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Classical nova explosions – hydrodynamics and nucleosynthesis

J. José[1,2*]

[1]*Dept. Física i Enginyeria Nuclear, EUETIB, Universitat Politècnica de Catalunya, E-08036 Barcelona*
[2]*Institut d'Estudis Espacials de Catalunya, E-08034 Barcelona, Spain*

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Abstract. Classical nova outbursts are thermonuclear stellar explosions driven by charged-particle reactions. Extensive numerical simulations of nova explosions have shown that the accreted envelopes attain peak temperatures ranging between 0.1 and 0.4 GK, for about several hundred seconds, and therefore, their ejecta is expected to show signatures of nuclear processing. Indeed, it has been claimed that novae play some role in the enrichment of the interstellar medium in a number of intermediate-mass elements. This includes ^{17}O, ^{15}N, and ^{13}C, significantly overproduced with respect to solar abundances, and a lower contribution to a number of species with $A < 40$, such as ^{7}Li, ^{19}F, or ^{26}Al. In this paper, we review the modeling of classical nova outbursts, from spherically-symmetric (1D) hydrodynamic models to recent multidimensional simulations. The predicted nucleosynthesis accompanying nova outbursts is briefly compared with the abundances determined in meteoritic presolar grains of putative nova origin. The impact of current nuclear uncertainties on the final yields is also outlined.

Keywords : accretion, accretion disks – convection – hydrodynamics – nuclear reactions, nucleosynthesis, abundances – stars: novae, cataclysmic variables – white dwarfs

1. Introduction

Classical novae are stellar explosions that have captivated the interest of astronomers for more than two millennia. They exhibit a sudden rise in optical brightness (from 8 to 18 magnitudes in 1 – 2 days), with peak luminosities reaching 10^4 – 10^5 $L_\odot$. Nova explosions take place in stellar

*email: `jordi.jose@upc.edu`

binary systems, consisting of a compact, white dwarf star (usually, CO- or ONe-rich) and a low mass companion (typically, a K or M main sequence star, although observations have revealed more evolved companions in some cases). The system is very close, with orbital periods < 16 hr, allowing mass transfer episodes caused by Roche Lobe overflow of the main sequence star. Since material carries angular momentum, it forms an accretion disk around the white dwarf. Ultimately, a fraction of this material spirals in and piles up on top of the white dwarf, building up an envelope in semi-degenerate conditions until a thermonuclear runaway (hereafter, TNR) ensues (see reviews by José & Hernanz 2007a; José & Shore 2008; Starrfield, Iliadis & Hix 2008).

Novae constitute a very common phenomena, being the second, most frequent type of stellar thermonuclear explosions in the Galaxy after type I X-ray bursts. Although only a handful, 3 to 5, are discovered every year, a much higher nova rate, around 30 ± 10 yr^{-1} (Shafter 2002), has been predicted from extrapolation of Galactic and extragalactic data (M31, in particular). The reason for the scarcity of detections in our Galaxy is extinction by interstellar dust. In contrast to type Ia supernovae, classical novae are expected to recur since neither the star nor the binary system are destroyed by the event. Predicted recurrence times for nova outbursts are of the order of 10^4–10^5 yr. Typical (observed) recurrence times for the class of recurrent novae range between 10 and 100 yr, likely implying masses for the white dwarf hosting the explosion close to the Chandrasekhar limit and high mass accretion rates. It is likely, however, that recurrence times must follow a nearly continuous sequence, ranging from the short values characteristic of recurrent novae to the long values predicted for classical novae. Another basic difference between novae and supernovae is the mean ejection velocity (> 10^4 km s^{-1} in a supernova, while several 10^3 km s^{-1} in a classical nova), as well as the amount of mass ejected (the whole star, ~ 1.4 M$_\odot$, in a thermonuclear supernova versus 10^{-3} – 10^{-5} M$_\odot$ for a nova).

2. The theory behind nova explosions

Nova explosions can naturally occur in carbon-oxygen-rich (hereafter, CO) and oxygen-neon-rich (ONe) white dwarfs. A few events have also been tentatively attributed to explosions on helium-rich white dwarfs, the first candidate being V445 Puppis 2000 (see Kato et al. 2000). The most frequent case involves a CO white dwarf, the remnant of a progenitor star with a mass smaller than ≈ 9 M$_\odot$ (Althaus et al. 2010), after subsequent H- and He-burning. For more massive progenitors, non-degenerate C-ignition leads to the formation of a degenerate core mainly made of oxygen and neon, with traces of magnesium and sodium. Nevertheless, the mass interval of the progenitor star leading to a particular white dwarf type is not well-constrained and depends on details of stellar evolution (e.g., the single or binary nature of the progenitor). Calculations show that CO white dwarfs are less massive than ONe white dwarfs. The mass cut distinguishing CO and ONe white dwarfs is however not well known (Doherty et al. 2010), but a value of ≈ 1.1 M$_\odot$ is obtained when binarity is taken into account (Gil–Pons et al. 2003).

