

Accreting White Dwarfs

Margarita Hernanz*

Institut de Ciències de l'Espai (CSIC-IEEC), Bellaterra (Barcelona) and Institut d'Estudis Espacials de Catalunya, Barcelona, Spain
E-mail: hernanz@ieec.uab.es

Jordi José

Departament de Física i Enginyeria Nuclear, EUETIB, UPC and Institut d'Estudis Espacials de Catalunya, Barcelona, Spain
E-mail: jjose@ieec.fcr.es

Thermonuclear (type Ia) supernovae are explosions in accreting white dwarfs, but the exact scenario leading to these explosions is still unclear. An important step to clarify this point is to understand the behaviour of accreting white dwarfs in close binary systems. The characteristics of the white dwarf (mass, chemical composition, luminosity), the accreted material (chemical composition) and those related with the properties of the binary system (mass accretion rate), are crucial for the further evolution towards the explosion. An analysis of the outcome of accretion and the implications for the growth of the white dwarf towards the Chandrasekhar mass and its thermonuclear explosion is presented.

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*Speaker.

1. Introduction

White dwarfs are the final stages of the evolution of stars with masses smaller than $8-11 M_{\odot}$. The final fate of such stars is just cooling to invisibility, whenever they are isolated. However, when they belong to interacting binary systems, more exciting phenomena can happen, like nova explosions and supernovae of the thermonuclear class, i.e., type Ia supernova explosions. Accretion of matter from the companion star is at the origin of such interesting phenomena, but there is a long and complicated path from the onset of accretion up to the final explosion, in case this is the final outcome of the evolution.

It is widely accepted that thermonuclear supernovae are the result of the explosion of a carbon-oxygen (CO) white dwarf, once it reaches the critical density for carbon ignition; this occurs either at the center of the star or off-center, always in strongly degenerate conditions. Therefore, it is expected that the properties of such explosions are quite uniform, in agreement with the observations, allowing the use of them as standard candles for cosmological purposes. In contrast, core collapse supernovae, where a massive star explodes because of the gravitational force, show a wide range of observational properties, since the range of masses of the progenitor stars is extremely large.

In spite of the importance of type Ia supernovae both as cosmological tools, as crucial contributors to the chemical and dynamical evolution of the Galaxy, and as the triggering mechanism for star formation, their exact scenario is still unknown. In addition, there are not yet successful simulations of the explosion (see the review by [15]). In this paper we concentrate on the scenario issue, with a special emphasis on the fundamental role played by accretion, and its link to the final fate of the white dwarf. The type of material accreted (either H, He -with some metals- or CO) and the rate at which matter falls onto the white dwarf (mass accretion rate) are strongly dependent on the type of interacting binary hosting the potential exploding white dwarf. The mass and chemical composition of the white dwarf itself, as well as its initial luminosity, are also crucial for its outcome. There is a complicated interplay between type of accretion and initial white dwarf conditions, such that it is not straightforward to reach the carbon ignition conditions. Once ignition occurs, other problems occur, related to the flame propagation; these are out of the scope of this paper, but are treated in other papers of this volume (e.g., Roepke's contribution [37]).

2. Scenarios of SNIa

There are two basic scenarios for the progenitors of type Ia supernova explosions: the single degenerate scenario, where the white dwarf is accreting matter from a main sequence or giant companion, and the double degenerate scenario, where the merging of two white dwarfs is the responsible for the final explosion. In the first case, accreted matter is always hydrogen-rich, except when the companion is a helium star [20] and therefore accreted matter is pure helium. In the double degenerate scenario, accreted matter can be either pure He or a mixture of carbon and oxygen, depending on the type of white dwarf companion.

The influence of accretion on the final outcome of the white dwarf will be discussed in next section. Here we just mention the observational problem related with accretion of H-rich matter, since it is a crucial point to disentangle between the single degenerate and the double degenerate scenarios. Accretion of H-rich material poses some problems, because hydrogen is not seen in

the spectra of type Ia supernovae (absence of hydrogen is one of the basic properties defining the type I -and in particular Ia- class). However, according to models, some hydrogen should be stripped from the secondary star during the explosion -in the single degenerate scenario- and, therefore, some hydrogen should exist in the ejecta [26, 27]. This hydrogen is predicted to be at small velocities (lower than ~ 10000 km/s), and its detection is hard at the stages where bulk material expands at larger speeds. In the last years, there have been serious attempts to search for hydrogen in the spectra of type Ia supernovae, and upper limits have been obtained which do not completely contradict the single degenerate scenario (see for instance [19] and references therein). In fact, there has been detection of circumstellar material, indicative of a giant companion (i.e., single degenerate scenario) in a few cases [10, 33].

