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Supernovae: the Final Fate of Stellar Evolution ⋆

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Abstract. We revise recent theoretical developments of models of Type Ia and Type II Supernovae, with particular attention to the evolutionary history of the progenitors.

1. Introduction

Stellar evolution naturally leads stars toward the development of a degenerate core. When the mass of this core exceeds the Chandrasekhar limit, it becomes unstable. The immediate future is not so evident. In some stars, the core collapses and forms a neutron star (NS) or a black hole (BH). Type II supernovae are connected with this phenomenon: after the formation of the stiff neutron star the collapse is reversed into an explosion. In other cases the core heats up and explosive thermonuclear burnings are ignited. This is the case of type Ia supernovae, which explode as a consequence of the uncontrolled C ignition in degenerate conditions. A summary of the present status of our knowledge in this field is reported in Tab. 1, where we show the final fate of single stars with different initial mass. In the following, we synthetically revise the theoretical study concerning the most frequent types of observed supernova events, namely: SNe Ia and SNe II.

⋆ Talk at http://sait.oat.ts.astro.it/MSAIS/3/POST/straniero_talk.pdf

Table 1. Final fate of single star evolution.

Mass($M_\odot$)	Lifetime	Final Fate
< 0.8	$> 1/H_0$	still in MS or pre-MS
0.8-8	0.03-15 Gyr	CO WD 0.5-1.1 $M_\odot$
8-11	10-30 Myr	ONeMg WD $\sim 1.3 M_\odot$
11-100	1-10 Myr	Fe core 1.2-2.5 $M_\odot$, collapse in NS or BH
> 100	≤ 1 Myr	O core suffers pair instability, BH or complete disruption

2. Type Ia Supernovae

Well established observational evidence demonstrates that type Ia Supernovae (SNe Ia) result from thermonuclear disruptions of CO White Dwarfs (WDs), which accrete matter from their companions in binary systems. This scenario, first proposed by Hoyle (1960), explains several observational properties of SNe Ia, like the optical outcomes, and the longevity of some progenitors.

Although this general picture is universally accepted, there is no clear consensus on the physical description of the flame propagation (see e.g. Hillebrandt (2000)). Since the nucleosynthesis induced by the thermonuclear explosion depends on the velocity of the burning front, the analysis of the SN ejecta may discriminate between different theoretical scenarios. In the case of pure deflagration models, the burning front moves outward with a velocity smaller than the local sound speed and, in turn, unburnt Carbon is left in the external layers. On the contrary, in detonation models, the burning front advances in supersonic regime and a complete incineration of the progenitor into Iron peak elements takes place. Both these occurrences does not fit the observed SNe Ia spectra, which exhibit the presence of intermediate mass elements. As it happens, the reality could be in the middle. Thus, it is common opinion that the flame initially propagates as a deflagration and, later on, when zones with density lower than a certain critical value (ρ_{tr}) are encountered, it suddenly accelerates becoming a detonation. This is the Delayed Detonation model Khokhlov (1991). As a matter of fact the presently available successful models of SNe Ia are obtained by assuming an *ad hoc* transition density between deflagration and detonation. These results are mainly based on 1D hydrodynamic calculations, while just preliminary results from multi-dimensional computations are available Reinecke (2002).

Alternative models have been also proposed, such as the He-Detonation one. In this case, a sub-Chandrasekhar progenitor suffers a violent shell He-burning that induces the formation of an inward and an outward shock waves. Nevertheless, this model also fails in reproducing the observed SNe Ia events. As a result, the ejecta should contain too much unburned helium and iron-peak elements than those measured in typical spectra at maximum of SNe Ia Woosley (1994).

