Supernovae, their Functioning, Lightcurves, and Remnants

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Abstract

Ever since Shklovskii's influential 1962 paper, the literature tends to model supernovae (SNe) with strong shock waves (or blast waves), implying reverse shocks, Sedov stages, and the like. Here I repeat my conviction since 1988, that all SNe are of the core-collapse type, and are expelled by the collapsing core's wound-up magnetic field plus its decay product – an ultra-high-energy (UHE) relativistic cavity – which serves as the ultimate piston. The piston's Rayleigh-Taylor instability tears the ejected envelope into a huge number ($\gg 10^3$) of (magnetized, filamentary) fragments, or splinters. The critical stellar mass M_{crit} for core collapse to happen is closer to 5 $M_\odot$ than to 8 $M_\odot$. SN remnants are former stellar windzones, collisionally heated when traversed by the shell of ejected SN splinters and by its relativistic piston (which has strongly cooled, though, via adiabatic expansion).

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Keywords: Supernovae; Core collapse; Relativistic Piston; Splinter Bomb; Hubble Flow.

Contents

1. The two (extreme) Types of Bomb

The supernovae we observe in the sky are known to be gigantic explosions of evolved stars, of masses M at and/or above some critical mass M_{crit} which is highly controversial, even though a straight-forward estimate from the lightcurve's transition from optically thick (photospheric) to optically thin (nebular) yields ejected shell masses that cluster around $(3 \pm 1) M_\odot$ (Kundt, 1988, 1990, 1998). Such (high) shell masses are expected for $M_{crit} \approx 5\ M_\odot$, and are inconsistent with the exploding-white-dwarf model for SNe of type Ia. (More reasonings against the latter will be given in section 4). A comparatively low M_{crit} (of 5 $M_\odot$) is independently implied by the large birthrate of neutron stars, 1 in $\lesssim$ 10 yr in the Galaxy, obtained from pulsar statistics and the conviction that pulsars are the younger brothers, on average, in evolved massive binary (or multiple) systems (Blaauw, 1985; Van den Bergh & Tammann, 1991; Kundt, 1998).

Independently of their detailed structure, sudden, high-speed mass ejections from some compact source classify as bombs. In a bomb, a sudden transfer of potential (chemical or nuclear) energy to some ambient matter gives rise to its high-speed ejection. In a pressure bomb (or blast wave), such a transfer takes place (essentially) to some surrounding gaseous medium, whilst in a splinter (shrapnel) bomb, most of the energy is transferred to dense fragments of a container. Thin-walled bombs are of the blast-wave type, whereas thick-walled bombs are of the shrapnel type, whose ejecta realize a Hubble-flow velocity distribution: $\overrightarrow{v}(\overrightarrow{r}) \sim \overrightarrow{r}$. Of course, in reality, any combination of energy transfers can occur. Figs.1 and 2 show examples of both types of bomb. In their seminal paper, Hoyle and Fowler (1960) assumed that SNe were powered by nuclear energy. Knowing the (thin-walled) morphology of nuclear explosions in the Earth's atmosphere, Shklovskii (1962) applied Sedov's (strong) shock-wave model to SNe. The impact of these two pioneering publications on the scientific community is still felt today. Instead, a consideration of the necessary energy transfer from the collapsing core to the extended envelope led me to explore the (thick-walled) splinter model (1976, 1988, 1990, 1998, 2003, 2005), variants of which have been independently pursued by Bisnovatyi-Kogan and collaborators ($\geq$1969), without convincing me in their details.

