Type Ia supernovae and the DD scenario

J. Isern\textsuperscript{1,2}, E. García–Berro\textsuperscript{2,3}, and P. Lorén–Aguilar\textsuperscript{2,3}

\textsuperscript{1}Institut de Ciències de l’Espai (CSIC), Facultat de Ciències, Campus UAB, Torre C5-parell, 08193 Bellaterra, Spain

\textsuperscript{2}Institute for Space Studies of Catalonia, c/Gran Capità 2–4, Edif. Nexus 104, 08034 Barcelona, Spain

\textsuperscript{3}Departament de Física Aplicada, Universitat Politècnica de Catalunya, c/Esteve Terrades 5, 08860 Castelldefels, Spain

Abstract. Type Ia supernovae are thought to be the outcome of the thermonuclear explosion of a white dwarf in a close binary system. Two possible scenarios, not necessarily incompatible, have been advanced. One assumes a white dwarf that accretes matter from a nondegenerate companion (the single degenerate scenario), the other assumes two white dwarfs that merge as a consequence of the emission of gravitational waves (the double degenerate scenario). The delay time distribution of star formation bursts strongly suggests that the DD scenario should be responsible of the late time explosions (Totani et al. 2008), but this contradicts the common wisdom that the outcome of the merging of two white dwarfs is an accretion induced collapse to a neutron star. In this contribution we review some of the most controversial issues of this problem.

1. Introduction

Supernovae are characterized by a sudden rise of their luminosity, by a steep decline after maximum light that lasts several weeks, followed by an exponential decline that can last several years. The total energy involved output turns out to be \( \sim 10^{51} \) erg. Such amount of energy can only be obtained in two ways, from the gravitational collapse of an electron degenerate core to form a neutron star or a black hole or from the thermonuclear incineration of a carbon-oxygen degenerate core.

From the spectroscopic point of view, Type Ia supernovae are characterized by the absence of hydrogen and the presence of a prominent Si II line at maximum light (in fact these are the characteristics that define the class). From the photometric point of view they experience a sudden rise to maximum of light, \( \langle M_B \rangle \sim -19^{\text{mag}} \), in 20 days or less, followed by a sudden decline of \( \sim 3^{\text{mag}} \) in 30 days, and an exponential tail with a characteristic time \( \sim 70 \) days. From the point of view of the galaxies hosting supernovae, it was immediately realized that SNIa occur in all galaxy types in contrast with all the other supernova types that only appear in galaxies with recent star formation activity. It is interesting to notice here that the SNIa rate correlates with the star formation rate (Sullivan et al. 2006), indicating that the progenitors must be able to produce prompt and delayed explosions. All these arguments immediately led to the conclusion that SNIa were caused by the thermonuclear explosion of a carbon-oxygen white dwarf.
near the Chandrasekhar mass in a close binary system, an idea strongly supported by the remarkable spectro-photometric homogeneity displayed by this kind of supernovae (Cadonau et al. 1985; Filippenko 1997).

However, despite the homogeneity of Type Ia supernovae, when observed in detail some differences have appeared over the years. It is known there is a group of SNIa with light curves showing very bright and broad peaks, the SN1991T class, that represents the 9% of all the events. There is another group with very dim and narrow peaks that lack of the characteristic secondary peak, the SN1991bg class, that represent the 21% of all the events. To these categories it has been recently added a new one that contains very peculiar supernovae, the SN2002cx class, that represents the ~ 4% of the total. These supernovae are characterized by a high ionization spectral features in the pre-maximum, like the SN1991T class, and by a very low luminosity and the lack of secondary maximum, like the SN1991bg class. The remaining ones, which amount to ~ 66%, present normal behaviors and are known as Branch-normal. However, even the normal ones are not completely homogeneous and show different luminosities at maximum and light curves with different decline rates (Li et al. 2011).