Another issue is to know the properties of the white dwarf itself, e.g., mass and chemical composition, which are strongly related. Three compositions are possible for white dwarfs: helium, carbon-oxygen (CO) and oxygen-neon (ONe). The mass range over which the white dwarf progenitor star undergoes either the AGB (from Asymptotic Giant Branch), without carbon ignition and leaving CO cores, or the super-AGB phase, which burns carbon and leaves ONe cores, is a bit controversial. The mass range for which an ONe white dwarf can form is between $\sim 8 - 10 M_{\odot}$, depending on the treatment of convection (and specially on the inclusion or not of overshooting) and mass loss during the previous binary evolution and during the thermal pulses themselves [36, 3]. Only CO white dwarfs are expected to be able to explode as type Ia supernovae, since they are carbon-rich. On the contrary, ONe white dwarfs are expected to collapse, because of the effect of electron captures on ^{24}Mg (see for instance [30, 32, 1, 9] and references therein).

Two possibilities have been suggested, concerning the mass of the white dwarf star: Chandrasekhar and sub-Chandrasekhar scenarios. The standard scenario is based on the explosion of a Chandrasekhar mass CO white dwarf, but it has been claimed that relatively low-mass CO white dwarfs could also explode. In this case, helium detonation on top of the white dwarf would drive the final central or off-center carbon ignition responsible for the explosion (see for instance [41]). The propagation of the outward carbon detonation through material at a lower density (than in the Chandrasekhar mass white dwarf) alleviates the problem of the absence of intermediate-mass elements (such as Si and S, for instance) of the old pure carbon detonation models of Chandrasekhar mass white dwarfs (see for instance [29]). But other problems arise in this sub-Chandrasekhar scenario, since it does not well reproduce the observed velocities of the intermediate-mass elements; however, this scenario has not been completely ruled out, and a lot of multidimensional works have been devoted to it (e.g., [7, 4] and references therein)

3. Accretion

There is a variety of nuclear burning regimes on top of accreting white dwarfs, depending mainly on the accreted mass composition, the mass transfer (and thus the mass accretion) rate and the mass of the white dwarf. For a narrow range of accretion rates, burning can occur in steady state, so that matter is burned at the same rate as it is accreted. Large accretion rates are needed to fulfill this condition: $3.066 \times 10^{-7} \times (M/M_{\odot} - 0.5357) M_{\odot}/\text{yr}$ for H-accretion [31, 38], the exact value depending on the metallicity of the accreted matter; for He accretion, steady burning occurs for mass accretion rates roughly 10 times larger [5, 6, 16, 18]. It is worth mentioning that for larger

Table 1: Properties of models with weak H-shell flashes, for an initial white dwarf mass $1.2 M_{\odot}$. Adapted from José, Hernanz & Isern [18]

| \dot{M} (M_{\odot}/yr) | P_{rec} (yr) | $T_{max,H}$ (10^8K) | $T_{min,H}$ (10^7K) | $\overline{T_H}$ (10^7K) | $\overline{\rho_H}$ (10^2g/cm^3) |
|-------------------------------------|----------------|--------------------------------|--------------------------------|-------------------------------------|---|
| 2×10^{-7} | 9 | 1.3 | 3.4 | 6.03 | 0.78 |
| 10^{-7} | 22 | 1.4 | 2.9 | 4.36 | 1.20 |
| 5×10^{-8} | 50 | 1.4 | 2.6 | 3.63 | 1.58 |
| 10^{-8} | 357 | 1.5 | 2.0 | 2.69 | 2.57 |
| 5×10^{-9} | 832 | 1.6 | 1.8 | 2.45 | 3.09 |
| 10^{-9} | 5828 | 1.7 | 1.5 | 2.04 | 4.47 |
| 5×10^{-10} | 13691 | 1.7 | 1.3 | 1.86 | 5.37 |
| 2×10^{-10} | 68640 | 1.9 | 1.2 | 1.66 | 8.32 |