Most of the international research on SNe has taken numerical approaches,

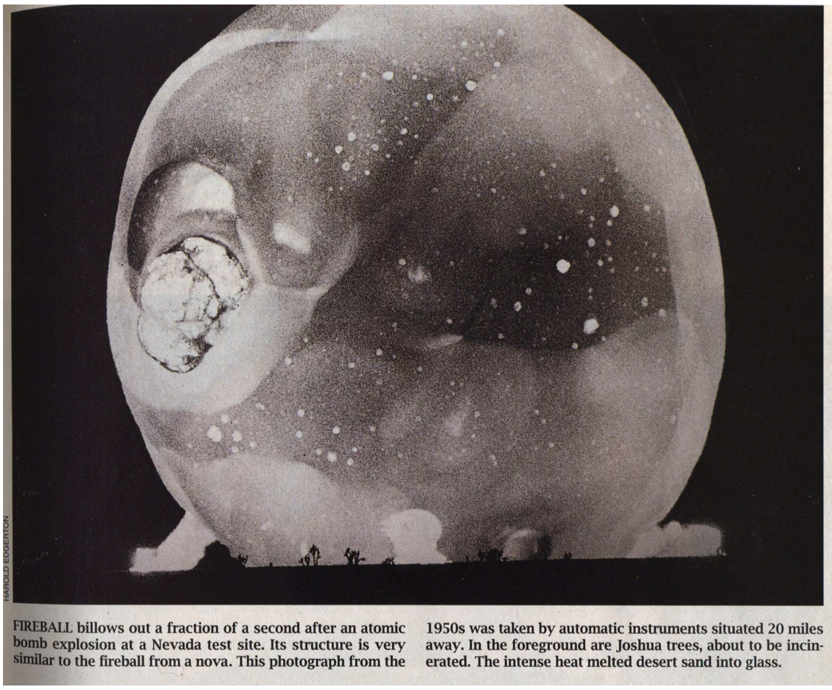


Figure 1: Hydrogen-bomb explosion in air at a Nevada test site, photographed within a fraction of a second after ignition by automatic instruments situated 20 miles away, in ≥1952; from Starrfield & Shore (1995). The Joshua trees in the foreground will soon be incinerated. Desert sand was melted into glass. This event was a close approximation to a Sedov-Taylor wave.

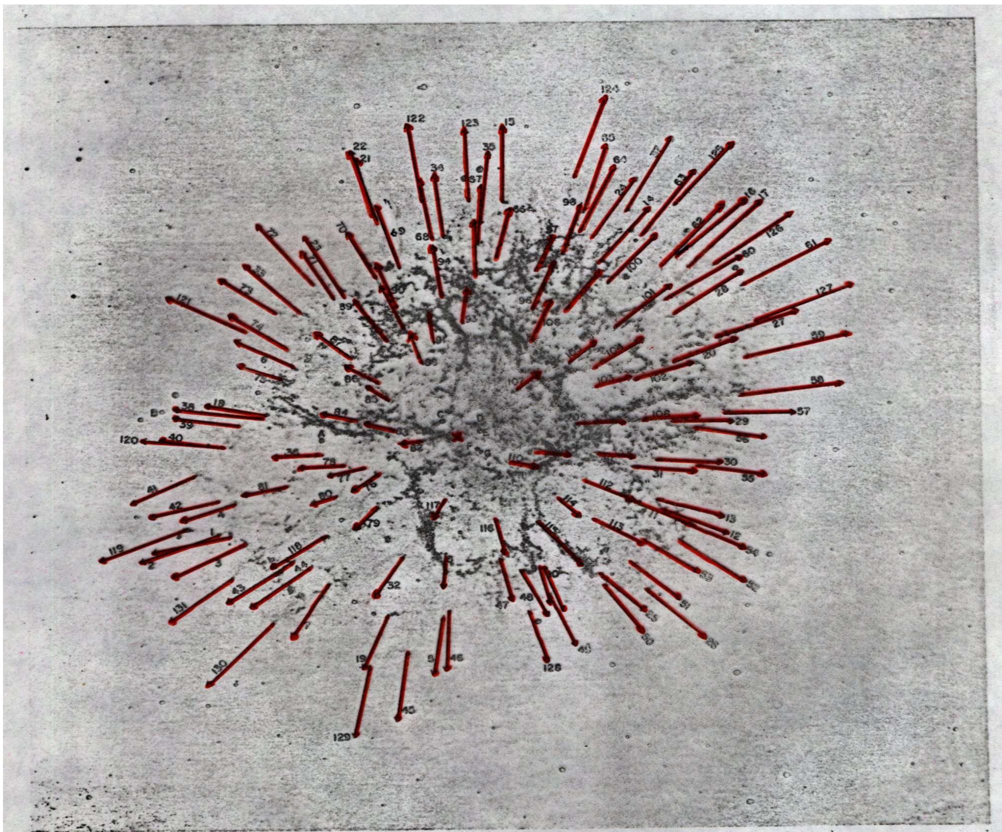


PLATE I (No. 1, Trimble). Proper motions for 132 positions in the Crab Nebula as listed in Table II. The arrows represent the distance the filaments will move in about **270 yr** at their present rates. The center of the expansion is located at the point marked *X*. The stars used to align the plates for measurement and those nearest the center of the nebula are lettered. The photograph was taken through an Hα interference filter on the 200-in. telescope by Münch.

Figure 2: Proper motions for 132 positions in the Crab Nebula, drawn by Virginia Trimble (1968) into a photograph taken through an Hα interference filter on the 22-inch telescope by Münch. The (numbered) arrows represent the distances the filaments will move in about 270 yr at their present rates. The center of the expansion is marked X. The stars used to align the plates for measurement and those nearest the center of the nebula are lettered. Clearly, we deal with a close approximation to a splinter bomb. For corroborative, improved recent data see Rudie et al (2007).