The precise nature of the binary system is also debated. In particular, the initial orbital parameters and the following evolutionary path of the stellar pair, leading to a successful explosion are still unknown. Two main scenarios have been proposed: the Single Degenerate (SD) and Double Degenerate (DD). The first implies a system composed by a WD and an unevolved star (dwarf or red giant). We recall that according to the current stellar evolution theory, the maximum WD mass should be substantially smaller than M_{Ch} (see Tab. 1). If the unevolved companion fills its Roche lobe, H-rich material is deposited onto the WD Whelan (1973). Similar systems do exist in nature in several evolutionary stages. They are well studied and produce a variety of observational events, such as classical novae, cataclysmic variables, dwarf novae and the like. In this framework, a SNe Ia event may be produced if the accreted Hydrogen can be converted, via nuclear burning, into Helium and, then, into a C-O, thus inducing the increase in mass of the underlying degenerate core up to M_{Ch}. However, recent numerical results (Cassisi (1998), Piersanti (1999), Piersanti (2000), Piersanti (2001)) show that in SD systems the WD can't grow up to M_{Ch}, for any reasonable H-accretion rate. The various evolutionary scenarios are summarized in Fig. 1. If the accretion rate is very small (lower than $10^{-9} M_{\odot} yr^{-1}$) the accreting structure experiences nova-like H-flashes and the major part (likely all) of the matter accreted during the quiescent phase is expelled. For higher values of the accretion rate ($10^{-9}-10^{-7} M_{\odot} yr^{-1}$) an He-buffer is piled up, as a consequence of the H-burning. In this case, the He-shell flash, which is ignited when the He-buffer reaches a critical mass, is rather violent. Even if this flash is not dynamical, it is so energetic to determine the expansion of the entire He-rich zone and of the overlying H-rich layers, thus producing a common envelope configuration; hence, the frictional interaction of

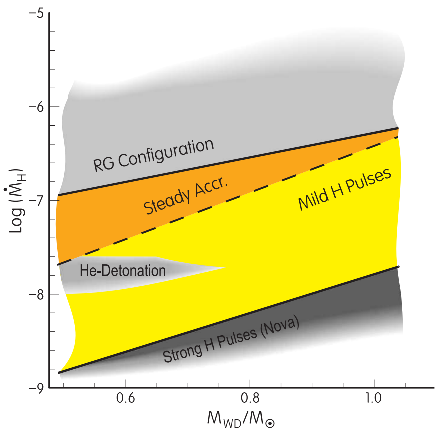

Fig. 1. Configurations of H-accreting CO WDs (SD scenario) as a function of accretion rate and mass of the WD.

the binary components with the common envelope determines the lost of a large part of the expanded material, thus preventing the efficient increase in mass of the core. In some cases, the accretion rate allows the accumulation of a massive He-rich layer and an He-Detonation occurs. Finally, a faster accretion ($\dot{M} > 10^{-7} M_\odot yr^{-1}$) induces an efficient H-burning in the top layer of the star, which directly becomes a red giant.

In the alternative scenario, the DD one, the progenitor system of SNe Ia is a binary composed by a pair of CO WDs, whose total mass is of the order of or greater than M_{Ch}. The initial separation should be such that the merging of the two components occurs in a time smaller than the Hubble time, as a consequence of the energy and angular momentum losses driven by gravitational wave emission (Iben (1984a), Iben (1984b), Webbink (1984)). In this case, the less massive component, which first fills its own Roche lobe, undergoes a dynamical mass transfer, thus completely disrupting itself and forming an accretion disk around the more massive one. As a consequence CO-rich matter is directly accreted onto the WD. This scenario well explains some observational features of SNe Ia, such as the total lack of Balmer lines in the spectra, and provides a very easy evolutionary path for the accreting WD to approach the Chandrasekhar mass limit (no problems with He-shell flash). Nevertheless, two main arguments have been arisen against this scenario:

1. the observational search of DD systems with the right orbital parameters to represents good candidates as SNe Ia progenitors has provided negative results (Robinson (1987), Bragaglia (1990), Saffe (1998));
2. on the theoretical point of view, if a merging occurs, the rate at which matter is effectively deposited onto the WD is very high (of the order of the Eddington limit) so that the growth in mass of the structure stops well before the Chandrasekhar limit due to the off-center ignition of C-burning. In this case the final outcome is an ONeMg WD, not a SN Ia event (Nomoto (1985), Saio (1985), Saio (1998)).

