Chapter 15

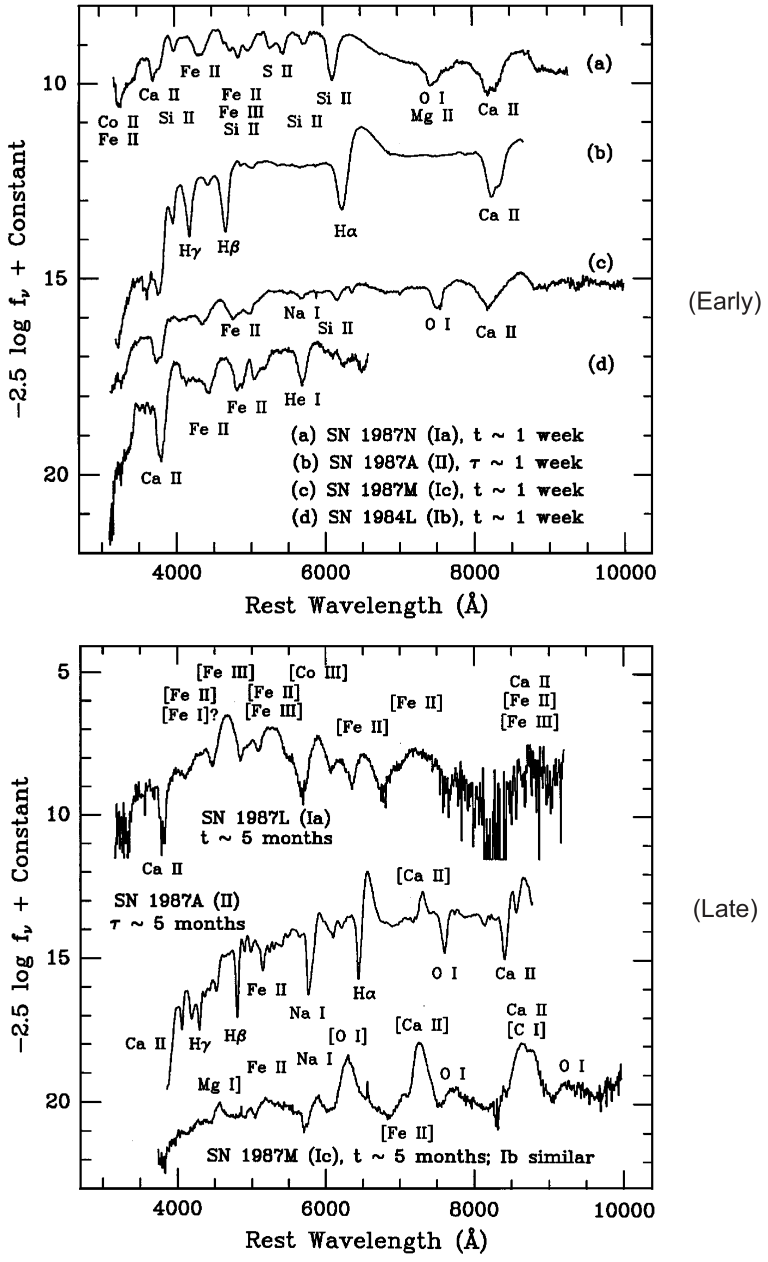
Supernovae

Supernovae represent the catastrophic death of certain stars. They are among the most violent events in the Universe, typically producing about 10^{53} erg, with a large fraction of this energy released in the first second of the explosion. For perspective, the total luminosity of the Sun is only about 10^{33} erg s^{-1}, and even a nova outburst releases only of order 10^{47} erg over a characteristic period of a few hundred seconds. There is more than one type of supernova, with two general methodologies for classification: (1) according to the spectral and lightcurve properties, or (2) according to the fundamental mechanism responsible for the energy release.

In addition to their intrinsic interest, supernovae of various types are of fundamental importance for a variety of astrophysical phenomena, including element production and galactic chemical evolution, potential relationship to some types of gamma-ray bursts, energizing and compressing the interstellar medium (implying a connection with star formation), gravitational wave emission, and applications in cosmology associated with standardizable candle properties. We begin our discussion by considering the taxonomy of these events.