which tend to be careful as concerns the nuclear reactions (at high densities and temperatures!) but unrealistic by ignoring the huge (equi-partition) magnetic field strengths expected to be generated during core collapse, and by ignoring their subsequent reconnection and conversion to relativistic (matter-antimatter) particles, with energies as high as 10^{20}eV, see (3) below. They thus lack the UHE relativistic piston without which the heavy, extended envelope of the exploding star cannot be ejected, already because of insufficient radial momentum (required to overcome gravity). When viewing the proceedings of the 5th workshop on ‘Astronomy with Radioactivities‘ edited by Hartmann et al (2006), I thus agree with the difficulty of "fallback in stellar collapse" highlighted by Fryer (p. 492): "Delayed ejections", as presented by Burrows et al (p. 487; also: Burrows et al, 2007), forget the radial-momentum balance when claiming to have "driven the explosion" (solely based on the energy balance), hence are inconclusive. And no jets form inside 3-d core-collapse SNe. For momentum reasons alone, I consider the title by Fröhlich et al (p.496) misleading: SNe cannot be "neutrino-driven". Höflich et al (p. 470) should be encouraged when they call the "current picture" of SNe Ia "incomplete"; (I call it wrong). And I am not convinced of the 13 $M_\odot$ mass estimate by Tsunemi & Katsuda (p. 521) for the progenitor star of the Vela pulsar (based solely on comparing an observed element ratio of O, Ne, and Mg with tables calculated by Thielemann), nor by Beacom's (p. 564) powering the lightcurve of SNe Ia with the radioactive decay of ^{56}Ni . Nor do I agree with the (too low) SN rate in the Galaxy stated by Peng (p. 483), of 3/century. All these critical remarks are meant to make myself understood, i.e. to characterize my dissatisfaction with our present-day understanding of the physics of supernovae, and will be further explained below. Supernovae have not yet found adequate treatment in the textbooks.

In the following section, I shall review my understanding of supernovae: as thick-walled bombs, which transfer the rotational energy of their collapsing (electron-degenerate) core to their (non-degenerate, vastly extended) mantle via their wound-up magnetic field, of strength $\lesssim 10^{17}$G, and its (subsequent) decay product, an ultra-high-energy matter-antimatter cavity, of initial particle energies $\lesssim 10^{20}$eV. This radial energy transfer to, and ejection of the stellar envelope happens fast, at a (supersonic) speed of some 10^4Km/s. Its piston are successively the pressures of the compressed magnetic field and of the UHE plasma generated by it. Obeying energy- and momentum- balance, this radial transfer must start immediately after the collapse, undelayed, on the timescale of seconds, as otherwise it would be overcome by self gravity.

Due to its lightness, the piston pushes gently, gently enough to avoid excessive neutrino losses (via overheating). During expansion, the piston cools adiabaticly, as $1/r$. Rayleigh-Taylor instabilities cause the (accelerated) envelope to tear into a huge number of (filamentary) fragments, converting it into a splinter bomb; cf. Fig.4.

In this SN ejection scheme, I have not mentioned the unavoidable liberation of nuclear energy by the compressed and heated matter of the collapsed core. It certainly helps ejecting the envelope. But it cannot perform the ejection because being non-relativistic, it would cool under adiabatic expansion as $1/r^2$ (if it had to perform work), down to small fractions of 1K, on its runway from $r = 10^6$cm to some 10^{13}cm. The SN piston must be relativistic.

2. The Functioning of Supernovae

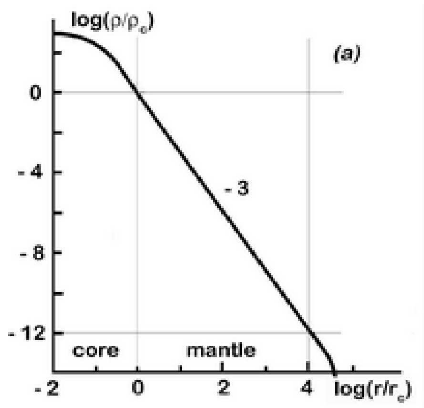
As already advertised in the last 2 paragraphs of the preceding section, I maintain that SNe are splinter bombs, driven by relativistic pistons – magnetic plus relativistic-plasma pressures – consistent with the broad velocity distributions in their (absorption and emission) spectra, with the morphologies of young SNRs [like the Crab, and the SN $\gtrsim$1500 in Orion from the expanding triple-star system {BN, I, Orion n}, (Kundt & Yar, 1997; Gomez et al, 2005)], and with the multiple velocity systems in Cas A (Kundt, 1988). They owe this splinter structure to their being thick-walled and heavy, driven by an extremely light-weight piston. I shall now review the most important ejection formulae for core-collapse SNe, after Kundt (1988, 1990, 2003).

The gravitational collapse of an overweight white dwarf, of radius R, surface gravity acceleration $g = GM/R^2$, to the small size of a neutron star, takes at least the time

$$t_{ff} \approx (2R/g)^{1/2} \lesssim 4 \text{ s} \quad . \tag{1}$$

The onset of this collapse may have to be synchronized between antipodal regions (at sound speed), stretching above collapse time to $t_{coll} \lesssim r/c_s \approx 10$ s $/\sqrt{T_8}$, with $T_8 := T/10^8$s .