Table 2: Properties of models with weak He-shell flashes, for an initial white dwarf mass $1.2 M_{\odot}$. Adapted from José, Hernanz & Isern [18]

| \dot{M} (M_{\odot}/yr) | P_{rec} (yr) | $T_{max,He}$ (10^8K) | $T_{min,He}$ (10^7K) | $\overline{T_{He}}$ (10^8K) | $\overline{\rho_{He}}$ (10^4g/cm^3) |
|-------------------------------------|----------------|---------------------------------|---------------------------------|--|--|
| 2×10^{-6} | 199 | 4.1 | 11.5 | 1.55 | 0.85 |
| 10^{-6} | 471 | 4.3 | 9.8 | 1.29 | 1.17 |
| 5×10^{-7} | 1124 | 4.5 | 8.7 | 1.15 | 1.44 |
| 10^{-7} | 9081 | 5.0 | 6.7 | 0.98 | 2.34 |
| 5×10^{-8} | 22129 | 5.2 | 6.1 | 0.93 | 2.82 |

accretion rates, the envelope expands and behaves like a red giant envelope, whereas for even larger rates the Eddington limit is reached, which inhibits further accretion (because radiation pressure force counteracts gravitational force).

An interesting case of steady burning of hydrogen corresponds to the so-called supersoft X-ray sources (SSSs); these objects emit just in the “super soft” X-ray energy range (i.e., below about 1 keV), and are interpreted as hot white dwarf photospheres, being hot because of steady burning of hydrogen) [39]. Provided that they have enough time to reach the Chandrasekhar mass, without any catastrophic mass-loss event, they are viable single degenerate scenarios for type Ia supernovae.

Whenever the accretion rate is smaller than the values corresponding to the steady burning regime, but larger than some critical values (explained below), accumulated matter reaches partial degeneracy and weak flashes occur. These flashes are not driving mass loss and they are strictly periodic. The general properties of these weak flashes are shown in Tables 1 and 2; these results were obtained by José, Hernanz & Isern [18], with a semi-analytical model in the plane parallel approximation. It is shown that the recurrence period (P_{rec}) increases as the mass accretion rate diminishes, because a larger mass needs to be accreted to attain ignition conditions, both for H- and He-rich accretion. As a consequence of this increase, the intensity of the flashes increases as the accretion rate decreases; the reason is that a larger accreted mass implies higher degeneracy and thus a stronger flash [18] (as seen by the larger maximum shell temperatures, T_{max} , and larger

difference between the maximum and minimum shell temperatures, $T_{max} - T_{min}$, obtained). The effect of the initial white dwarf mass goes in the same direction: the larger the initial white dwarf mass, the higher the pressure at the base of the accreted envelope (for a given accreted mass) and then the stronger the flash. Another indication of the strength of the flash is the ratio of the “on phase” duration to the recurrence period: the strongest flashes have small ratios, whereas the milder flashes have larger ratios (i.e., they stay in the “on phase” longer; see [16, 18] for details). The average values of shell temperatures T_H and T_{He} ($\overline{T_H}$ and $\overline{T_{He}}$) and densities ($\overline{\rho_H}$ and $\overline{\rho_{He}}$) along the period are shown in Tables 1 and 2.

Up to now we have described direct accretion of H and He, but it is worth noticing that H burning (steadily or through weak flashes) leads to the accumulation of He. Therefore, one indirect way to accrete He is through weak H flashes; in fact, double H-He flashes are expected for a range of direct H accretion rates, e.g., those mentioned above as non problematic for H (see [18] and the complete hydrostatic simulations from Cassisi, Iben & Tornambe and Piersanti et al. [2, 34]). As shown in Tables 1 and 2, the typical period of single He flashes is about 400 times larger than that of H flashes, for a given (large) accretion rate; but the ratio $P_{rec,He}/P_{rec,H}$ changes when double flashes are considered. The existence of a top hydrogen shell influences the evolution of the bottom He layer, leading to a shorter recurrence period and, therefore, to a milder flash [18]. On the other hand, the accumulation of He as a consequence of H accretion can prevent the growth of the white dwarf mass up to the Chandrasekhar limit, since dynamical He flashes are probable [2, 34]. More details, in the framework of hydrodynamical simulations, about the final flashing of He are given below, but just for direct He accretion.