15.1 Classification of Supernovae

The traditional classification of supernovae is based on observational evidence, primarily spectra and lightcurves. Some representative supernova spectra are displayed in Fig. 15.1 and some typical lightcurves are illustrated in Fig. 15.2. In most cases now we have at least a schematic model that can be associated with each class and that can account for the observational characteristics of that class. Those models suggest that all supernova events derive their enormous energy from either gravitational collapse of a massive stellar core or a thermonuclear runaway in dense, degenerate matter.



A. V. Filippenko, Annu. Rev. Nucl. Part. Sci. **35**, 309 (1997)

Figure 15.1: Early time and late time spectra for several classes of supernovae [58].

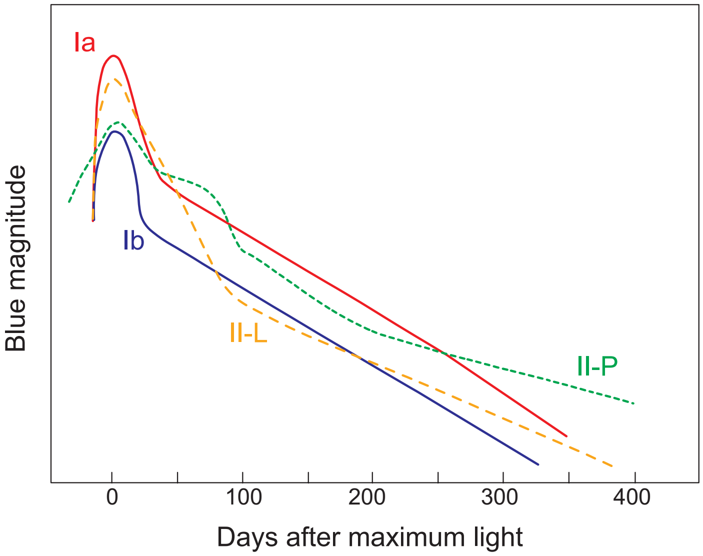


Figure 15.2: Schematic lightcurves for different classes of supernovae [58].

The observational characteristics of supernovae derive both from the internal mechanism causing the energy release (for example, collapse of a stellar core) and the interaction of the initial energy release with the surrounding outer layers or extended atmosphere of the star. Thus, some observational characteristics are direct diagnostics of the explosion mechanism itself, while others are only indirectly related to the explosion mechanism and instead are diagnostics for the state of the star and its surrounding medium at the time of the outburst. The standard classes of supernovae and some of their characteristics are illustrated in Fig. 15.3. The primary initial distinction concerns whether hydrogen lines are present in the spectrum, which divides supernovae into Type I (no hydrogen lines) and Type II (significant hydrogen lines). The standard subclassifications then correspond to the following characteristics:

15.1.1 Type Ia

A Type Ia supernova is thought to be associated with a thermonuclear runaway under degenerate conditions in a white dwarf that is accreting matter from a companion. This class of supernovae is sometimes termed a *thermonuclear supernova*, to distinguish it from all other classes that derive their power from gravitational collapse and not from thermonuclear reactions. No hydrogen is observed but calcium,