The most important quantity in determining the strength of a nova outburst is the *proper pressure* at the core-envelope interface, $P_\star$, which is a measure of the pressure exerted by the layers overlying the burning shell (Fujimoto 1982):

$$P_\star = \frac{GM_{wd}}{4\pi R_{wd}^4} \Delta M_{env} \tag{1}$$

To account for mass ejection, $P_\star \geq 10^{20}$ dyn cm^{-2} is required, for a solar composition envelope. Smaller values have been predicted for CNO-enhanced abundances (e.g., $P_\star \sim 2\times 10^{19}$ dyn cm^{-2} for $Z_{CNO} = 0.51$; see MacDonald 1983a). Equation 1 reveals that the mass of the accreted envelope depends only on the white dwarf mass, because of the direct relationship between M_{wd} and R_{wd}. Moreover, since the white dwarf size is inversely proportional to its mass, ΔM_{env} decreases as the white dwarf mass increases, and hence, it becomes easier to produce a nova outburst on a massive white dwarf. Typical accreted envelope masses range between 10^{-3} – 10^{-5} M$_\odot$ (see also Townsley & Bildsten 2004, for a detailed study of accreted–ignition–masses and their relation to ejected masses).

Equation 1 suggests as well that, for a given white dwarf mass, the envelope mass required to power a nova explosion is independent of the mass accretion rate. But detailed hydrodynamic simulations (Glasner & Truran 2009; Prialnik & Kovetz 1995; Shara et al. 2010; Starrfield et al. 1998; Yaron et al. 2005) have revealed some influence of the mass accretion rate on the properties of the outbursts. Indeed, high mass accretion rates result in more energy released from gravitational compression of the envelope, and hence, times to reach ignition conditions are reduced. As a result, as the mass accretion rate increases, the envelope mass decreases. Unfortunately, the mass accretion rate is not a well constrained quantity from an observational viewpoint. Mass transfer rates (rather than mass accretion rates) between components, in the range $\dot{M} \sim 10^{-7}$ – 10^{-11} M$_\odot$ yr^{-1}, have been inferred in cataclysmic variables, obeying the empirical relation (Patterson 1984):

$$\dot{M} = 5.1^{+3}_{-2} \times 10^{-10} \left(\frac{P_{orb}}{4\,\mathrm{hr}}\right)^{3.2\pm0.2} \tag{2}$$

where P_{orb} is the orbital period. Observationally, systems in the range $0.7 < \mathrm{P_{orb}(hr)} < 3.3$, are characterized by low mass transfer rates, $\dot{\mathrm{M}} \sim 10^{-10}$ – 10^{-11} M$_\odot$ yr^{-1}, while those with larger orbital periods, $0.7 < \mathrm{P_{orb}(hr)} < 3.3$, exhibit higher rates, $\dot{\mathrm{M}} \sim 10^{-8}$ – 10^{-9} M$_\odot$ yr^{-1}. How these mass transfer rates translate into mass accretion rates is however a matter of debate. According to the semi-analytic analysis of MacDonald (1983a), for a given white dwarf mass, there is a maximum value of the mass accretion rate that leads to a nova outburst. But several hydrodynamic simulations have shown that mass ejection results even for higher mass accretion rates and more luminous white dwarfs than the critical values derived by MacDonald. For instance, Yaron et al. (2005) reported mass ejection from models of 1 M$_\odot$ white dwarfs accreting solar-like material at a rate as high as 10^{-7} M$_\odot$ yr^{-1} (for models of very luminous white dwarfs see also Shara et al. 2010). It is also worth noting that Yaron et al. (2005) have computed nova models with very low mass accretion rates, $\dot{\mathrm{M}} = 5 \times 10^{-13}$ M$_\odot$ yr^{-1}. In turn, Glasner & Truran (2009) have explored the possibility of CNO-breakout in novae, in the context of low luminosity white dwarfs accreting matter at low rates, $\dot{\mathrm{M}} = 10^{-11}$ M$_\odot$ yr^{-1}. Finally, it is important to stress that the mass accretion rate is assumed to be constant in many of the reported hydrodynamic nova simulations (an exception being Yaron et al. 2005, who performed simulations with a time-dependent mass accretion rate based on changes of the stellar masses and binary separation).

The effect of the initial white dwarf luminosity (or central temperature) on the strength of the outburst has also been discussed in a number of papers. Schwartzman, Kovetz & Prialnik (1994) pointed out a double effect: in cold, low luminous white dwarfs, heat conduction into the core can delay the ignition. As a result of the longer accretion phase, larger masses and hence, larger proper pressures are achieved, which translate into more violent outbursts (similar effects have been described elsewhere; see, for instance, Starrfield et al. 1998; Prialnik & Kovetz 1995; Shara et al. 2010; Yaron et al. 2005; José & Hernanz 2007b). On the other hand, in hot, luminous white dwarfs the outermost core layers become convective, and larger levels of mixing through the core-envelope interface are found. Notice that if the white dwarf is initially too luminous, the shell source is not strongly degenerate when the thermonuclear runaway develops and a mild runaway without mass ejection may occur.