By this time, the spin energy E_{rot} of the collapsing core should have grown (via angular-momentum conservation) in proportion to r^{-2}, to its maximum value of $E_{rot} = I\Omega^2/2 \lesssim 10^{52.7}$erg I_{45}, ($I :=$ moment of inertia $\approx 10^{45}$gcm^2), limited by onsetting centrifugal instability at its equator (for angular velocity $\Omega_{\max} = 10^4$/s), which exceeds the maximal spin energy of pulsars (with $P \gtrsim 1.5$ ms, or $\Omega \lesssim 10^{3.6}$/s) by a factor of 6. The core's final spin energy is therefore large enough to give birth to a SN – of kinetic energy



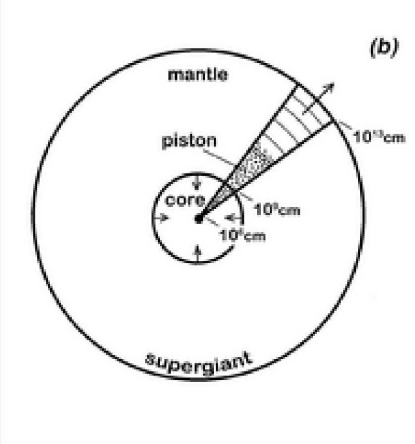
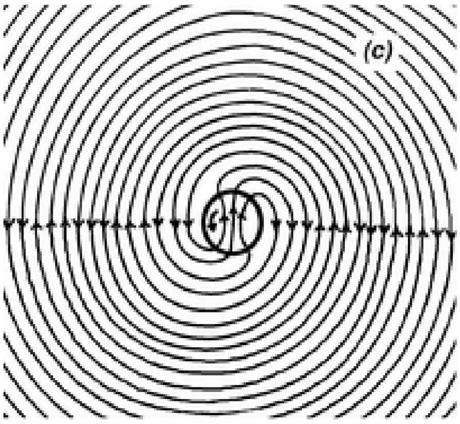


Figure 3: Typical mass-density profile of a SN progenitor star, extracted from the literature (cf. Wilson et al, 1986): Mass density $\rho(r)$ is plotted logarithmically versus radial distance r . For a power-law index of -3 in most of the mantle, there are equal masses in equal logarithmic radial intervals; in particular, there tends to be more mass in the envelope than in the core.

Figure 4: Schematic, non-linear section through a pre-SN star, during the ejection of its mantle (envelope). For an assumed spherical symmetry, energy- and radial-momentum balance can be applied to a narrow conical sector. When at some time, the white-dwarf core collapses, on the timescale of seconds, to the (tiny) scale of a neutron star, a piston forms (from magnetic fields and extremely relativistic matter) that ejects the overlying mantle. Throughout the ejection, the piston's pressure must carry its own weight plus (largely) exceed the column weight per area of the overlying matter. For a supergiant of radius 10^{13}cm, the ejection takes a few hours.



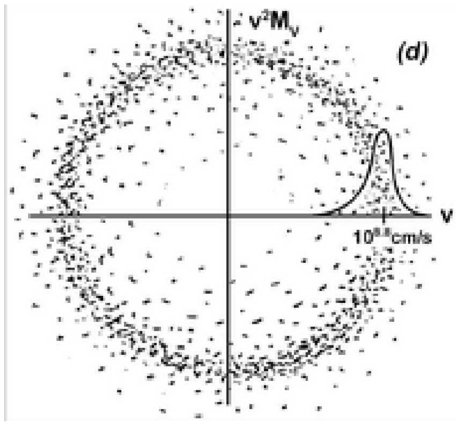


Figure 5: Cartoon sketching the magnetic-flux winding around the rapidly spinning neutron-stellar core, in cross section, of a SN progenitor star.

Figure 6: Cartoon sketching the spherical cloud of radially ejected filaments from a young SN. The filaments' inferred mass distribution – as a function of velocity – is indicated, as a broken power law (drawn for linear scales).

$10^{51.1}$erg – at a transfer efficiency of (only) 2%, and at the same time give birth to (even) the fastest observed pulsar.

How strong can the (toroidal) magnetic field B_φ grow during collapse? Equality of rotational and magnetic energy ($E_{mag} = VB^2/8\pi$) sets the upper limit

$$B_\psi \lesssim (3I\ /R^3)^{1/2}\Omega \approx 10^{17}\mathrm{G}\ \Omega_{3.5} \quad , \tag{2}$$

which is only reached for a sufficiently strong initial B-field of the collapsing white-dwarf core, and only for times shorter than the reconnection time of the strongly wound-up toroidal component (with its multiple reversals); cf. Fig.5.