Nevertheless, the recent detection of one DD system with the right orbital parameters to represent good candidate as SNe Ia progenitors has driven the attention once again to DD systems Koen (1998). In particular, it has been demonstrated that the evolution of the two degenerate components should be significantly revised if stellar rotation is properly taken into account (Piersanti (2003)). Due to the tidal interaction between the two WDs, the system becomes synchronized on a very short time scale. Thus, at the epoch of the merging, each component rotates around its own rotational axis with the keplerian angular velocity of the system, which is very large (~ 0.2 rad s^{-1}). If rotation is included in modeling both the thermal evolution of the accreting WD and the evolution of the thick disk from which matter is accreted, the final outcome of a merging is substantially changed. In fact, due to the very high rate at which matter is deposited onto the WD, the structure expands; in addition the deposition of angular momentum by the accreted matter determines the spinning up of the WD. As a consequence, the star attains a critical configuration in which the centripetal force becomes equal to the gravitational one at the equator. As a consequence of the inward diffusion of heat, the accretion rate decreases and the star contracts. During this phase, rotation acts as a tuning mechanism of the accretion process. The occurrence of the gravitational instability plays a pivotal role: from one hand it prevents the occurrence of the off-center C-burning and, on the other one, determines the decrease of the accretion rate. Due to the continuous increase of the angular velocity, caused by angular momentum deposition from the accretion disk, the accreting WD breaks the spherical symmetry and adopts a tri-axial configuration. Thus, rotational energy is lost by Gravitational Wave Radiation (GWR) and an almost stationary accretion is attained. The accretion rate is now definitively lower than the Eddington limit. When the WD approaches the Chandrasekhar mass limit (for our rotating structure it is $\sim 1.5M_{\odot}$), a central carbon ignition takes place, giving rise of an SNe Ia event. Viscous dissipations affecting the final part of the steady accretion phase may eventually accelerate the occurrence of the thermonuclear explosion.

3. Type II Supernovae

These kind of Supernovae are commonly related to the gravitational collapse of the iron core of massive stars. Even if there are many observations confirming this connection, the available theoretical models actually fail in demonstrating that a minimal part of the total energy generated by the core collapse (1 % of $\sim 10^{53}$ ergs) may be converted into explosion energy. This is one of the most intriguing open questions in modern physics and astrophysics. A detailed description of the progenitor evolution can be found in Limongi (2000) (see also the contribution of M. Limongi). The core evolves and contracts in such a way that the central density is nearly proportional to T^3. Deviations from this general rule are due to the nuclear burning contribution to the energy balance. They are more pronounced in less massive stars, where the partial degeneracy of the electron component of the stellar plasma in the core induces a more violent reaction to the fuel ignition. From the C-burning up to the core collapse, the evolution of the progenitors is dominated by energy loss due to thermal neutrino production rather than by photon emission, as it happen in *normal* stars. The corresponding evolution of the various convective regions (after the core He-burning) are reported in Fig. 2. These convective regions are driven by powerful sources of energy, so that the figure illustrates the efficiency of the various core and shell burning stages. Since the end of the central Oxygen burning, the number of electrons per nucleon (Y_e) is lowered by weak interactions. The internal profile of Y_e at the onset of the core collapse is shown in Fig. 3. Note that gravity is mainly balanced by the pressure of degenerate electrons. The iron core is limited by the external border of the convective zone powered by the shell Si-burning. This border is clearly marked by an evident drop in the Y_e profile. Taking $Y_e = 0.45$ as an average value representative of the pre-collapse core, for a perfect fully degenerate gas, one find $M_{Ch} = 1.18$, which is somewhat lower than the calculated final core masses[1]. If the degenerate core exceeds M_{Ch}, it should collapse on a thermal timescale. This collapse is helped by electron captures (which reduce the electron contribution to the total pressure) and, in more massive stars, by photodisintegrations (which absorb the thermal energy released by the core contraction).

When the innermost part of the collapsing core approaches the nuclear density, a sort of giant nucleus (of the order of $1M_{\odot}$) forms and, in turn, the pressure suddenly rises up. Nevertheless, due to

[1] For a more precise evaluation of M_{Ch}, deviations from the perfect gas as well as corrections due to the non complete degeneracy should be considered.