Degeneracy is indeed a key ingredient for a successful explosion. White dwarfs are basically supported by the pressure exerted by electrons, a fermion gas ruled by Pauli's exclusion principle that forces particles to occupy quantum states in a regulated manner (i.e., first, the ground state, followed by ordered low-energy excited states that become successively occupied). Conditions are such that during the accretion stage, the envelope is degenerate, that is, the thermal energy of the electrons, $3/2kT$, is smaller than the Fermi energy, E_F. The condition for degeneracy can be written, in a very approximate way for a fully ionized electron gas, as:

$$\frac{3}{2}kT < \frac{\hbar^2}{2m_e}\left(\frac{3\pi^2(Z/A)\rho}{m_H}\right)^{2/3} \tag{3}$$

or alternatively,

$$\frac{T}{\rho^{2/3}} < 1.3 \times 10^5 \left(\frac{Z}{A}\right)^{2/3} \mathrm{K\,cm^2\,g^{-2/3}}. \tag{4}$$

Equation 4 points out that the smaller the value of $T/\rho^{2/3}$, the larger the degeneracy. Notice that at the center of a 1.3 $M_\odot$ white dwarf (with $\rho_c \sim 5 \times 10^8$ g cm^{-3}), for a wide range of possible central temperatures (i.e., 10^6 – 10^8 K), $T/\rho^{2/3}$ ranges between 2 and 200, so complete degeneracy is a good approximation for white dwarf interiors. During the early stages of a nova outburst, densities at the base of the envelope are relatively large while temperatures are moderate, such that $T/\rho^{2/3}$ is small. Hence, most of the envelope is degenerate. As accretion goes on, compressional heating rises the temperature and nuclear reactions ensue. Because the envelope is degenerate, it does not react to the temperature increase with an expansion, since in such conditions the pressure is nearly independent of the temperature. These circumstances pave the road for a thermonuclear runaway. The large energy released by nuclear reactions can not be evacuated only by radiation, and hence convection sets in as soon as superadiabatic gradients are established within the envelope. Convection spreads a fraction of the short-lived β^+-unstable nuclei ^{13}N, ^{14,15}O and ^{17}F, synthesized deep inside the envelope, to the outer cooler regions. A fraction of the energy released by the β^+-decay of these short-lived species is transformed into kinetic energy, powering the ultimate expansion and ejection stages. It is worth noting that the runaway is halted by envelope expansion rather than by fuel consumption.

Finally, the effect of the envelope metal content (i.e., CNO abundance) on the nova outburst turns out to be similar to that previously described for the mass accretion rate or for the initial luminosity. Indeed, a decrease in the CNO abundance delays ignition since less nuclear reactions are produced (and hence, less energy is released). This translates into an increase in the duration of the accretion stage that leads to larger accreted masses, larger pressures in the envelope, and more violent outbursts. Even though simulations have confirmed that envelopes with solar metallicity can give rise to explosions resembling *slow novae* (Sparks, Starrfield & Truran 1978; Prialnik, Shara & Shaviv 1978), only envelopes with CNO-enhanced abundances (in the range $Z_{CNO} \sim 0.2 - 0.5$) can reproduce the *gross* properties of a *fast nova* (Starrfield et al. 1972; Starrfield, Truran & Sparks 1978). The origin of the CNO enhancements required by models and inferred as well spectroscopically has been regarded as controversial. In principle, one may think of two possible sources: nuclear processing during the explosion or mixing at the core-envelope interface. Peak temperatures reached during a nova explosion are constrained by the chemical abundance pattern inferred from the ejecta and do not exceed 4×10^8 K, so it is unlikely that the observed metallicity enhancements can be due to thermonuclear processes driven by CNO breakout. Instead, mixing at the core-envelope interface appears as a more likely explanation. Although several mixing mechanisms have been proposed to date, including diffusion-induced mixing (Prialnik & Kovetz 1984; Iben, Fujimoto & MacDonald 1991; Fujimoto & Iben 1992), shear mixing at the disk-envelope interface (Durisen 1977; Kippenhahn & Thomas 1978; MacDonald 1983b; Kutter & Sparks 1987; Sparks & Kutter 1987), convective overshoot-induced flame propagation (Woosley 1986), or mixing by gravity wave breaking on the white dwarf surface (Rosner et al. 2001; Alexakis et al. 2004), none has proven fully successful. See Sect. 3.2 for additional details.