During B-field reconnections, which will happen at Alfvenic speed, particles are expected to be created whose energies W range up to

$$W = e\int(\overrightarrow{\beta} \times \overrightarrow{B})\ d\overrightarrow{x} \ \leq\ 10^{20}\ \mathrm{eV}\ \beta_{-1}B_{16}(dx)_{2.5} \quad , \tag{3}$$

starting (at the low-mass end) with electron-positron pairs, and ranging through pions and proton-antiproton pairs all the way up to high-energy short-lived resonances. This freshly created UHE plasma will serve as the ultimate piston, ejecting the overlying mantle during its adiabatic expansion.

In order to see this, we calculate the ejection speed v_{ej} from the ram-pressure balance $\rho_{mantle} v_{ej}^2 = p_{piston} = E_{piston}/3V_{piston}$, getting

$$v_{ej} = (E_{piston}/3\rho_{mantle} V_{piston})^{1/2} = c\ r_6^{-1/2} \tag{4}$$

for a piston of energy $E = 10^{52}$erg and volume $V = 10^{18.5}$cm^3 pushing a plasma of typical mass density $\rho = 10^{12}$gcm^{-3}. I.e. according to this crude estimate, the piston's pressure can achieve ejection at relativistic speed at the (innermost) radius of 10^6cm, but already at its pre-collapse radius (of 10^9cm), the ejection speed has shrunken to 10^9cm/s. Beyond this distance, the piston's energy stays almost constant – as the sum of the energy of the UHE plasma and that of the already pushed material – and so does the target mass ρV for a stellar mass profile like that shown in Fig.3, so that the ejection will continue at mildly decreasing speed, converging towards the observed (average) bulk SN speed of $10^{8.8}$cm/s. The ejection time t_{ej} results as

$$t_{ej} = R_{SG}/v_{ej} = 10^4\text{s}\ R_{13} \quad , \tag{5}$$

of order 2 hours for a SuperGiant progenitor of radius $R_{SG} = 10^{13\,\pm\,0.5}$cm.

What temperatures are generated during the ejection? According to shock dynamics, the pushed mantle material is transiently heated to kinetic temperatures of

$$T_{shock} = (2mv^2/k)(\kappa - 1)(\kappa + 1)^2 = 10^{9.4}\text{K}\ (m/m_p)\ v_9^2 \tag{6a}$$

for an average ionic mass m, and an adiabatic index $\kappa = 5/3$, which kinetic energy is quickly shared with the photon bath, via collisional thermalization, resulting in true temperatures of

$$T = [(f/32\pi^2)(\Delta M/m)(kT_{shock}c/\sigma_{SB}R^2\Delta R)]^{1/4} \approx 10^{6.5}\text{K} \quad , \tag{7}$$

where $f = 4/(\kappa - 1)$ counts the number of degrees of freedom of the (ionised) mantle gas, and where ΔM denotes the involved shell mass, corresponding to the radial interval ΔR .

This high temperature during launch, some $10^{6.5}$K, causes a short UV flash, emitted during the piston's crossing the photosphere, of local duration msec, and of peak luminosity

$$L_{peak} = 4\pi R^2 \sigma_{SB} T^4 = 10^{49}\text{erg s}^{-1}\ R_{13}^2 T_{6.5}^4 \quad . \tag{8}$$

The integrated UV flash contains only a small energy of $\lesssim 10^{46}$erg – small compared with the typical radiated SN energy, of order $10^{49.5\,\pm\,0.5}$erg – whose light echo has, however, been observed for SN 1987A, in the form of Napoleon's hat, encircled by rings (McCray, 1993; Sugerman et al, 2005). For a distant observer, this flash arrives at retarded times of $\lesssim R_{SG}/c \approx 10^{2.5}$s $= 5\,$min from different surface elements of the exploding supergiant, so that its observable luminosity stays of order 10^{44}erg/s ; cf. Fig.7b.

Since the star's mantle material is some 10^9 times heavier than its accelerating piston, the ejection must be strongly Rayleigh-Taylor unstable, hence tear the mantle into a huge number of fragments. This conclusion follows more quantitatively from the filling factor f_{th} of the thermal component, if it were distributed homogeneously, in pressure equilibrium with the relativistic gas:

$$f_{th} := p_{therm}(\mathrm{hom})/p_{rel} = 2nkT/(E_{rel}/3V) = 10^{-3}\; T_{6.5}\; \Delta M_{(0.5)} \quad ; \qquad (9)$$

i.e. f_{th} is of order 10^{-3} for a shell of mass $\Delta M = 3M_{\odot}$ at temperature $10^{6.5}$K, and even smaller locally for an r-dependent estimate. The ejected shell gets torn and squeezed into many thousands of small-filling-factor magnetized filaments; cf. Fig.6.