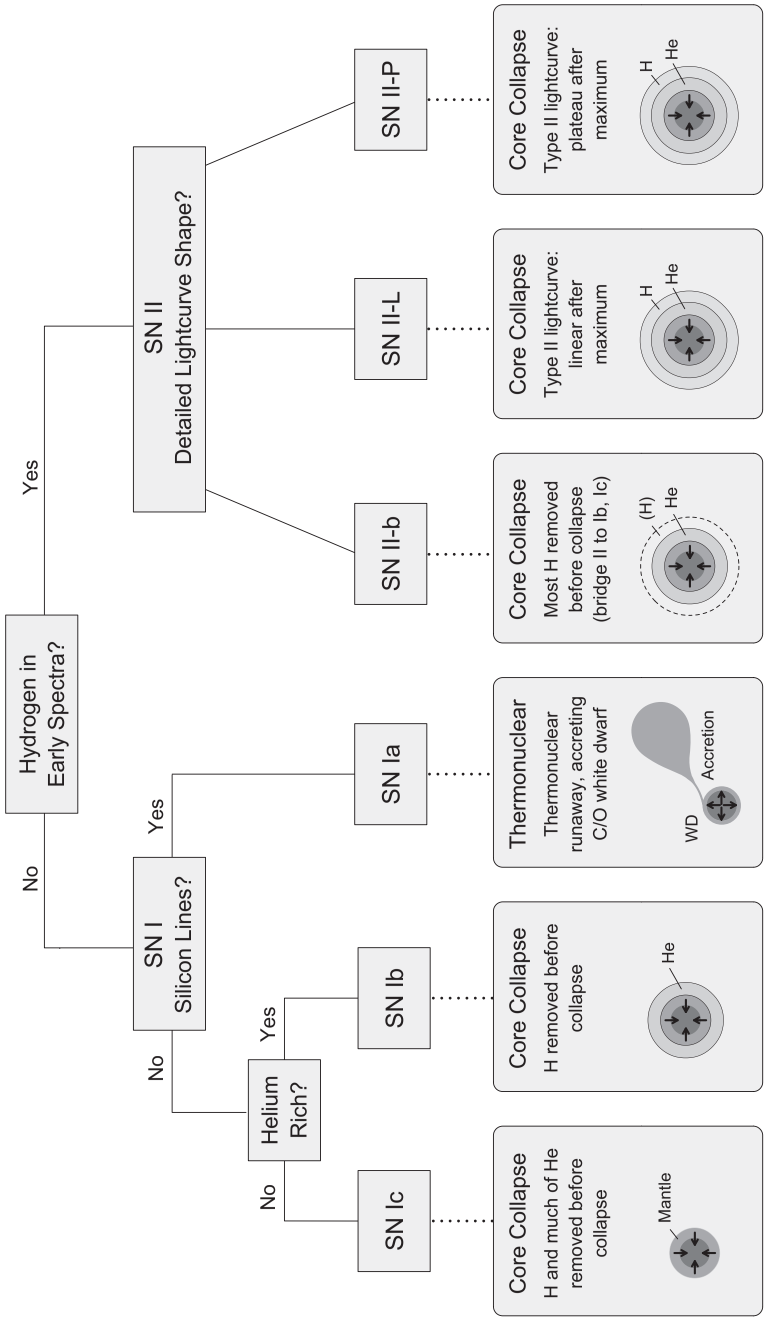


Figure 15.3: Classification of supernova events. Note that Type II-n is not shown here but discussed in the text.

oxygen, and silicon appear in the spectrum near peak brightness. Type Ia supernovae are found in all types of galaxies and their standardizable candle properties make them a valuable distance-measuring tool (see Box 15.1).

Box 15.1 Standard and Standardizable Candles

A *standard candle* is a light source that always has the same intrinsic brightness under some specified conditions. A *standardizable candle* is a light source that may vary in brightness but that can be standardized (normalized to a common brightness) by some reliable method. Standard candles, or standardizable candles, then permit distance measurement by comparing observed brightness with the standard brightness. Different Type Ia supernovae have similar but not identical lightcurves. Hence they are not standard candles. However, there are empirical methods that allow the lightcurves of different Type Ia supernovae to be collapsed to a single curve. Thus, they are standardizable candles. Type Ia standardizable candles are particularly valuable because their extreme brightness makes them visible at very large distances. The standardizable candle and brightness properties of Type Ia supernovae have made them a central tool in modern cosmology. For example, they are the most direct indicator that the expansion of the Universe is currently accelerating, implying that the Universe is permeated by a mysterious *dark energy* that can effectively turn gravity into antigravity.

15.1.2 Type Ib and Type Ic

Type Ib and Ic supernovae are thought to represent the core collapse of a massive star that has lost much of its outer envelope because of strong stellar winds or interactions with a binary companion (these are called *Wolf–Rayet stars*). For both Type Ia and Ib supernovae hydrogen and silicon spectral lines are absent, but helium lines are present for Type Ib supernovae. The distinction between Types Ia and Ib is thought to lie in whether only the hydrogen envelope has been lost before core collapse (Type Ib), or whether most of the helium layer has also been expelled (Type Ic). There is some observatational evidence (for example, from the polarization of detected light) that these classes of supernovae involve highly asymmetric explosions. Type Ib and Ic supernovae are found only in spiral galaxies, implying a relationship with regions of strong star formation (since such regions are characteristic of most spiral galaxies but not of elliptical galaxies).