3. Nova models

3.1 Parametric and one-dimensional models

Different approaches have been adopted to date in the modeling of nova explosions. A first category includes *parametrized one-zone models* (e.g., Hillebrandt & Thielemann 1982; Wiescher et al. 1986; Weiss & Truran 1990; Wanajo, Hashimoto & Nomoto 1999), in which the envelope's history relies on the time evolution of the temperature and density in a single layer (usually, the envelope base). Such thermodynamic quantities are often calculated by means of semi-analytic models, or occasionally correspond to T-ρ profiles directly extracted from hydrodynamic simulations. This approach, although representing an extreme oversimplification of the physical conditions governing nova envelopes, was widely used in the past to overcome the strong time limitations that arose when large nuclear reaction networks were coupled to computationally intensive numerical codes. More recently, it has also been used as a feasible tool to estimate the impact of nuclear uncertainties on the final nova yields (Iliadis et al. 2002). This often requires thousands of calculations that are still prohibitive with hydrodynamic codes. A few detailed post-processing, multi-zone calculations, using appropriate T-ρ profiles for a suite of envelope layers extracted from hydro models have also been performed (see e.g., Hix et al. 2003). This approach requires a decision regarding how material is mixed between individual layers, since nova envelopes become fully convective close to the peak of the outburst.

A second, somewhat improved approach relies on semi-analytic models directly coupled to a nuclear reaction network. An example of this category can be found in Coc et al. (1995), which is based on the semi-analytic model of MacDonald (1983a). The models assumes a *fully convective* envelope in *hydrostatic* equilibrium. Therefore, key aspects of the evolution, such as the way convection settles, extends throughout the envelope and recedes from its surface, are completely ignored.

So far, the state-of-the-art in nova nucleosynthesis relies on 1D *hydrodynamic models* (e.g., Prialnik & Kovetz 1995; Starrfield et al. 1998; José & Hernanz 1998; Yaron et al. 2005; Starrfield et al. 2009; Shara et al. 2010). The underlying assumption of any 1D model is spherical symmetry. This simplifying hypothesis demands that the explosion must occur simultaneously along a spherical shell.

3.2 Multidimensional models

Despite many observational features that characterize the nova phenomenon being successfully reproduced by hydrodynamic simulations under the assumption of spherical symmetry, certain aspects like the way in which a thermonuclear runaway sets in and propagates, or the treatment of convective transport clearly require a multidimensional approach.

Shara (1982) was the first to address localized TNRs on the surface of white dwarfs by means of semi-analytic models. He suggested that heat transport was too inefficient to spread a localized TNR to the entire surface, concluding that localized, *volcanic-like* TNRs were likely to occur. But, his analysis included only radiative and conductive transport, and hence ignored the major role played by convection on the lateral thermalization of a TNR. The importance of multidimensional effects for TNRs in thin stellar shells was revisited by Fryxell & Woosley (1982). On the basis of dimensional analysis and flame theory, the authors derived an expression for the velocity of the deflagration front spreading along the surface for nova conditions, in the form:

$$v_{def} \sim (h_p v_{conv}/\tau_{burn})^{1/2}$$

where h_p is the pressure scale height, v_{conv} the characteristic convective velocity, and τ_{burn} the characteristic timescale for fuel burning. Typical values for nova outbursts yield $v_{def} \sim 10^4$ cm s^{-1}, that is, the flame propagates halfway along the stellar surface in about $\sim$ 1.3 days.

The first, pioneering studies that addressed this question in the framework of multidimensional hydrodynamic calculations were performed by Shankar, Arnett & Fryxell (1992) and Shankar & Arnett (1994). To this end, an accreting 1.25 $M_\odot$ white dwarf was evolved with a 1D hydro code and subsequently mapped into a 2D domain (a spherical-polar grid of 25×60 km). The explosive event was then followed with a 2D version of the Eulerian code *PROMETHEUS*. A 12-isotope network, ranging from H to ^{17}F, was included to account for the energetics of the explosion. Unfortunately, the subsonic nature of the problem, coupled with the use of an explicit code (with a timestep limited by the Courant-Friedrichs-Levy condition), posed severe limitations on the study, which had to be restricted to very extreme conditions, characterized by huge temperature perturbations of about $\sim 100 - 600\%$, in small local regions of the envelope base. The overall computed time was also extremely small (about 1 second). The calculations revealed that instantaneous, local temperature fluctuations cause Rayleigh-Taylor instabilities. The rapid rise and subsequent expansion cools down the hot material and halts the lateral spread of the burning front, suggesting that such local temperature fluctuations do not play a relevant role in the initiation of the TNR. The study, therefore, favored the occurrence of *volcanic-like* TNRs, as argued by Shara (1982).