Coming back to direct accretion, we have shown that the strength of the H or He flashes increases with decreasing accretion rate. For low enough accretion rates, flashes are not weak anymore, because accumulated matter can reach degenerate conditions and drive a hydrodynamic event, with potential mass loss. For H-rich mass accretion, nova explosions occur, leading to a large increase of visual luminosity and mass-loss at large velocities, from hundreds to thousands of km/s [13, 17]. For He accretion, there is a range of accretion rates for which there is a strong He flash (probably leading to a He detonation, i.e., supersonic burning propagation; see below). Therefore, weak flashes leading to a growing CO core towards the Chandrasekhar mass are not possible for this range of mass accretion rates.

The critical accretion rates for surface degenerate burning and ensuing strong flashes are different for H and He. The lower limits for which weak H flashes occur are $\sim 10^{-9} - 10^{-10} M_{\odot}/\text{yr}$, the exact values depending on the initial mass and luminosity of the white dwarf and on the metallicity of the accreted matter [25]. Concerning He, a strong flash is expected whenever the accretion rate ranges between $\sim 5 \times 10^{-8}$ and $10^{-9} M_{\odot}/\text{yr}$ [29, 40], for any initial white dwarf mass. For smaller accretion rates, a strong flash is again predicted for white dwarf masses below $\sim 1.1 M_{\odot}$, but no He flash occurs if the white dwarf is more massive; alternatively, weak He flashes allowing for the increase of the white dwarf mass, as in the case of He accretion rates larger than $5 \times 10^{-8} M_{\odot}/\text{yr}$, would happen [28].

The further hydrodynamical evolution after a strong He flash on top of an accreting CO white dwarf has been subject to debate during many years, in the framework of both one dimensional and multidimensional simulations. It is worth noticing that in 1D simulations with spherical symmetry, ignition can only occur either at the center or simultaneously along a spherical shell. This

instantaneous ignition throughout a shell seems unphysical, requiring multidimensional analyses; in fact, the initial stages of He ignition play a crucial role which deserves particular attention (see for instance [7] and [4] and references therein). The original 1D works (e.g., [29, 40]) tried first to elucidate if a He detonation wave propagating outwards formed as a consequence of the strong He flash. A related issue is to determine if the initial He detonation induces a carbon detonation at the core envelope interface, propagating inwards and leading to the so-called double detonation supernova [29]. More recent studies devoted to CO white dwarfs with initial sub-Chandrasekhar mass accreting at the critical regime leading to external He detonation, indicated that C was not ignited at the core-envelope interface, so that there was not an inward C detonation wave; instead a compressional shock wave propagating inwards was responsible for the final C ignition, at the center or near it [21, 41, 12].

As a summary, the outcome of He accretion in the critical range of accretion rates is not clear at all. Just as an illustration, let's mention Livne & Glasner [23], who analyzed the consequences of an off-center He detonation: in 1D they did not obtain a double detonation, whereas in 2D they could neither confirm nor exclude it, but they mentioned that rarefaction effects not included in their analysis most probably would prevent it. In later numerical simulations [24], they concluded that a double detonation occurred for masses larger than $1.2 M_{\odot}$, but was prevented in less massive white dwarfs. Fortunately, the gross nucleosynthesis predictions seem quite robust, and the predictions of 1D and 2D models agree quite well (see [22]; a recent analysis of the nucleosynthesis constraints on the type of burning propagation can be found in [8]).

