they burn predominantly to silicon, sulphur, calcium, and argon. Finally, these products ignite to produce iron and its congener isotopes near the peak of the nuclear binding energy curve. Fusion is exothermic only for the assembly of lighter elements into elements up to the iron group, not beyond. Hence, at the end of a massive star's thermonuclear life, it has an 'onion-skin' structure in which an iron or oxygen–neon–magnesium core is nested within shells comprised of elements of progressively lower atomic weight at progressively lower densities and temperatures. The outer zone consists of unburned hydrogen and 'primordial' helium. A typical nesting is Fe → Si → O → He → H. The oxygen in the 'oxygen' zone is the major source of oxygen in the Universe, for little oxygen survives in the ejecta of the rarer type Ia supernovae. These shells are not pure,

Table 1 Supernovae that have exploded in our Galaxy and the Large Magellanic Cloud within the last millennium

Supernova	Year (AD)	Distance (kpc)	Peak visual magnitude
SN1006	1006	2.0	–9.0
Crab	1054	2.2	–4.0
SN1181	1181	8.0	?
RX J0852-4642	~1300	~0.2	?
Tycho	1572	7.0	–4.0
Kepler	1604	10.0	–3.0
Cas A	~1680	3.4	~6.0?
SN1987A	1987	50 ± 5	3.0

These 'historical' supernovae are only a fraction of the total, because the majority were shrouded from view by the dust that pervades the Milky Way. Thus, it is estimated that this historical cohort represents only about 20% of the galactic supernovae that exploded since AD1000. Included are SN1987A, which exploded not in the Milky Way but in the Large Magellanic Cloud (one of its nearby satellite galaxies), RX J0852-4642 (ref. 77, ref. 11), a supernova remnant whose recent (~AD1300) and very nearby birth went unrecorded, perhaps because it resides in the Southern Hemisphere (but in fact for reasons that are as yet unknown), and Cas A, a supernova remnant that was born in historical times, but whose fiery birth was accompanied by a muted visual display that may have been recorded only in the ambiguous notes of the seventeenth-century astronomer John Flamsteed (ref. 78). The distances and peak visual magnitudes quoted are guesses at best, except for SN1987A. Astronomical magnitudes are logarithmic and are given by the formula $M_V = -2.5\log_{10}(\mathrm{brightness}) + \mathrm{constant}$. Hence, every factor of ten increase in brightness represents a decrease in magnitude by 2.5. For comparison, the Moon is near –12 magnitudes, Venus at peak is –4.4 magnitudes, and good eyes can see down to about +6 magnitudes.

but are mixtures of many elements and isotopes, with one eponymous element. The above description is a gross simplification of the composition and nuclear astrophysics of a massive star. Curiously, although the inner regions are hot, their high densities and the ordered arrangement of their constituent nucleons into nuclei results in a low specific entropy. In fact, from birth to death, the drama of a star's evolution is the inexorable decrease of its core entropy. At low entropies, pressure is derived mostly from the zero-point Fermi motion of degenerate free electrons and not from the ideal gas of nuclei. Importantly, the concept of a limiting Chandrasekhar mass is relevant only for such degenerate material.

At core collapse, the outer shells are not moved. They are oblivious to their impending fate until the supernova shock wave generated in the core hits and ejects them. Hence, the basic composition of most of the debris is determined during the quiescent burning stages of the massive star. The supernova explosion merely lifts the shells into space (at speeds of $\sim$10,000 to $\sim$20,000 km s^{-1}). However, shocked inner-mantle material does achieve temperatures sufficient to explosively burn some of the 'silicon' shell into iron-peak nuclei, some of the 'oxygen' shell into iron-peak and intermediate-mass nuclei, and some of the 'carbon' shell into oxygen. This post-processing alters the yields of the intermediate-mass and iron-group elements and is responsible for the generation of radioactive isotopes, such as ^{56}Ni, ^{57}Ni and ^{44}Ti, in the inner ejecta[10]. These radioisotopes are important power sources for the late-time light curve of a core-collapse supernova and have in fact been directly detected by γ-ray satellites (SN1987A, ref. 8; Cas A, ref. 11). On average, the theoretical and observational yields of ^{56}Ni, ^{57}Ni and ^{44}Ti hover around $0.07M_\odot$, $0.0015M_\odot$ and $0.0001M_\odot$, respectively, per core-collapse supernova, though there are individual exceptions. These average yields, galactic supernova rates, and theories of galactic evolution are consistent with the current cumulative abundances in the Solar System of their stable daughter isotopes, ^{56}Fe, ^{57}Fe and ^{44}Ca.