Later on, Glasner & Livne (1995) and Glasner, Livne & Truran (1997), revisited the scenario: new 2D simulations were performed with the code *VULCAN*, an arbitrarily Lagrangian Eulerian (ALE) hydrocode with capability to handle both explicit and implicit steps. As in Shankar, Arnett & Fryxell (1992), only a slice of the star (i.e., 0.1 π^{rad}), in spherical-polar coordinates with reflecting boundary conditions, was adopted. The resolution near the envelope base was 5×5 km. As before, the evolution of an accreting 1 $M_\odot$ CO white dwarf was initially followed by means of a 1D hydro code (to overcome the early, computationally challenging phases of the TNR), and then mapped into a 2D domain as soon as the temperature at the envelope base reached $T_b \sim 10^8$ K. As in previous work, the 2D runs relied on a 12-isotope network. The simulations revealed a good agreement with the *gross* picture outlined by 1D models (e.g., the critical role played by the β^+-unstable nuclei ^{13}N, ^{14,15}O, and ^{17}F in the ejection stage, and consequently, the presence of large amounts of ^{13}C, ^{15}N, and ^{17}O in the ejecta). However, some remarkable differences were also found: first, the TNR was initiated as a myriad of irregular, localized eruptions at the envelope base caused by convection-driven temperature fluctuations. This suggested that combustion proceeds as a chain of many localized flames–not as a thin front–each surviving only a few seconds. Nevertheless, the authors concluded that turbulent diffusion efficiently dissipates any local burning around the core. As a result, the fast stages of the TNR cannot be localized and therefore, the runaway *must* spread along the stellar surface. Second, the core-envelope interface is now convectively unstable, providing a source for the metallicity enhancement through Kelvin-Helmholtz instabilities (a mechanism bearing a clear resemblance to the convective overshooting proposed by Woosley 1986). The efficient dredge-up of CO material from the outermost white dwarf layers accounts for a $\sim 30\%$ metal enrichment of the envelope (the accreted envelope was assumed to be solar-like, without any arbitrary pre-enrichment), in agreement with the values inferred from the ejecta of CO novae. And third, larger convective eddies, extending up to 2/3 of the envelope height, with characteristic velocities $v_{conv} \sim 10^7$ cm s^{-1}, were found. Nevertheless, and despite of these differences, the expansion and progress of the TNR towards the outer envelope was almost spherically symmetric (although the initial burning process was not).

Results from other 2D simulations were published, shortly after, by Kercek, Hillebrandt & Truran (1998), aimed at confirming the general features reported by Glasner, Livne & Truran (1997). In this case, a version of the Eulerian *PROMETHEUS* code was used. A similar domain (a box of 1800 × 1100 km) was adopted, despite a Cartesian, plane-parallel geometry (to allow the use of periodic boundary conditions) was chosen. Two resolution runs, one with a coarser 5×5 km grid (as in Glasner et al. 1997), and a second with a finer 1×1 km grid, were performed. Calculations used the same initial model as Glasner et al., and provided qualitatively similar results but somewhat less violent outbursts (i.e., longer TNRs with lower T_{peak} and v_{ejec}), caused by large differences in the convective flow patterns: whereas in Glasner et al. (1997), a few, large convective eddies dominated the flow, most of the early TNR was now governed by small, very stable eddies, which led to more limited dredge-up and mixing episodes.

The situation worsened with the publication of a 3D simulation of mixing in novae by Kercek, Hillebrandt & Truran (1999). The run, that adopted a computational domain of 1800×1800×1000 km, with a resolution of 8×8×8 km, revealed erratic flow patterns dramatically different from those found in their 2D simulations. Mixing by turbulent motions took place on very small scales. The peak temperatures achieved were slightly lower than in the 2D case, a consequence of the slower and more limited dredge-up. And finally, the envelope attained a maximum velocity that was a factor $\sim$ 100 smaller than the escape velocity and, presumably, no mass ejection was expected (except for a possible late wind mass-loss phase). In view of these results, the authors concluded that CO mixing *must* take place prior to the TNR, in contrast with the main results reported by Glasner et al. (1997). In summary, two independent studies, based upon the same initial model, yielded different conclusions about the strength of the runaway and its capability to power a fast nova. The origin of these differences was carefully analyzed by Glasner, Livne & Truran (2005), who concluded that the early, quasi-static stages of the explosion, prior to the onset of the TNR, are highly sensitive to the adopted outer boundary conditions. Indeed, the study stressed that Lagrangian simulations, where the envelope is allowed to expand and mass is being conserved, are consistent with spherically symmetric solutions, while for Eulerian schemes, which utilize an outer boundary condition with free outflow (the choice likely adopted in Kercek, Hillebrandt & Truran 1998), the outburst can be artificially quenched.