3. Supernova Lightcurves and Types

Why are there so many different SN types: Ia, Ib, Ic, Id, IIP, IIL, IIb, IIn, IIN ? They correspond to different lightcurves – $\log L$ vs t , cf. Figs. 7 – and to different peculiarities of their (initially absorption, later emission) spectra. On the theoretical side, we deal with exploding red and blue supergiants, whose envelopes differ in radius by factors of $\lesssim 10^2$, implying similar factors in their gravitational potentials (and hence escape energies) from which their mantles have to be ejected. Note for instance that the lightcurves of SNe Ia and Ib differ essentially (only) by the latter being one magnitude dimmer, corresponding to a factor of 2.51 difference in their binding energies at launch.

Another important difference in structure of the exploding star is the chemical composition of its envelope, (mainly) hydrogen, helium, or else. Helium-rich envelopes, as in Wolf-Rayet stars, supply only one electron per 4 nucleons when (weakly) ionized, in contrast to hydrogen with its one electron per proton. This causes a 4-times lower opacity of a helium shell compared with a hydrogen shell of the same mass, hence a faster evolution of its lightcurve by a factor of two: SNe of type I change from 'photospheric'

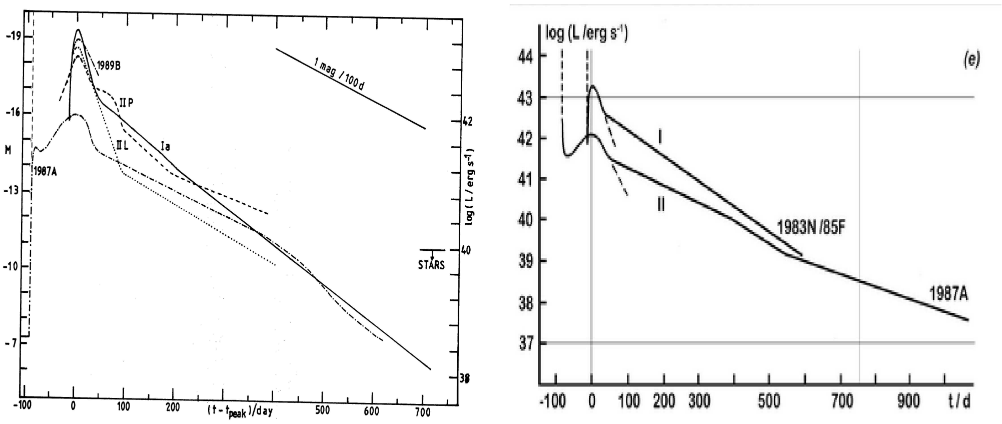


Figure 7: Representative collection of SN lightcurves, logarithmic luminosity log$L$ ($\simeq$ M) vs time t, aligned w.r.t. their maxima. (a). Note that near outbursts, SNe are several orders of magnitude brighter than the brightest stars. Their (logarithmic) slopes after maximum are initially steeper, later occasionally flatter than mag/100d (indicated above). (b). In these 2 lightcurves, their initial UV flash is drawn in broken, as well as the late evolution of the continuum flux.

to 'nebular' within some 50 days after launch, whilst those of type II take $\gtrsim 10^2$ days. Correspondingly, these two types reach their light maxima after $\{\gtrsim 16, \lesssim 10^2\}$days. This opacity-controlled behaviour can be expressed by the following formula for the expected transition time t_{tr} from opaque to transparent in the continuum:

$$t_{tr} = r_{tr}/v = [(\Delta M/m)\sigma_T/4\pi v^2]^{1/2} = 10^{7.1}\text{s } (\Delta M_{(0.5)}\ m_p/m)^{1/2}/v_9 \ , \quad (10)$$

which predicts an onset of the nebular stage after several months ($10^{7.1}$s) for a hydrogen shell of mass $3M_\odot$, whilst $10^{6.8}$s for an equally massive helium shell (Kundt, 1988, equ.(13)).

SN Types	Blue Supergiant	Red Supergiant
Post-Hydrogen Envelope	I b	I a
Hydrogen Envelope	II L	II P

How are the SN lightcurves powered? In the literature, a common explanation proposes the radioactive decay of ^{56}Ni to ^{56}Fe via ^{56}Co. They thereby assume a complete conversion of the radioactively emitted γ-rays into shell heating, even for transparent regions of a shell, and still postulate more radioactive Ni in the exploding shell than judged from independent knowledge, by factors of several. And they ignore frequent deviations of the fading time of the lightcurve from the known radioactive decay times of ^{56}Ni and ^{56}Co. Note that the (integrated) lightcurve energy amounts to $\int L dt = 10^{49.5 \pm 0.5}$erg, whilst the decay energy of one solar mass of Ni (whose ^{56}Ni share is 3%) amounts to 10^{49}erg, so that a typical SN lightcurve would require $3 M_\odot$ of Ni in the ejected shell (for 100% conversion into radiated energy!).