The origin of the elements has been a central focus of astrophysics for the last forty years[12], but equally important is the determination of the mechanism by which core-collapse supernovae explode. One might have thought that the bounce and rebound of the imploding core that creates the young shock wave and drives it with a single massive thrust would have been all that was necessary to explain both the supernova blast and the simultaneous creation of a protoneutron star[13]. However, formed at a radius of $\sim$20–30 kilometres, the shock has to plough through many tenths of solar masses of infalling material. In the process, at the many MeV (1 MeV $\equiv \sim 10^{10}$ K) temperatures created behind the initially strong shock, the heavy nuclei it encounters are disassociated into nucleons. This is an endothermic process. In addition, and almost uniquely to supernovae, at the high temperatures and densities that are achieved during collapse, neutrinos of all three flavours (in particular, ν_e neutrinos created by electron capture on the newly-liberated free protons) are copiously radiated. The initial neutrino luminosities can reach $\sim 10^{54}$ erg s^{-1}, equivalent to $\sim 0.5 M_\odot c^2$ per second[14]. Between neutrino energy losses and nuclear breakup, the young shock has no chance; such energy and pressure penalties sap it of strength and within only 10–20 ms of its birth, it stalls between a radius of 100 and 200 km into a quasi-stationary accretion shock[15]. Effectively, the front stops propagating outward in radius, although it continues to propagate outward in interior mass, as infalling shells of matter with speeds of $-$30,000 to $-$70,000 km s^{-1} reach it, are shock-compressed and heated, and then settle onto the nascent protoneutron star.

Since the progenitor's outer radius is 10^6–10^9 km and much of the matter in the accretion-shock-bounded protoneutron star has a negative velocity, this is an unsatisfactory state of affairs. The theorist's modern quest is to determine how the accretion shock is revived and revitalized into a supernova explosion (with a healthy representation of positive velocities!). In the past 15 years, there has been substantial progress towards solving this puzzle in the pit of the enshrouding star, quite literally a riddle wrapped in a mystery inside an enigma.

The solution seems to involve neutrinos as the drivers of explosion[16–18]. The protoneutron star is exotic on many counts, not the least of which is that despite the notoriously weakly interacting nature of neutrinos with matter, they are partially trapped in the superdense core. Upon creation, they do not stream out immediately at the speed of light, but must diffuse to escape. As the neutrino absorption and scattering mean-free-paths in the centre are metres[19] and the number of mean-free-paths from the centre to infinity is $\sim 10^4$–10^6, the object is a 'neutrino star' with a surface of emission, the neutrinosphere, akin to the photosphere of the Sun. Instead of leaving the protoneutron star within milliseconds, the characteristic loss time for neutrinos is seconds. It takes this long for the trapped leptons and energy to leak out of the hot and extended protoneutron star, in order to effect its conversion into the more compact, cold neutron star[20]. Such an evolutionary timescale was verified by the detection in two deep underground mines 13 years ago over periods of $\sim$5.5 and $\sim$12.5 seconds of the neutrinos from SN1987A (refs 21, 22). These observations are consistent with the emission in neutrinos of all species of $\sim(2\text{–}3) \times 10^{53}$ ergs, equal to the gravitational binding energy of a neutron star and more than 100 times the kinetic energy of the blast. During this brief pulse, the supernova neutrino luminosity can rival the total optical output of the observable universe. Hence, in an energetic sense, the optical supernova is a sideshow to the main event: the neutrino burst that attends the formation of a neutron star. In principle, neutrinos are the best direct probes of the internal dynamics of both the supernova mechanism and neutron star birth[21–29]. As a consequence, in anticipation of the next galactic core collapse, a network of massive underground neutrino telescopes that, with luck, will collect thousands of supernova neutrino events now stands guard[25–29].