15.1.3 Type II

Type II supernovae are characterized by prominent hydrogen lines. They are thought to be associated with the core collapse of a massive star and are found only in regions of active star formation (they are almost never found in elliptical galaxies, for example). Type II supernovae are further subdivided according to detailed spectral and light-curve properties:

1. ***Type II-P***: In the designation Type II-P, the P refers to a plateau in the light curve.
2. ***Type II-L***: In the designation Type II-L, the L refers to a linear decrease of the light curve in the region where a Type II-P lightcurve has a plateau.
3. ***Type II-b***: In a Type II-b event the spectrum contains prominent hydrogen lines initially, but the spectrum then transitions into one similar to that of a Type Ia,b supernova. The suspected mechanism is core collapse in a red giant that has lost most but not all of its hydrogen envelope through strong stellar winds, or through interaction with a binary companion. Type II-b supernovae are thus viewed as a link between Type II supernovae and Type Ib,c supernovae. Type II, Type Ib, and Type Ic all involve core collapse of a massive star, with the distinctions coming in how much of the envelope has been lost before the collapse of the core.
4. ***Type II-n***: In this class of core-collapse supernova, narrow emission lines and a strong hydrogen spectrum are present. Type II-n supernovae are thought to originate in the core collapse of a massive star embedded in dense shells of material ejected by the star shortly before the explosion.

Thus, all of the Type-II subcategories, and the Type Ib and Type Ic subcategories, correspond to a similar core-collapse mechanism. The observational differences derive primarily from differences in the outer envelope and their influence on the spectrum and lightcurve, not in the primary energy-release mechanism.

15.2 Type Ia Supernovae

A Type Ia supernova is thought to correspond to a thermonuclear explosion of an electron-degenerate, carbon–oxygen white dwarf that is triggered by accretion from a companion star in a binary system. Thus it differs fundamentally from all of the other classes of supernovae in Fig. 15.3.