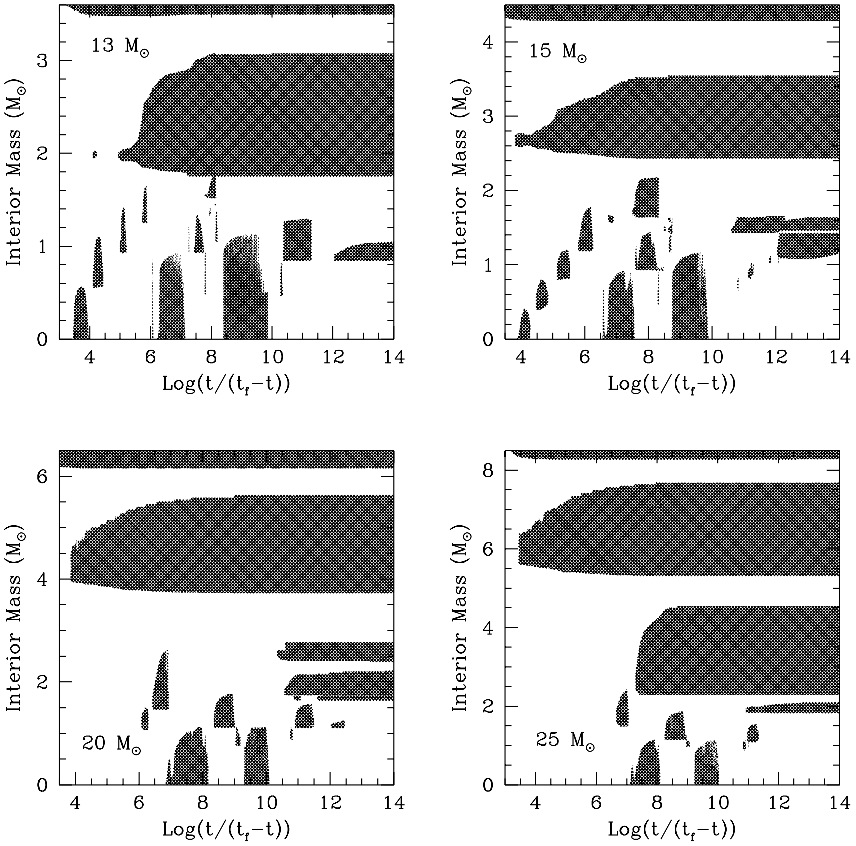

Fig. 2. Convective regions (shaded areas) which develop during the advanced evolution of massive stars.

the acquired kinetic energy, the density of this homologous core ($v \propto r$) can exceed the nuclear density by a factor of several. Then, like a spring, it re-bounces outward, while, immediately outside, matter continues to fall in and a shock wave forms. By neglecting energy losses, the outward motion of the core should be capable to push backward the infalling material, well outside its pre-collapse position, thus explaining the observed explosions. This is not the case. The outcoming shock heats up the matter; as the temperature increases, photo-disintegrations take place. As a consequence, the shock spends about 10^{51} erg passing through 0.1 $M_{\odot}$ of infalling material. A second important dissipation process that prevents the prompt explosion is the energy loss by neutrino emission. Neutrinos are trapped only if the density is larger then $10^{12} gcm^{-3}$. At lower density, a consistent part of the shock energy is converted into neutrinos (via $e^{-}, p \rightarrow n, \nu_e$) and it is lost. For this reason, the most recent calculations found that this energy dissipation stalled the shock, except in the case of a particularly low core mass of the progenitor (Bruenn (1989a), Bruenn (1989b), Myra (1989), Baron (1990)). It is now believed that a correct treat-

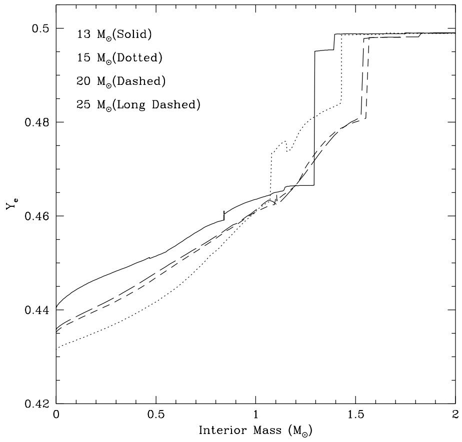

Fig. 3. Number of electron per nucleons (Y_e) in the Iron core of massive stars at the onset of the collapse.

ment of the convective mixing could allow a deposition of part of the neutrino energy, thus reviving the shock after about 0.1 s. Multidimensional calculations are obviously required in order to describe the convective energy transport (Herant (1992a), Burrows (1993a), Herant (1994b), Bruenn (1994c), Burrows (1995b), Janka (1995a), Janka (1996b), Mezzacappa (1998a), Mezzacappa (1998b), Kifonidis (2000)).

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