But how does the leakage of energy by neutrino radiation from the gradually settling inner core re-energize the shock and launch an explosion? The key lies in the fact that though energy is being radiated from the inner core and this core is becoming more and more bound with time, its accretion-shock-bounded mantle is being heated by the absorption of a fraction of the escaping neutrino flux. The region just interior to the stalled shock in which there is net heating is called the 'gain' region[30]. This neutrino-mediated energy transfer from the core to the mantle is the essence of the mechanism, as it is currently envisioned. If there were no mass accretion from the still-collapsing outer core, the neutrino-heated mantle would be unstable enough to explode[31]. The accretion pressure tamp is all that is keeping the shock bottled up. However, since mass accretion is being fuelled by zones which are infalling from progressively further out in the star, the mass accretion rate ($\dot{M}$) onto the core is inexorably subsiding. Hence, the supernova is a race between a decaying neutrino luminosity and a subsiding $\dot{M}$. Any process that expands the gain region, maintains or boosts the neutrino luminosity, or decreases $\dot{M}$ facilitates explosion. The specific details of neutrino transfer as neutrinos decouple from matter are also important[32]. Therefore, the stalled shock is just biding its time, perhaps for hundreds of milliseconds to seconds, until the critical condition for explosion is achieved[33].

The behaviour in the pit during this pause is the focus of current research. Variations from progenitor to progenitor in both density and rotation profiles[34] are all part of the mix and should result in a spread of outcomes, final neutron star masses, ^{56}Ni yields, and explosion energies. Indeed, two supernovae, SN1994W and SN1997D, have kinetic energies of $\sim 0.5 \times 10^{51}$ erg and ^{56}Ni yields of $\sim 2.0 \times 10^{-3} M_\odot$, both significantly below the norm[35,36]. This implies that the explosion mechanism supports variations from supernova to supernova, perhaps as a function of progenitor mass, that theorists have yet to explain. Some cores may be too dense to explode before the protoneutron star itself becomes gravitationally unstable to general relativistic collapse. A black hole would then be the inevitable and irreversible result. Whether a supernova could be launched in such a circumstance is unknown. Furthermore, a supernova might be launched in canonical fashion, only to witness the subsequent collapse of its 'launching pad' into a black hole after many seconds of cooling and neutronization or matter fall back. This type of event may depend upon the existence of as yet unverified soft phases of nuclear matter at supranuclear densities[27,38].

There is another important and generic characteristic of supernova explosions: symmetry breaking. Rayleigh–Taylor and Kelvin–Helmholtz fluid instabilities, akin to those that explain why water falls out of a glass, why a shaken vinagrette mixes, why a flag flaps, and why an atomic explosion on Earth assumes the shape of a mushroom cloud, are ubiquitous in supernova explosions. Indeed, the maintenance of spherical symmetry in a context of severe density gradients, subjected to extreme and variable acceleration and gravity fields, would seem bizarre. Collapse and explosion must be quite aspherical and asymmetrical. In particular, it can be shown[31,39,40] that the gain region interior to the stalled shock is also a region of vigorous transonic convection, driven by neutrino heating 'from below'. This is analogous to the boiling of water on a stove. Many theorists believe that such convection increases the efficiency of mantle neutrino heating, increases the size of the gain region, and, therefore (as described above), is an important factor in the mechanism of explosion. Furthermore, once the shock wave is re-energized, as it propagates down the density gradient of the outer progenitor star and encounters the carbon–helium and helium–hydrogen composition boundaries, new Rayleigh–Taylor instabilities are tripped[41]. Clearly, there is every theoretical reason to believe that such supernova debris should be clumpy and aspherical. In fact, optical and infrared line profile measurements[42], the images of young supernovae and SNRs, and polarization studies[43] all demonstrate that these explosions are far from spheres, particularly in their inner reaches. In some cases, fast rotation will impose a characteristic axis that could lead to a bipolar explosion structure.

However, one of the most spectacular indications that the explosion that leaves behind a neutron star is asymmetric in some important way comes from the radio pulsar population. It is now known that the eccentric orbits of many binaries containing neutron stars, including neutron-star–neutron-star-pulsar systems, and the observed transverse motions of radio pulsars across the sky cannot be explained without often evoking a violent kick at birth. The speed with which the nascent neutron is rocketed out of its cradle is measured to average $\sim$450 km s^{-1} (ref. 44). Some pulsars[45] reach speeds of $\sim$1,500 km s^{-1}, far in excess of the escape velocity ($\sim$300–600 km s^{-1}) from our Milky Way. Such speeds cannot be explained by the slow orbit speeds of their progenitor stars in the binary systems in which many supernovae arise. Such speeds require an asymmetry in the supernova explosion itself. There may be a bimodal distribution of kicks, with a fraction with speeds near zero and a fraction with an average speed of $\sim$600 km s^{-1} (ref. 46). Be that as it may, whether the young neutron star recoils due to asymmetric mass ejection or asymmetric neutrino radiation is not yet known; it is one of the central unsolved mysteries of supernova research.