Despite the substantial advances made during the last years, the basic question of which systems explode has not been satisfactorily answered yet. There is a wide consensus that the progenitors have to be composed by a carbon-oxygen white dwarf and a close enough companion able to provide the mass necessary to trigger the thermonuclear instability. Several evolutionary paths leading to the instability have been identified (Postnov & Yungelson 2006). The systems able to explode can be classified according to the nature of the donor (normal or degenerate stars, also known as SD or single degenerate scenarios and DD or double degenerate scenarios) and the composition of the accreted matter (hydrogen, helium or a mixture of carbon and oxygen).

The first systems identified as potential supernova progenitor were those formed by a white dwarf that accretes hydrogen (Whelan & Iben 1973). There are many types of these systems: cataclysmic variables, classical novae, recurrent novae, symbiotic stars and supersoft X-ray sources. If the accretion rate is smaller than ~ $10^{-9}\ M_\odot\ yr^{-1}$, the accreted matter becomes degenerate and experiences a strong flash that can be identified with a nova. However, such events not only eject all the accreted mass but also erode the white dwarf preventing it from reaching the critical mass. The accreted mass can only be retained if $M_{\text{WD}} > 1.35\ M_\odot$, but white dwarfs with such initial masses are made of oxygen and neon (Gil-Pons & García–Berro 2001; Gil-Pons et al. 2003) and cannot explode as a SNIa. Thus, only white dwarfs that have experienced a previous accretion episode can reach the Chandrasekhar’s mass at such rates. For intermediate rates, $10^{-9} \leq M_{\text{H}} (M_\odot/\text{yr}) \leq 5 \times 10^{-7}$, hydrogen burns steadily or through mild flashes which accumulate a helium buffer on top of the carbon-oxygen core. If the accretion rate is high enough, the freshly formed helium is converted into carbon and oxygen through weak flashes or steady burning and the white dwarf can approach to the Chandrasekhar mass. But if the accretion rate is roughly in the range $10^{-9} \leq M_{\text{H}} (M_\odot/\text{yr}) \leq 5 \times 10^{-8}$, the helium layer explodes under degenerate conditions and can trigger the explosion of all the star (Nomoto 1982).

One of the problems posed by the SD scenario is that to avoid the constraint imposed by novae, the accretion rates have initially to proceed at a high rate and this makes white dwarfs hot and potentially detectable as X-ray sources. If it is assumed that all SNIa come from supersoft X-ray sources, the number necessary to sustain the estimated rate of supernovae in M31 or the Milky Way is ~ 1 000 while current surveys have only
detected between $\sim 10$ and $100$. In the case of elliptical galaxies the problem seems to be even worst. At the first glance it seems that this argument favors the DD scenario. However, to form a DD the system must evolve through two common envelope stages and this means that they will appear for some time, $> 10^6$ yr, as symbiotic stars with a white dwarf burning hydrogen at the surface. It is therefore clear that the problem lies on the observational properties of these high-rate accreting sources (Di Stefano 2010).

A possible way to overcome this problem could consist on the formation of heavy winds able to hide the nuclear burning white dwarf, as well as to consider variable accretion rates able to produce successively symbiotic stars, supersoft X-ray sources and, when the white dwarf is massive enough, recurrent novae. In any case, plausible evolutionary paths have been advanced (Hachisu et al. 2008). Minor possible objections to this scenario come from the non-detection of the hydrogen stripped from the companion by the explosion and the non-detection of the surviving star in the case of recent events in the Milky Way.

Close enough binaries formed by two intermediate-mass stars can experience two episodes of common envelope evolution and form a double degenerate system made of two carbon-oxygen white dwarfs. The emission of gravitational waves further reduces the orbit and, if the separation of both white dwarfs is not too large, they eventually merge in less than a Hubble time (Webbink 1984; Iben & Tutukov 1985). The main advantages of the DD scenario are that there are several known systems able to merge in a short time, although their mass is smaller than the critical mass, and that the time distribution of the persistent component of SNIa in galaxy clusters is only compatible with the merging of two white dwarfs (Maoz et al. 2010). The main problem of this scenario is that if the accretion rate is spherically symmetric, $\dot{M} \geq 2.7 \times 10^{-6} M_\odot$ yr$^{-1}$ and the entropy of the infalling matter is neglected, the white dwarf ignites off center and becomes an oxygen-neon white dwarf (Nomoto et al. 1985) that eventually collapses to a neutron star (Nomoto & Kondo 1991). Probably, this approach is extremely simple since the accreted matter has also angular momentum that it is incorporated to the white dwarf. Therefore it is obvious that the coupling between the disk and the rotating white dwarf is a critical issue (Piersanti et al. 2003a,b; Saio & Nomoto 2004).