The final fate of all the scenarios described above, as well as the main characteristics of the ensuing type Ia explosion -whenever it occurs- are tightly related to the details of the burning propagation, which are reviewed by Roepke in this volume [37]. However, it is worth reminding that the presupernova evolution, leading to the initial stages of the ignition, also plays a very important role on the further development of the explosion, whatever the scenario is. For instance, the presence of ^{14}N in the accreted material is critical, since it allows the operation of the $^{14}\text{N}(e^-, \nu)^{14}\text{C}(\alpha, \gamma)^{18}\text{O}$ (NCO) reactions (above the density threshold 10^6g cm^{-3}), which compete with the 3α ones at low temperatures and high densities [11, 41]. The main consequence is that the He layer is heated and ignition density becomes lower than in the models where the NCO reactions are not included; this could prevent the development of a strong He flash. However, Piersanti, Cassisi & Tornambe [35] obtain that the NCO energy contribution is not able to keep the He shell hot enough to avoid strong electron degeneracy, and thus a He flash results, for realistic initial models of white dwarfs. The reason is that for low initial metallicities there is not enough ^{14}N , whereas for solar or larger metallicities the densities attained are below the threshold for triggering the NCO reactions (notice that their models are for sub-Chandrasekhar mass white dwarfs, of 0.6 and $0.8 M_{\odot}$).

Last but not least: an important factor which determines the effect of accretion onto white dwarfs is rotation. Yoon & Langer [42] studied the effect of the white dwarf spin-up caused by accretion of angular momentum, and the further rotationally induced chemical mixing; they deduced that the heating of the He envelope by friction related to differential rotation made it ignite under less degenerate conditions, and thus He detonation might be avoided (leading to a recurrent He nova explosion instead of a type Ia supernova).

4. A particular scenario for type Ia supernovae: the RS Oph symbiotic recurrent nova

There is a particular scenario for type Ia supernova that deserves attention, specially because there is a lot of recent and accurate observational information related with it: the symbiotic recurrent nova RS Oph. This phenomenon is related with H-accretion leading to nova outbursts, but with the peculiarity that the mass of the white dwarf is expected to increase (and not decrease) as a consequence of the explosion. Therefore, for an initial white dwarf massive enough, the Chandrasekhar mass can be reached in a reasonable amount of time.

RS Oph has undergone various recorded nova outbursts (that's why it belongs to the recurrent nova class), with a recurrence period of 21 years, the last one in 2006. It was observed at practically all wavelengths, spanning the range from radio to hard X-rays. Its orbital period is 456 days and the companion of the white dwarf is a red giant star, with a wind. This scenario is different from the scenario of "standard" classical novae, where the companion is a main sequence star and the periods - and thus orbital separations - are much smaller. As a consequence, the accretion rate in RS Oph is much larger and the time needed to accrete the critical mass to develop a nova outburst much shorter (some decades, instead of the typical recurrence periods $\sim 10^4 - 10^5$ years of classical novae). According to what was mentioned in the previous section, for large accretion rates, e.g. $10^{-6} - 10^{-7} M_{\odot}/\text{yr}$, there is not degenerate H-burning and thus no nova explosion is expected; however, if the initial mass of the white dwarf is large enough (very close to the Chandrasekhar mass), the explosion occurs even for such large accretion rates. Recent models by Hernanz & José [14], have successfully reproduced the global properties of RS Oph, with white dwarf initial masses 1.35 and 1.38 M_{\odot} and accretion rates (of matter with solar composition, from the red giant companion) about $2 \times 10^{-7} - 10^{-8} M_{\odot}/\text{yr}$. An important result is that the accreted masses are larger than the ejected ones, so that the mass of the white dwarf grows towards the Chandrasekhar mass; it increases by $10^{-6} M_{\odot}$, typically, after each eruption. The corresponding time needed to reach the mass limit, i.e., to reach explosion conditions, ranges between 3 and 7×10^5 years (for an accretion rate of $2 \times 10^{-7} M_{\odot}/\text{yr}$).

Therefore, RS Oph and its relatives (just a few -less than 5- in the Galaxy) are potential type Ia candidates, in the framework of the single degenerate scenario. But a problem remains with this scenario: a white dwarf of such large initial mass should be made of ONe, and not of CO, according to standard stellar evolution; then it would collapse and not explode as a type Ia supernova. There is not a clear way to solve this conflict, unless there was some previous epoch of steady burning or very weak flashes, allowing for the growth of the mass from $\sim 1.1 M_{\odot}$ (the maximum mass of a CO core "at birth") to the values of the white dwarf mass required to explain the short recurrence period ($\sim 1.35 - 1.38 M_{\odot}$). An additional problem with this scenario is how to get rid of the hydrogen, which has been observed in large amounts in the expanding ejecta. But this is a long standing problem of the single-degenerate scenario, which, however seems not to be in contradiction with the observations (see section 1), according to some recent papers.

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