The emerging supernova–γ-ray burst connection

Gamma-ray bursts were discovered in the 1960s by the Vela constellation of satellites established to monitor nuclear treaties and explosions in the near-Earth environment. For decades, these bursts, each lasting from a fraction of a second to minutes and boasting a featureless spectrum of MeV photons, were thought to be associated with our galaxy, but poor angular resolution and the lack of optical, radio, or X-ray counterparts denied us the means to pinpoint the culprits with precision. As a consequence, almost nothing was known of their source or engine and throughout the 1970s and 1980s the ratio of theories to detected photons was uncomfortably high. In 1991, the Compton Gamma-ray Observatory was launched and due to its sensitivity was expected to see the edge of the γ-ray burst population. Since this population was thought to be in the galaxy, its angular distribution was expected to be concentrated towards the Milky Way. It was not. In fact, it was isotropically distributed on the sky, implying either a local, a galactic halo, or a cosmological distribution. The breakthrough came in 1997 when the Italian–Dutch satellite, Beppo-SAX (refs 47, 48), detected first an X-ray counterpart to GRB970228 (ref. 49), and then a few months later a counterpart to GRB970508, for which respectable angular resolution was then achievable. Given a small angular error box, the sources of the bursts were identified and quick optical follow-up was possible. That follow-up yielded a fading optical source at the position of GRB970228 (ref. 50), and then an optical spectrum for GRB970508. The spectrum contained absorption lines due to singly ionized iron and magnesium (Fe II and Mg II) at a redshift of $z = 0.835$, proving that this burst at least was of cosmological origin[51]. Soon, many optical and radio counterparts were detected and other high redshifts were obtained. Bursts are found to coincide with galaxies in the Hubble flow, perhaps even in their star-forming regions. The γ-ray burst itself and its $\sim t^{-2}$ power-law decay afterglow is now explained in the broad context of an extremely relativistic blast wave, with a very large initial Lorentz factor $\Gamma \gtrsim 100$, that interacts with and propagates through its local gaseous environment[52]. These are found through the Universe. Many important aspects have yet to be worked out and much remains to be understood, but several recent discoveries are starting to connect some γ-ray bursts with supernovae. After a few weeks, the optical afterglows of GRB970228 (ref. 53) and GRB980326 (ref. 59) deviated from the simple power-law decay expected in the relativistic blast model and can be interpreted as a superposition of 'classic' power-law afterglows with supernova light curves. GRB980425 actually coincided in time and direction with the peculiar type Ic supernova, SN1998bw, that exploded in a nearby galaxy[55]. SN1998bw had very broad spectral features and may have been more energetic than most such supernovae[56]. However, from the accumulating observational record, the association between a subset of γ-ray bursts and a subset of supernovae seems excitingly credible. But what could it all mean? Statistical arguments, existing supernova data, and a variety of physical arguments indicate that most supernovae cannot be associated with a γ-ray burst. Nevertheless, since they are at cosmological distances, if they radiate isotropically, most γ-ray bursts must be "hypernovae"[52,57] and liberate $\sim 10^{51}$ to $\sim 10^{53}$ erg, values that are interestingly close to supernova energies, to the binding energies of neutron stars, and to the orbital energies of tight binaries of compact objects such as neutron stars and black holes, but are close to the 'available' energy of almost nothing else. If γ-ray bursts are not isotropic, but beamed, then less energy is required. However, the intrinsic γ-ray burst rate must go up correspondingly. It may be that some supernovae, through the agency of very rapid rotation, strong magnetorotational effects[58,59], and/or neutrino–antineutrino pair production along baryon-poor bipolar channels[60], may be able to generate a relativistic beam of e^+/e^- pairs that can punch through a vestigial supernova progenitor envelope to spawn a γ-ray burst and its early afterglows. The relativistic flow is later followed by the much slower supernova explosion, still recognizable as such. But it is not yet known what tail of the core-collapse distribution could do this.