There are two scenarios in which a white dwarf can directly accrete helium. One is a double degenerate with a secondary made of helium that merge as a consequence of the emission of gravitational waves, the other is a single degenerate scenario in which the secondary is a non-degenerate helium star and the mass transfer is powered by helium burning. One-dimensional models indicate that helium can ignite just above the base of the freshly accreted mantle under degenerate conditions. The high flammability of helium together with the low density of the envelope induces the formation of a detonation that incinerates the envelope and triggers the thermonuclear explosion of all the accretor despite the fact that its mass is smaller than the Chandrasekhar’s mass (Nomoto 1982).

Sub-Chandrasekhar models are not the favorites to account for the bulk of supernovae. The reason is that they predict the existence of a very fast moving layer made of $^{56}$Ni and $^4$He that is not observed (Hoeflich et al. 1996). However, if it were possible to neglect the contribution of this outer layer, these explosions could nearly reproduce the gross features of SNIa explosions with a single parameter, the initial mass of the white dwarf (Sim et al. 2010). In this sense, it is important to realize that the process of formation of the mantle is quite complex and far from the simple description of matter accreted with spherical symmetry, at a constant rate and with the same entropy as the
envelope, opening the possibility to trigger the detonation of the white dwarf without incinerating the outer He layer (Guillochon et al. 2010).

2. The fate of DD mergers

The temporal evolution of the merging of two white dwarfs has been computed using SPH techniques by several groups (Benz et al. 1990; Rasio & Shapiro 1994; Segretain et al. 1997; Guerrero et al. 2004; Rosswog 2007; Lorén-Aguilar et al. 2009). A common feature of all these simulations is that the secondary is destroyed in a dynamical timescale, i.e. a few orbital periods, after filling the Roche lobe and forms a thick and hot accretion disk around the primary. The impact of the disrupted secondary on the primary is not able to induce a prompt ignition (Guerrero et al. 2004) and a rotating hot corona surrounded by a thick disk formed. Because of the timescales involved, a detailed self-consistent simulation of the evolution of such a configuration (corona and disk) has not yet been performed. However, by mapping the 3D results into 1D simulations, Yoon et al. (2007) were able to find the conditions to avoid the off-center ignition. They found that the interface do not reaches the ignition temperature when quasi-static equilibrium is achieved, that the timescale for neutrino cooling is shorter than the timescale for angular momentum dissipation, and finally that the mass accretion rate is \( \leq 5 \times 10^{-6}, 10^{-5} M_\odot \text{yr}^{-1} \).

These results were challenged by D’Souza et al. (2006) and Motl et al. (2007) on the basis of simulations performed using grid techniques. The main difference was that in grid based methods the donor was not destroyed on a dynamical timescale but suffered mass transfer episodes during many orbital periods. Therefore, if the mass transfer is stable, the accretion rate would be determined by the rate at which gravita-
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Figure 2. Temperature distribution after merging. The presence of a hot corona surrounded by a thick Keplerian disk is clearly seen.

Confocal waves remove angular momentum. The problem was reexamined by Dan et al. (2011), who have shown that the origin of the discrepancies is at the initial conditions imposed to the SPH simulations. In these simulations, the Roche limit was very deep in the secondary and the initial mass transfer very large. When the reliable initial conditions are adopted, carefully allowing the stars to relax to their equilibrium configuration before the beginning of the mass transfer, the binary can survive for hundreds of orbital periods (Dan et al. 2011).