Instead, there are at least three further energy inputs into a SN lightcurve: (i) In the process of envelope ejection, splinters from the inner mantle acquire higher speeds than those from further out, and overtake the latter (at speeds $\lesssim 10^{9.6}$cm/s); in this way, a significant fraction of the original kinetic energy, $>10^{51.1}$erg, of the ejected shell is converted into heat, via overtaking crashes. The full lightcurve requires $\lesssim 2.5\%$ thereof. (ii) The collapsed core of a (core-collapse) SN leaves a hot, newborn neutron star behind, whose internal temperature is thought to start at $\gtrsim 10^{8}$K, after abundant neutrino losses. Were this temperature exposed to the outside world, it would correspond to a blackbody input into the surrounding shell of $\gtrsim 10^{41}$erg/s, a significant fraction of the lightcurve, cf. Fig.7. A mechanism to achieve this would be convective neutron-star cooling, e.g. via volcanoes, as was first proposed by Freeman Dyson. (iii) A third expected energy input into the lightcurve of a SN is non-thermal radiation from its relativistic piston, verified by SN 1987A through its early radio emission, and by several young SNRs through their hard non-thermal spectral components.

How to understand the different successive epochs of a SN lightcurve? Initially, the hot expanding shell of ejecta emits cooling-blackbody radiation, $L = 4\pi R^2 \sigma_{SB} T^4$, whose time-variable factor $(RT^2)^2$ contains the initially (first day) linearly increasing photospheric radius $R(t) \leq vt$, and the initially rapidly decreasing photospheric temperature $T(t)$ – from $10^{6.5}$K down to 10^{4}K – such that $(RT^2)^2$ first drops rapidly, (so far solely observed for SN 1987A), then increases to 'the' SN maximum, and subsequently drops again, at first increasingly fast, subsequently at a slower rate, with approximate exponential slopes of one magnitude in $\{\leq 10, 10^2\}$days; cf. Fig.7b.

This non-monotonic luminosity evolution is a consequence of an initially diffusion-controlled shell cooling, approximated by (McCray, 1999; Kundt, 1998):

$$L(t) = 10^{42}\text{erg/s} \;\; t_5^{-1} \; (R_{SG})_{12.5} \; (E_{51}^3/\Delta M_{(0.5)} \sigma_{-22}^2)^{1/4} \;\; \text{for} \;\; 10^{3.5} < t/\text{s} \lesssim 10^5 \qquad (11)$$

that slows down eventually, on approach of a photospheric constant value of $10^{3.7\,\pm\,0.1}$K ($\simeq B-V\approx 0$), stabilized by hydrogen recombination. Note that above initial cooling luminosity L scales as $1/t$ for $t \lesssim$ one day, i.e. falls rapidly right after the explosion, and scales as R_{SG} with the supergiant's radius R_{SG} (because of its gravitational potential $\sim R_{SG}^{-1}$, which reduces the escape energy of the ejecta); σ is the outer shell's molecular opacity.

At later times, $t \gtrsim$ week, L rises again, roughly in proportion to R^2, up to its (second) maximum, which is reached between 16 and 10^2 days after the explosion, see Fig.7a. Almost all SNe are detected during this recovery epoch (= second rise) of their lightcurve.

A new era starts when the SN shell becomes transparent in the continuum, at $t_{tr} = \{\approx 50, \gtrsim 10^2\}$days after the explosion for SNe of type {I, II}; Fig.7a shows extreme time intervals of {30, 200}d for SNe {1993J, 1988A}. At this transit time, which was estimated in equ.(10), the spectrum changes from optically thick (photospheric) to thin (nebular). Thereafter, the expanding shell has lost most of its continuum photons, but still contains all of its resonance-line photons; it becomes an (energy-conserving) storage bag for the latter photons, (a bag that is likewise present in the slowest long-duration GRBs, mimicking a SN). Its luminosity L_{lines} was found to obey

$$(\partial_t + \tilde{t}^{-1})L_{lines} = 0 \quad \text{with} \quad \tilde{t} := \Delta r/v \approx 10^7\text{s}\ (\Delta r)_{16}/v_9 \qquad (12)$$

in (Kundt, 1988, equ. (22)) via a radiation-transfer calculation: Line photons suffer resonance scatterings on the atoms inside the filaments for months to years, during which time their diffusive leakage from the shell drops exponentially, with time constant $\tilde{t}$, as given in equ.(12).