Using supernovae to do cosmology

The brightness of supernovae naturally suggests their use in surveying the Universe. If they were standard candles, a comparison between their apparent brightness and their intrinsic (or 'absolute' brightness) would yield their distance. A spectrum taken with a large-aperture telescope capable of precision measurements of dim objects, made dim by distance, would yield the spectral redshift (z)

of the supernova (actually, that of its host galaxy) in the Hubble flow of the expanding Universe. A collection of these measurements would provide redshift–distance and redshift–magnitude relations which can be used to distinguish different models of the cosmos, to determine its geometry and mass-energy content, and to help determine its ultimate fate.

Surveying standard patches of the sky over months and years to discern changes in them that are characteristic of supernova explosions, two groups of astronomers[6,7] may recently have done just that. The Supernova Cosmology Project (SCP, ref. 6) and the High-Z Supernova Search Team[7,61] have culled more than 80 and 50, respectively, of the rarer, though brighter, type Ia supernovae. These collections include supernovae at redshifts from ~0.2 to ~1.0 and, hence, are penetrating into the non-linear regions of the Hubble flow to probe the curvature of the Universe. A 'Hubble diagram' for type Ia supernovae, depicting brightness versus redshift, is given in Fig. 2a, taken from the SCP. The high-redshift data are those newly obtained and the low-redshift data are from the previous Calán–Tololo[62] survey of nearby type Ia supernovae. The latter provides a reference benchmark that anchors the curve of data in Fig. 2a to allow a measurement of its curvature. This curve's change in slope has a bearing on whether the Universe is geometrically open or closed (that is, what its curvature parameter, k, is), whether it is accelerating, and whether it has a non-zero cosmological constant (Λ, Einstein's self-proclaimed "biggest mistake").