We have performed a new simulation of the merging of two white dwarfs, of 0.8 and $0.6 \, M_\odot$ respectively, made of a realistic mixture of carbon and oxygen. The procedure was the same as in Lorén-Aguilar et al. (2009) except that the initial conditions were obtained more carefully. In this case we introduced an artificial braking term and we allowed the two stars to approach to their equilibrium configuration. Figure 1 displays the evolution of the orbital and rotational velocities after the first episode of braking that shows the tendency to synchronize. Our results clearly confirm those of Motl et al. (2007) and Dan et al. (2011), namely that the merging does not proceed on a dynamic timescale but it can take many orbits to occur. However, once started, the accretion rate tends to increase rapidly until it becomes catastrophic, leading to the formation of a hot corona surrounded by a thick disc around the primary (see figure 2).

However, this behavior is the result of preliminary calculations, and can be due to the low mass resolution, $\sim 5 \times 10^{-6} \, M_\odot$, so it has to be taken with some care.

Since the masses of carbon-oxygen white dwarfs are not larger than $\sim 1.1 \, M_\odot$ (García–Berro et al. 1997; Ritossa et al. 1999), the primary is, at the beginning, always far from the Chandrasekhar’s mass and consequently it will not be able to reach the critical value before the bulk of mass transfer sets in. Thus, it is hard to see, if our
calculations are correct, how to avoid the episode of high mass-transfer that follows the total disruption of the secondary and the subsequent off-center ignition of carbon followed by an accretion induced collapse.

3. Discussion and conclusions

There are, in principle, three ways to account for the observed (Maoz et al. 2010) temporal distribution of supernova eruptions: i) for some physical reason the ignition is prevented, ii) the rotation of the primary stabilizes the accretion rate to a value of $\sim 10^{-7} M_\odot$ yr$^{-1}$, eventually leading to a supernova explosion, and iii) the responsible of the explosion is the merger of a carbon-oxygen white dwarf and a helium white dwarf. We examine them in the following.

The reason why the first point has to be considered is twofold. On one hand, the cross section of the $^{12}$C+$^{12}$C reaction at low energies is not well known. Firstly, there are some claims about the existence of low energy resonances, which would favor the ignition of carbon (Bravo et al., in preparation), but also, there is a claim of the existence of a hindrance that could prevent the ignition of carbon at low temperatures (Gasques et al. 2007). On the other, the size of the network of reactions usually adopted to describe carbon burning is usually minimal, so carbon burning is treated in a very simplified way (Förster et al. 2010). Another possibility comes from the claim that axions exist and could be responsible of the suspected anomalous cooling of white dwarfs (Isern et al. 2008, 2010). If this were the case, the ignition line would be modified just in the region of the density temperature plane where the off-center ignition of carbon occurs (see figure 3) and the velocity of propagation of the flame would also change. The impact of such effect has not been yet elucidated.
The second point relies on the fact that if the accretion rate is initially high, near the Eddington limit, as expected, thermal energy has no time to diffuse from the outer layers and produces their expansion. Meanwhile, the angular velocity of the primary increases as a consequence of the accreted angular momentum until the equatorial layers reach the critical value where centrifugal and gravitational forces become equal and no matter can be added to the configuration. This allows the star to redistribute the thermal energy and the angular momentum and re-start the accretion process once more. The net result is that the accretion rate is regulated by the heat transfer time (Piersanti et al. 2003b). As the primary heats up, this mechanism becomes less and less efficient and stops well before reaching the critical mass. If the primary adopts a triaxial configuration as a consequence of rotation, it can loose angular momentum by the emission of gravitational waves and the process of accretion can re-start once more until the star reaches the Chandrasekhar’s mass and explodes as a SNIIa (Piersanti et al. 2003a). The main difficulty of this scenario is how to couple the primary and the disk to avoid mass losses.

The third possibility to obtain delayed explosions is the merging of a helium and a carbon-oxygen white dwarf. In this case it is necessary to prevent the formation of large envelopes of helium to avoid the presence of large amounts of $^{56}$Ni in the outer layers of the supernova debris. This could be achieved by focusing the shock wave induced by the detonation of small amounts of helium in the outer layers of the primary (Fink et al. 2010; Guillochon et al. 2010).

In conclusion, there are strong observational evidences suggesting that the merging of two white dwarfs could produce some supernova events, specially the most delayed ones. The main difficulty to prove that this is the case is the extreme difficulty of modelling the long-term behavior of the disk and the primary.

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