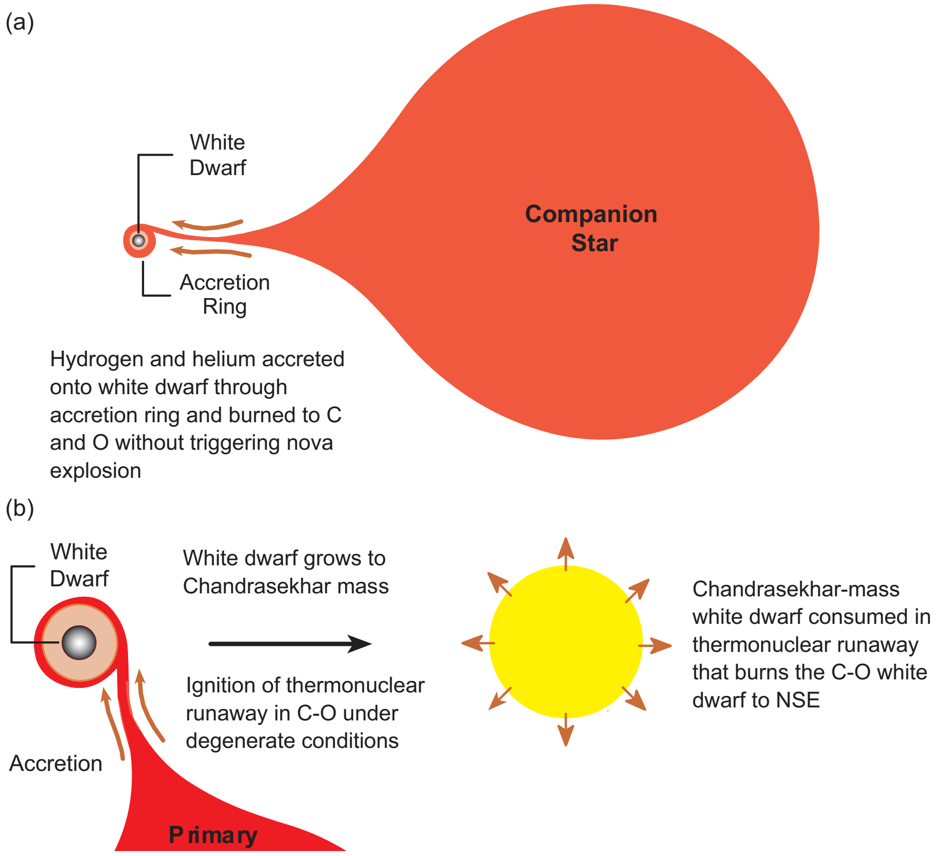


Figure 15.4: Mechanism for a Type Ia supernova.

15.2.1 The Favored Type Ia Mechanism

The Type Ia scenario is illustrated in Fig. 15.4. It is related to the nova scenario discussed in Ch. 14, in that both events are triggered by accretion from a companion onto a white dwarf. The difference is that in a nova situation a thermonuclear runaway is initiated in a thin surface layer after a certain amount of accretion and the white dwarf remains largely intact after the layer is ejected in the explosion, but in the Type Ia situation the matter accumulates on the surface of the white dwarf over a long period without triggering a runaway in the accumulated surface layers.

As the unburned matter accumulates, the mass of the white dwarf grows and can eventually approach the Chandrasekhar limit discuss in § 12.4.2. Near the Chandrasekhar limit the white dwarf becomes gravitationally unstable and fluctuations can trigger a thermonuclear runaway in the interior of the star that initially ignites carbon and oxygen and quickly (in a matter of a second or less) burns a large percentage of the mass of the white dwarf to iron-group nuclei, with an enormous release of energy (most of the iron in the Universe probably originates in Type Ia, and to a somewhat lesser degree, core-collapse, supernovae). Thus, unlike a nova, or a core-collapse supernova that we discuss further below, a Type Ia supernova does not leave behind a significant remnant of the obliterated white dwarf. An explanation of how this mechanism can lead to the standardizable candle properties of Type Ia supernovae, and a possible alternative explanation for the mechanism, are discussed in Box 15.2.

Box 15.2 Singly-Degenerate and Doubly-Degenerate Scenarios

The Type Ia mechanism proposed here is sometimes termed the "singly-degenerate model", since it involves only one degenerate object (the white dwarf). An alternative mechanism proposes the triggering of a thermonuclear burn by merger of two white dwarfs in a binary system. This is called the "doubly-degenerate" model, because it involves two degenerate objects. At present the singly-degenerate model appears to be in better accord with data, but neither model can yet describe all aspects of a Type Ia explosion without making assumptions that are not well tested by current observations.

One side benefit of the singly-degenerate model is that it can provide a plausible explanation for the observation that all Type Ia explosions are similar in intrinsic brightness (the standardizable candle property discussed in Box 15.1 that is crucial to modern cosmology). The Chandrasekhar mass is almost the same for all white dwarfs, so if the white dwarf that explodes is always near the Chandrasekhar mass it makes sense that the total energy produced by different Type Ia events is similar. In contrast, for the doubly-degenerate model there is no obvious reason for the sum of the masses of the two white dwarfs that merge to be similar in different events.

15.2.2 Thermonuclear Burning under Extreme Conditions

Because of the gigantic energy release in a small region over a very short period of time, the conditions in a Type Ia explosion are extreme. Simulations indicate that temperatures in the hottest parts can approach 10^{10} K, with densities as large as $10^9\ \mathrm{g\,cm^{-3}}$. The physics of the Type Ia explosion presents a number of issues that are difficult to deal with in the large numerical simulations that are required to model such events, as discussed in Box 15.3.