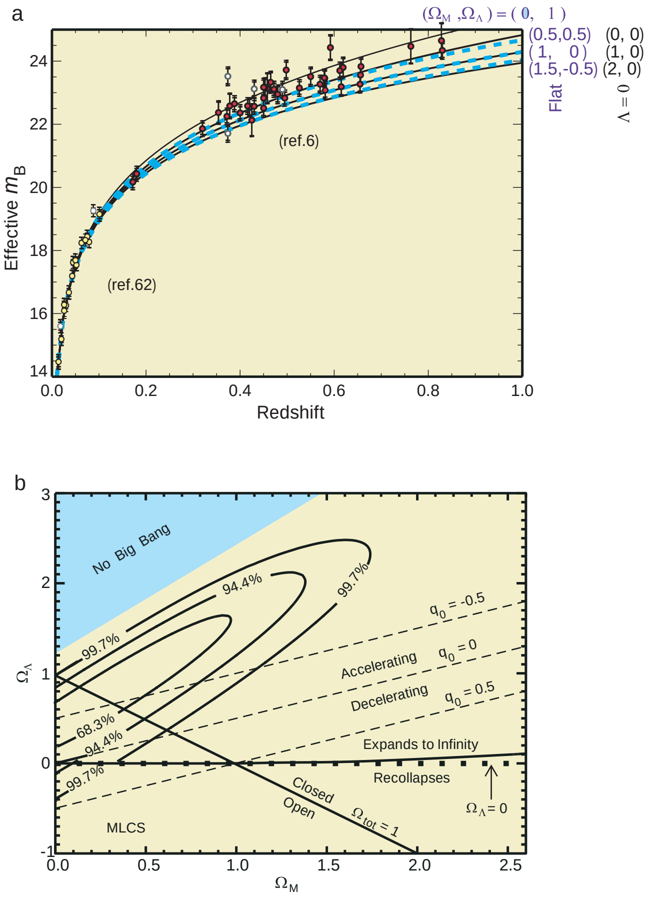

Figure 2 The effective brightness of supernovae with redshift, and how those data are used to reveal cosmological parameters. **a**, A Hubble diagram depicting the calibrated peak blue brightness L_{peak} in astronomical magnitudes ($M_B = -2.5 \log_{10} L_{peak} +$ constant) versus redshift of the collection of type Ia supernovae discovered and studied by the Supernova Cosmology project (ref. 6, red and white circles). Superposed are various curves representing predictions for different cosmologies, indicated by values for (Ω_M, Ω_Λ) in parentheses. Also shown are data from ref. 62 (yellow circles). The dashed curves are for $\Lambda = 0$. The data seem to fit only the uppermost curves, associated with an accelerating universe. **b**, A plot of Ω_Λ versus Ω_M (where Ω_Λ and Ω_M are the cosmological-constant and matter fractions of the mass-energy content Ω_{tot} of the cosmos) taken from the analysis done by the High-Z Supernova Team (ref. 7) using their type Ia supernova data. Shown are the 1, 2 and 3σ confidence contours, the $\Omega_\Lambda + \Omega_M = 1$ line of the inflationary universe (curvature parameter, $k = 0$), and three dashed lines depicting solutions for various deceleration parameters (q_0). It may be seen that a solution with a non-zero Ω_Λ is favoured. (MLCS stands for Multicolor Light Curve Shapes, and the dotted curve is for $\Omega_\Lambda = 0$.)

As Fig. 2a suggests, what both groups find is that not only will the Universe expand forever, but that it seems to be accelerating. Such acceleration implies, in the context of general relativity and the inflationary model of the Universe, that Λ, the cosmological constant, is non-zero, and more than that, that it dominates all the matter in the Universe—dark, baryonic and neutrino—in determining the current expansion rate. In the canonical inflationary universe, Ω_M and Ω_Λ are, respectively, the matter and Λ fractions of the mass-energy content of the cosmos (see Box 1). An approximate fit to the oval in Fig. 2b is: $0.8\Omega_M - 0.6\Omega_\Lambda = -0.2 \pm 0.1(1\sigma)$. Hence, given the inflationary paradigm, Λ seems to represent ~70% of the mass-energy equivalent of the Universe, with most of the other ~30% coming from the dark matter, whatever that may be. (Other arguments suggest that baryons constitute no more than ~5%; ref. 63.) Figure 2b shows the confidence regions in Ω_Λ versus Ω_M space, as calculated by the High-Z Supernova Search Team. A value of zero for Ω_Λ is excluded to better than 3σ, particularly under the assumption of an inflationary 'Big Bang'. A cosmological constant is akin to a non-zero mass-energy density for the vacuum, with a negative pressure, and its possible physical origin is currently a topic of hot speculation[64]. If Ω_Λ is indeed non-zero, this would be one of the most revolutionary scientific discoveries of the decade.

How firm is this startling finding? How much does it depend on the physics of type Ia supernovae? In fact, though much is known about the thermonuclear explosions of white dwarfs, much is not. We do not know whether the burning wave propagates through the white dwarf as a supersonic detonation or as a subsonic deflagration. We do not understand the details of initial ignition and

Box 1

A brief cosmology primer

The relationship between the various cosmological parameters is

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3}G\rho - k\frac{c^2}{R^2} + \Lambda/3$$

$$= \frac{8\pi}{3}G(\rho + \Lambda') - k\frac{c^2}{R^2}$$

$$= H_0^2\left(\frac{\rho + \Lambda'}{\rho_{crit}}\right) - k\frac{c^2}{R^2}$$

$$= H_0^2(\Omega_M + \Omega_\Lambda) - k\frac{c^2}{R^2}$$

where R is the scale of the universe, c is the speed of light, H_0 is the Hubble constant (the current ratio of the Hubble recession velocity to distance and a fundamental cosmological parameter), $\rho_{crit} (= 3H_0^2/8\pi G)$, is the critical mass-energy density for a given H_0, Ω_M is the density parameter due to matter, Ω_Λ is the density parameter due to the cosmological constant, Λ' is the cosmological constant in units of mass-energy density, and ρ is the mass-energy density of matter (that for pressureless particles is proportional to $1/R^3$). The universal curvature parameter k is either 0 (flat), –1 (open), or +1 (closed). If the inflationary paradigm of the universe is assumed, then $\Omega_M + \Omega_\Lambda = 1$ and $k = 0$.

runaway. We do not know the nature of the binary companion that feeds the white dwarf—whether it is a main sequence star, a subgiant star, a giant star, or another white dwarf. All these types of companions might occur with some frequency, in different environments. The hint that only type Ia supernovae occur in elliptical galaxies has not clarified the situation, nor do we know whether novae, which are much weaker (by a factor of 10^6) thermonuclear explosions of hydrogen on the surfaces of accreting white dwarfs, and type Ia supernovae are connected in any way. The result of all this ignorance is that theorists cannot predict—from first principles and with sufficient precision—the ^{56}Ni yields, explosion energies, light curves, and spectra of type Ia supernovae to justify them as cosmological theodolites.