A final important quantity to estimate is the onset time of radio emission from a SN, which should be controlled by the transparency of its progenitor's windzone at radio frequencies. In Kundt (1990, equ. (36)), its thermal free-free opacity τ_{ff} has been found to be

$$\tau_{ff} = (\int n_e^2\, ds)_{26.5}\ /\ T_5^{3/2}\ \nu_9^2 = \left\{ \begin{array}{c} 10^{-2.5}\ r_{15}^{-3}\ (\dot{M}_{(-6)}/\ v_8)^2 \\ 10^{0.5}\ r_{16}^{-3}\ (\dot{M}_{(-5)}/\ v_6)^2 \end{array} \right\} \nu_9^{-2} \quad , \qquad (13)$$

showing that the (thin, fast) windzone of a blue progenitor, of mass rate $\dot{M}$ velocity v – described by the upper line – is fully transparent ($\tau_{ff} \ll 1$) at GHz ($\nu_9 = 1$) already at radial distances beyond $r = 10^{14.5}$cm, whereas the (thick, slow) windzone of a red progenitor – lower line – stays opaque ($\tau_{ff} \gg 1$) at GHz out to radial distances beyond $r = 10^{16}$cm, corresponding to SN expansion ages (at $v_9 \approx 1$) of at least several months.

4. Supernovae of Type Ia, and SN Statistics

In the literature, one finds quite often the claim that SNe of type Ia came from exploding white dwarfs, even though already Oemler & Tinsley (1979) criticised it, (based on the frequent existence of short-lived progenitors). The debate is still fully alive, see Branch & Nomoto (2007). Why am I not convinced by this claim, (besides trusting Oemler & Tinsley)?

To begin with, (i) all SNe involve quite similar luminosities, energetics, timescales, masses, even morphologies, so that I would be surprised if a qualitatively different ejection mechanism existed. (Most considered mechanisms have a low ejection efficiency, hence would give rise to quite different appearances). In particular, (ii) SNe of type Ib look identical to those of type Ia, except for an intensity shift downward by one magnitude, but have been shown to stem from massive progenitors. Such a shift downward is readily explained by a deeper gravitational potential well, corresponding to a blue rather than a red progenitor. And (iii) the equal evolution timescales of SNe of type Ia and Ib are readily explained by involving similar masses of their ejected shells. Moreover, (iv) the erstwhile impression that the lightcurves of type Ia were all identical has long since given way to the recognition of a large scatter among them, i.e. to a number of different subtypes. More indirectly, (v) Frank Ritter (1986) has often stressed that white dwarfs tend to lose mass during their lives (towards 0.6 $M_\odot$), via explosions at their surfaces that overcompensate the gains; we would certainly deal with a small subset of all white dwarfs. And (vi) the Galactic scale height of $\lesssim$ 180 pc of the SNe of type Ia agrees with that of massive runaway stars. Finally, (vii) nuclear-chemically exploding white dwarfs may leave low-mass white dwarfs behind (instead of disintegrating), and be visible by forming planetary nebulae.

An ultimate concern of this communication are SN statistics: how abundant must their progenitors be? In particular: if the SN progenitors consist of all stars above some critical mass M_{crit}, how large must M_{crit} be? Historically, to my knowledge, $M_{crit}/M_\odot$ started out with 3, during the late 1970s, then gradually grew towards 5 – based on the relative numbers of white dwarfs, neutron stars and black-hole candidates, their birth events (novae and supernovae), and non-stellar remnants (planetary nebulae and SNRs) – but continued growing during the 1990s towards a present value of ≥ 8. Are there enough massive stars, above $8M_\odot$, to replenish the (large) neutron-star reservoir? I do not think so (Kundt, 2005).

In 1985, Blaauw counted the numbers of pulsars within 0.5 Kpc of the Sun, and the numbers of massive stars in the same volume, and concluded that M_{crit} had to equal $6M_\odot$ for their replenishment in a steady-state situation. In 1985, we had no good estimate yet of the (large) incompleteness of our knowledge of pulsars (with increasing distance), nor was it clear how many pulsars had non-pulsar (elder) brothers, observed as X-ray sources; (I estimate "all" of them have one, on average). So I like to read Blaauw's estimate with a "5" instead of the "6". This (slightly revised) estimate of Blaauw's is consistent with mine of 1998 (p.51), where I have evaluated the birth interval of neutron stars Δt in the Galaxy as

$$\Delta t = t \ f \ / \ N \lesssim 10 \text{ yr} \quad , \tag{14}$$

in which t (=$10^{6.4}$yr) is the mean lifetime of a pulsar (Taylor et al, 1993), f ($\epsilon(0.2, 1)$) its average beaming fraction, and N ($\gtrsim 10^{5.4}$) is the number of neutron stars in the Galaxy, corrected for incompleteness via their decrease with distance from the Sun (beyond 150 pc). From the initial-mass function of the Galaxy, I get above estimate of "5", (Kundt, 1998, 2005).

5. Summary

An update is presented of my lifelong work on supernovae, whose key building blocks are a saturated magnetic field and its decay product, a UHE relativistic cavity.

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