15.2.3 Element and Energy Production

The energy released in a Type Ia supernova explosion derives primarily from the thermonuclear burning of carbon and oxygen to heavier nuclei. If the explosion lasts long enough to achieve nuclear statistical equilibrium (NSE), the primary final products of this burning will be iron-group nuclei (unless the temperature becomes so high that all nuclei photodisintegrate into alpha particles). An example of network evolution under conditions typical of the Type Ia explosion in the deep interior of the white dwarf is illustrated in Fig. 15.5. In this calculation the initial temperature was $T_9 = 2$, the initial density was $\rho = 1 \times 10^{-8}$ g cm^{-3}, and the initial composition was assumed to be equal mass fractions of ^{12}C and ^{16}O.

The explosion is initiated by carbon burning, which quickly raises the temperature (see the inset to the figure) and initiates burning of oxygen and all the reaction products that are produced by carbon and oxygen burning. The rapid temperature rise is associated with the coupling of the large energy release from the thermonuclear burning described by the reaction network to the fluid of the white dwarf, which is described by hydrodynamics. The rise in the energy released is given by the curve marked with $+$ symbols in Fig. 15.5, which corresponds to the integrated energy released by the network to that point (in units of MeV per nucleon). This energy release (through the equation of state) causes a rapid rise in temperature in the fluid representing the white dwarf, and this in turn increases rapidly the rate of nuclear reactions in the network. The net result is the almost vertical rise in temperature from $T_9 \sim 2$ to $T_9 \sim 6.6$ in a period of less than 10^{-5} s, during which time the isotopic species in the network have increased from two to about five hundred, with significant population of the iron group of nuclei already evident (see the population distribution versus proton number and neutron number in the lower portion of Fig. 15.5).

The very narrow range in time in Fig. 15.5 over which the network releases much of its energy and over which the temperature rises from $T_9 \sim 2$ to $T_9 \sim 6.6$ is illustrated in greatly expanded scale in Fig. 15.6. In this case the rate of energy production dE/dt, in units of MeV per nucleon per second, is indicated by the curve with $+$ symbols. Notice the rapid increase in population for hundreds of new elements. Under these conditions, as the thermonuclear flame burns through the white dwarf the carbon and oxygen fuel in each region is burned in a tiny fraction of a second, and the entire white dwarf is consumed on a timescale of less than a second.

Box 15.3 Thermonuclear Burns: DeFlagration and Detonation Waves

In the Type Ia explosion there is a thermonuclear burn corresponding to conversion of carbon and oxygen fuel into heavier elements by nuclear reactions that release large amounts of energy. This burn is extremely violent and involves energy and temperature scales far beyond our everyday experience, but it shares many qualitative properties with ordinary chemical burning. There is a *burn front* that proceeds through the white dwarf, with “cooler” (that being a relative term!) unburned fuel in front and hot burned products (ash) behind. This burn front can be remarkably narrow—as small as millimeters. Thus there are two extremely different distance scales characterizing the explosion: the size of the white dwarf, which is of order 10^4 km, and the width of the burn front that consumes it, which can be billions of times smaller. This presents severe difficulties in accurately modeling Type Ia explosions, since standard numerical approaches to solving the eqations governing the explosion cannot handle such disparate scales without drastic approximation.

In thermonuclear and ordinary chemical burning there is an important distinction associated with the speed of the burn front. If the burn front advances through the fuel at a speed less than the speed of sound in the medium (subsonic), it is termed a *deflagration wave.* In a deflagration fuel in front of the advancing burn is heated to the ignition temperature by conduction of heat across the burn front (recall that matter described by a degenerate equation of state is a very good thermal conductor, much like a metal). On the other hand, if the burn front advances at greater than the speed of sound in the medium (supersonic) it is called a *detonation wave.* In a detonation a shock wave forms and the fuel in advance of the burn front is heated to ignition temperature by shock heating. Generally detonation is much more violent than deflagration.

Deflagrations and detonations produce different isotopic abundance signatures in the ash that is left behind (roughly, deflagration tends to burn rather completely to iron-group nuclei but detonation produces also many isotopes intermediate in atomic number between carbon–oxygen and iron). The detailed observational characteristics of Type Ia supernovae (in particular, the elemental abundances detected in the expanding debris) could be accounted for most naturally if we assume that part of the burn is a deflagration and part of it is a detonation. This is a difficulty for the theory because general considerations suggest that the explosion starts off as a deflagration and it is not easy to get the burn in computer simulations to transition to a detonation without making significant untested assumptions. Thus, we believe that the proposed Type Ia mechanism is plausible in outline, but there are bothersome details that leave some doubt about whether we understand fully the mechanism of these gigantic explosions.