Confirmation of the feasibility of this mixing scenario was provided by a set of independent 2D simulations (Casanova et al. 2010, 2011a), proving that even in an Eulerian scheme–such as the *FLASH* code–with a proper choice of the outer boundary conditions, Kelvin-Helmholtz instabilities can naturally lead to self-enrichment of the accreted envelope with core material, at levels that agree with observations. It is well known, however, that 2D prescriptions for convection are unrealistic (Arnett, Meakin & Young 2009). Indeed, the conservation of vorticity, imposed by the 2D geometry, forces the small convective cells to merge into large eddies, with a size comparable to the pressure scale height of the envelope. In contrast, eddies will become unstable in 3D in fully developed turbulent convection, and consequently will break up, transferring their energy to progressively smaller scales (Pope 2000; Shore 2007). These structures, vortices and filaments, will undergo a similar fate down to approximately the Kolmogorov scale,

$$\eta \sim (\nu^3/\epsilon)^{1/4} \tag{5}$$

where ν is the kinematic viscosity and ϵ is the energy dissipation rate. In this framework, a pioneering 3D simulation of mixing at the core-envelope interface during nova explosions (Casanova et al. 2011b; see Fig. 1) has shown hints on the nature of the highly fragmented, chemically enriched and inhomogeneous nova shells, observed in high-resolution spectra: this, as predicted by the Kolmogorov theory of turbulence, has been interpreted as a relic of the hydrodynamic instabilities that develop during the initial ejection stage. Although such inhomogeneous patterns inferred from the ejecta have been usually assumed to result from uncertainties in the observational

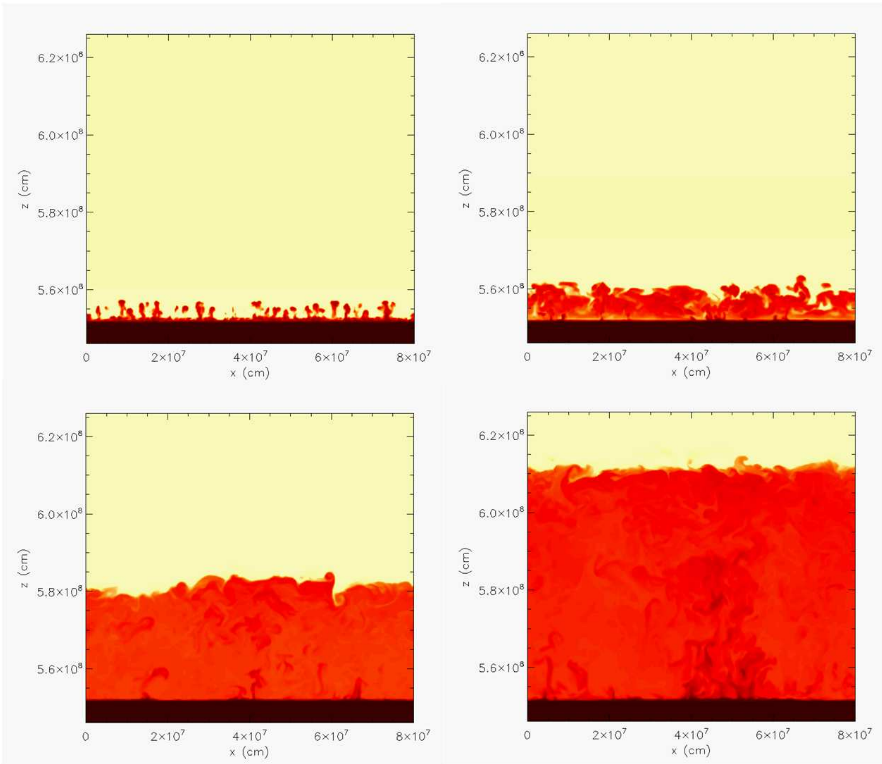

Figure 1. Two-dimensional snapshots of the development of hydrodynamic instabilities, in a 3D simulation of mixing at the core-envelope interface during a nova explosion, shown in terms of the ^{12}C mass fraction in logarithmic scale. Dredge-up of core material by Kelvin-Helmholtz instabilities translates into a mass averaged abundance of CNO-nuclei in the envelope of 0.118 (upper left panel; t = 152 s), 0.129 (upper right; 192 s), 0.157 (lower left; 297 s), and 0.182 (lower right; 381 s). The mean CNO-mass fraction at the end of the simulation reached 0.20. Simulations were run at the MareNostrum supercomputer, requiring about 150,000 CPU hours, with a maximum resolution of 1.56 km $\times$ 1.56 km $\times$ 1.56 km. Adapted from Casanova et al. (2011b).

techniques, they may represent a real signature of the turbulence generated during the thermonuclear runaway. Clearly, more multidimensional studies are needed to assess the feasibility of this mixing mechanism under different physical conditions.

A final word of warning with regard to multidimensional models: they are extremely time consuming and the handful of 2D and 3D simulations performed to date assumed reduced computational domains (i.e., a box containing a small fraction of the overall star) as well as limited nuclear reaction networks. Indeed, only a handful of isotopes (from H to F) have been considered in all previous multidimensional nova simulations, to approximately account for the energetics of the explosion. Hence, no reliable nucleosynthesis predictions can be inferred from these studies.