However, they need not do so. Astronomers have shown observationally that though there is variation from explosion to explosion in the peak luminosity of type Ia supernovae, there is a correlated variation in their peak duration and light curve shape. In the absence of theoretical guidance, observers have determined empirically that, for whatever reason, type Ia supernova light curves are approximately a one-parameter family that, through the use of light-curve templating[7] and/or the empirical “Phillips” relation between peak brightness and the brightness 15 days after peak[65], can be made into standard candles. In fact, in this sense, type Ia supernovae are excellent distance indicators, providing one of the best current measures of the Hubble constant, H_0. From the low-redshift intercept in Fig. 2a (note that this is a log-linear plot), a value of ~64–69 km s^{-1} Mpc^{-1} is obtained[66,67], amply within the error bars of competing techniques[68,69]. However, the absence of an absolute calibration from theory means that, as with other forefront techniques for measuring H_0, the use of supernovae is tied to the astronomical distance ladder. Unfortunately, the LMC is a rung on this ladder and the distance to the LMC is not known to better than 10%.

Nevertheless, given this H_0, the age of the Universe can be calculated and the result is quite interesting. If the Universe were flat and $\Lambda = 0$, the age of the Universe would be a mere $2/3H_0 = 10$ Gyr. This age is incompatible with the age of the oldest globular clusters (11.5–13.5 Gyr), inferred from stellar evolution theory[70,71], and is also mildly at odds with the age obtained using radioactive nucleo-cosmochronometers, such as thorium-232 (15.6 ± 4.6 Gyr; ref. 72), which are themselves products of core-collapse supernovae. However, an accelerating universe changes all this. With the non-zero cosmological constant, a back-extrapolation from the present epoch yields an age of ~14.5 Gyr. This age brings the various age estimates of the Universe into rough agreement, lending some credence to the idea that the Universe is indeed accelerating.

However, as with other techniques, there may be systematic effects or errors in the supernova-derived value of Λ. Neutrally absorbing dust may be scattered throughout the Universe, thereby corrupting supernova brightness measurements at large redshifts[73]. With increasing redshift, gravitational lensing becomes a larger and larger correction. Type Ia supernovae in the early Universe and at large redshifts may have systematically different origins and/or light curves[74,75]. This would be all the more plausible if type Ia supernovae could occur in different types of progenitor binary systems, with different evolutionary timescales and overall rates. These rates might themselves depend on galaxy type, age, and/or metal content, itself a function of age, given that supernovae of all types build up the Universe’s complement of heavy elements. The history of our galactic halo, with stars that span a full range of metal contents, may provide a key to the history of a universe in which the heavy elements, as the results of supernovae, gradually accumulated. Hence, much remains to be worked out, for supernovae are only now at the threshold of their partnership with cosmology. We need to obtain more supernovae at higher redshifts. Beyond redshifts of 1.0, much of the supernova’s light is shifted into the infrared. With the Next Generation Space Telescope, planned for the next decade and optimized in the infrared, and with the world’s expanding array of large-aperture ground-based telescopes, we will soon capture type Ia supernovae at redshifts of 5 or 10 and core-collapse supernovae at redshifts greater than 3 (ref. 76). With such instruments, we will witness the first epochs of star and galaxy formation and the production by supernova of the first generation of heavy elements.

Thus we see that in important ways, the histories of star and galaxy formation and of supernovae are inextricably linked. Progress in understanding one demands progress in understanding the other. Today, as we attempt to fathom the mechanisms of supernova explosions, the origin of the elements, the death of stars, and the birth of neutron stars and black holes, we are simultaneously advancing the means by which we can comprehend our origins. Crucial to the development of the Universe, supernovae tell a story that goes beyond the exotic physics, the state-of-the-art numerical technique, and their role in surveying the Universe, to the heart of mankind’s ability to comprehend its home. □

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