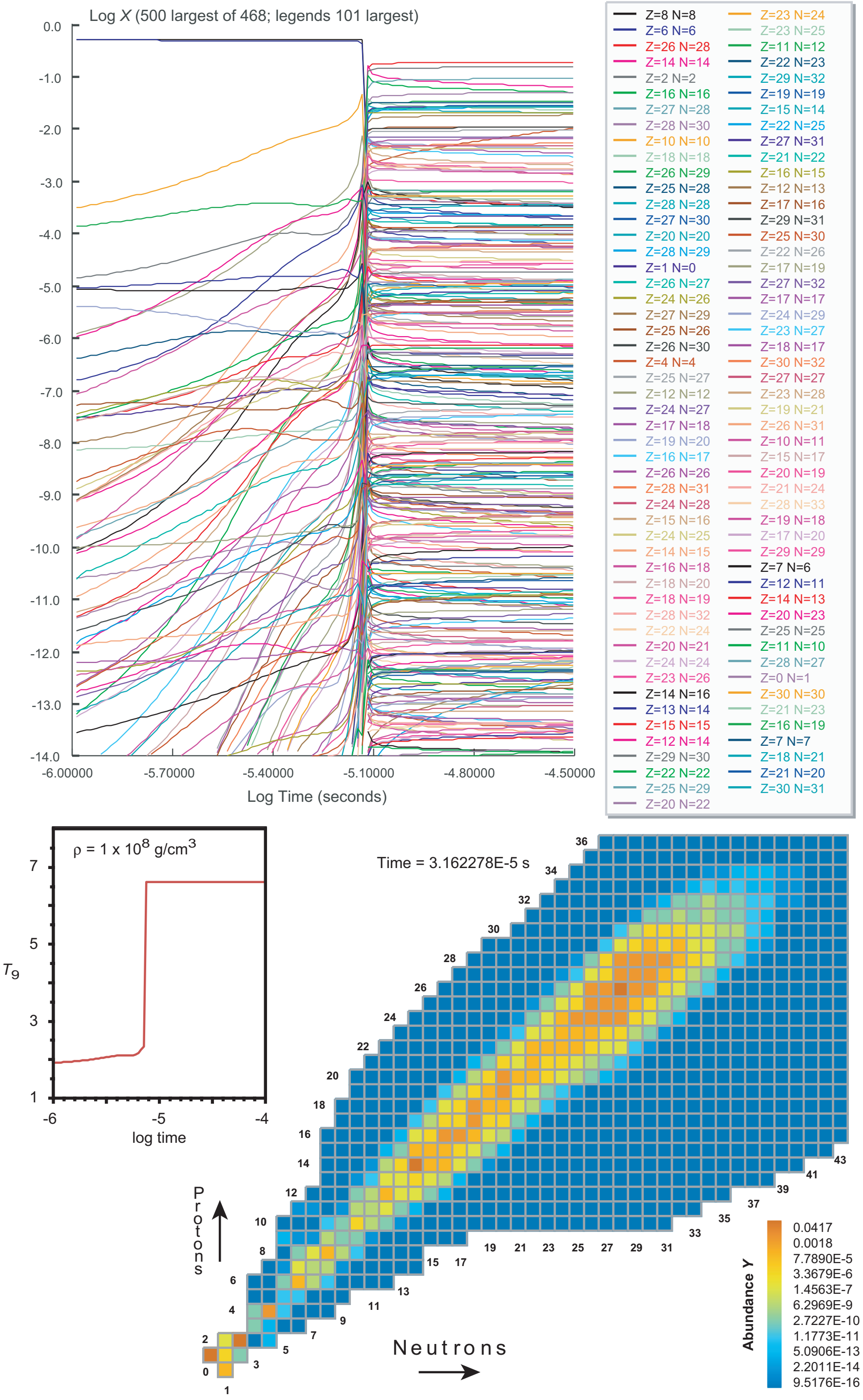


Figure 15.5: Element production in a Type Ia explosion. Upper: mass fractions X for 468 isotopes and integrated energy production $\sum E$ in MeV per nucleon. Lower: distribution of abundances Y for all isotopes at end of calculation in the upper figure. Inset on left shows the variation of temperature with time (density remains almost constant over this time period).