4. Nucleosynthesis

The early evolution of the thermonuclear runaway is dominated by the operation of both the proton-proton chains as well as the cold CNO cycle (i.e., ^{12}C(p, γ)^{13}N(β^+)^{13}C(p, γ)^{14}N). As the temperature increases, the characteristic timescale for proton captures onto ^{13}N becomes shorter than the corresponding β^+-decay time, favoring a number of reactions of the hot CNO-cycle, such as ^{13}N(p, γ)^{14}O, together with ^{14}N(p, γ)^{15}O and ^{16}O(p, γ)^{17}F. Convection settles in the envelope when temperature exceeds $\sim 2 \times 10^7$ K, and plays a critical role in the nova explosion, carrying a substantial fraction of the short-lived, β^+-unstable nuclei ^{13}N, ^{14,15}O and ^{17}F, synthesized in the CNO-cycle, to the outer, cooler layers of the envelope. The energy released by these species during their decay powers the expansion and ejection stages of the outburst (Starrfield et al. 1972; see also Sect. 2). Moreover, the large amounts of ^{13}N, ^{14,15}O, and ^{17}F synthesized during the outburst translate into large amounts of their daughter nuclei ^{13}C, ^{15}N, and ^{17}O in the ejecta.

From a nuclear physics viewpoint, novae are unique stellar explosions: their nuclear activity, limited to about a hundred relevant species (A<40) linked through a (few) hundred nuclear reactions, as well as the moderate temperatures achieved during the explosion (10^7–4×10^8 K), allow us to rely primarily on experimental information (José, Hernanz & Iliadis 2006). As shown in Fig. 2, the main nuclear path in nova outbursts runs close to the valley of stability, and is driven by p-capture reactions and β^+-decays, with no significant contribution from any n- or α-capture reaction. The key role played by nuclear reactions has sparked a suite of different studies aimed at identifying the most critical reactions whose uncertainty has the largest impact on nova nucleosynthesis (see, for instance, Iliadis et al. 2002, for a sensitivity study based on 7350 network calculations). Many of the important reactions identified have been re-evaluated in recent years. Actually, the number of reactions whose uncertainty has still a strong impact on nova nucleosynthesis is small, being mainly dominated by the challenging reactions ^{18}F(p, α)^{15}O, ^{25}Al(p, γ)^{26}Si, and ^{30}P(p, γ)^{31}S.

Current predictions, based on 1D hydrodynamic models of nova outbursts, suggest that Ca is the likely nucleosynthetic endpoint, in agreement with observations of ejected nova shells. There is, in general, good agreement between the abundance patterns inferred from observations and those derived from numerical simulations. However, it is worth noting that the specific chemical abundance pattern spectroscopically inferred shows huge enhancements in metals, with characteristic mass fractions in the ejecta ~0.5 for neon novae and ~0.25 for non-neon novae. In order to match the observed abundances, 1D models have (often) to artificially assume mixing between core material and the (solar-like) accreted envelope, since the temperatures achieved during the explosion do not allow significant CNO-breakout. Moreover, spectroscopic abundance determinations yield only atomic values, so comparison with theoretical predictions is rather limited in this respect. Several species synthesized during classical nova outbursts provide potentially detectable γ-rays: this includes ^{13}N and ^{18}F, that power a prompt γ-ray emission at and below 511 keV, as well as the longer lived ^{7}Be and ^{22}Na, that decay when the envelope is optically thin to γ-rays, powering line emission at 478 and 1275 keV, respectively. ^{26}Al is another important radioactive isotope synthesized during nova outbursts, although only its cumulative emission can be observed because of its slow decay. Indeed, the contribution of novae to the Galactic content