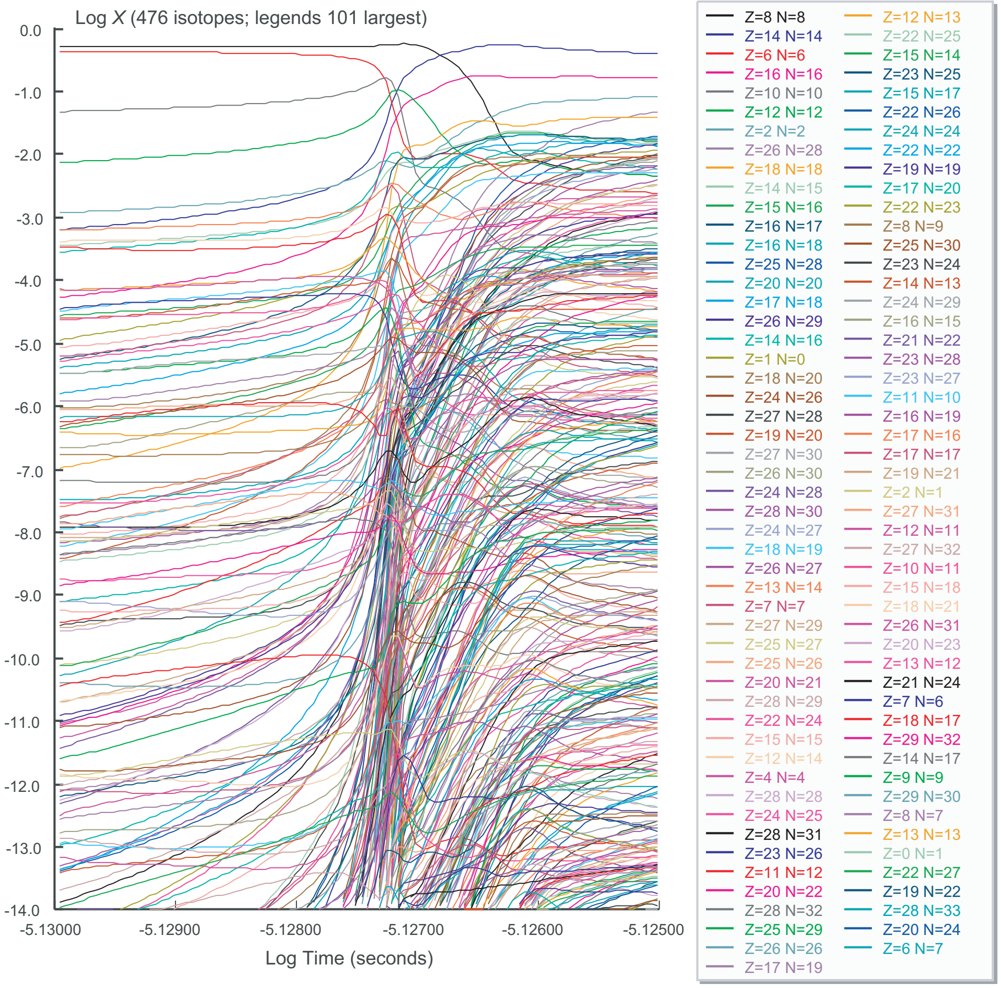


Figure 15.6: Calculation of Fig. 15.5 with the timescale greatly expanded in the region where much of the energy is released and there is a rapid increase in temperature.

15.3 Core-Collapse Supernovae

A core-collapse supernova is one of the most spectacular events in nature, and is almost certainly the source of the heavy elements that are produced in the rapid neutron capture or r-process. Considerable progress has been made over the past two decades in understanding the mechanisms responsible for such events. This understanding was tested both qualitatively and quantitatively by the observation