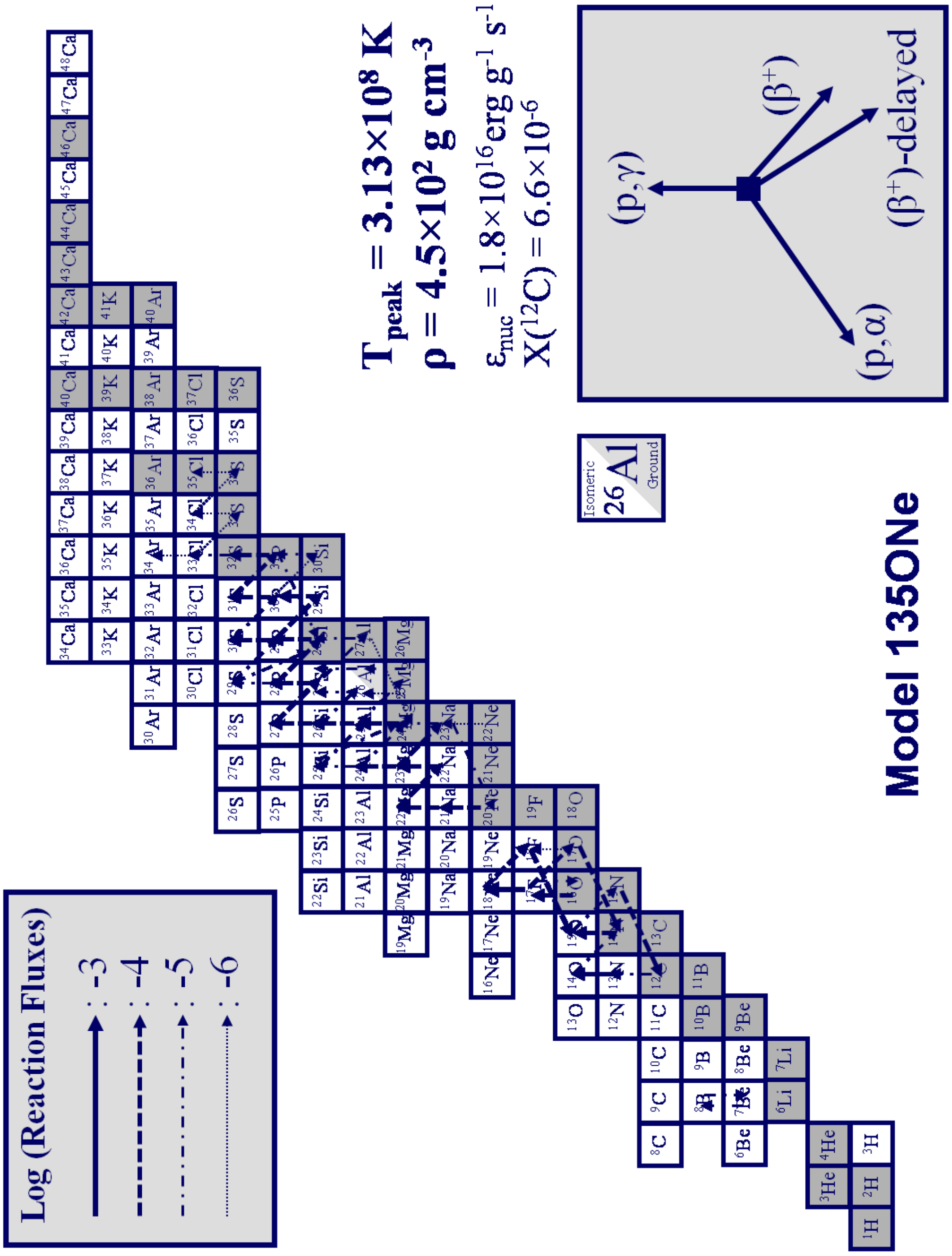

Figure 2. Main reaction fluxes at the innermost envelope shell for a nova model with a 1.35 $M_\odot$ ONe white dwarf accreting at a rate of 2×10^{-10} $M_\odot$ yr^{-1}, as calculated with the 1D hydrodynamic code *SHIVA* (José & Hernanz 1998).

of ^{26}Al is expected to be small (~20%). We refer the reader to Hernanz (2012: this volume) for a review of past and current theoretical predictions of the γ-ray output from classical novae, initiated with the seminal paper by Clayton & Hoyle (1974).

Better perspectives to constrain theoretical nucleosynthesis results are offered by laboratory analyses of presolar meteoritic grains. Infrared and ultraviolet observations have revealed dust forming episodes in the shells ejected during classical nova outbursts (Gehrz et al. 1998). Since the pioneering studies of dust formation in novae by Clayton & Hoyle (1976), all efforts devoted to the identification of potential nova grains relied mainly on the search for low ^{20}Ne/^{22}Ne ratios. Since noble gases, such as Ne, do not condense into grains, the presence of ^{22}Ne was attributed to *in situ* ^{22}Na decay, a signature of a classical nova explosion. Indeed, Clayton and Hoyle pointed out several isotopic signatures (i.e., large overproduction of ^{13,14}C, ^{18}O, ^{22}Na, ^{26}Al or ^{30}Si), that may help in the identification of grains of putative nova origin. More than three decades later, most of these signatures still hold, in view of our current understanding of nova explosions, except for ^{14}C, bypassed by the main nuclear path in novae, and ^{18}O, which is slightly overproduced by novae but grains nucleated in this environment are expected to be much more anomalous in ^{17}O. A major step forward in the discovery of presolar nova candidate grains was achieved by Amari et al. (2001), who reported on several SiC and graphite grains, isolated from the Murchison and Acfer 094 meteorites, with an abundance pattern qualitatively similar to nova model predictions: low ^{12}C/^{13}C and ^{14}N/^{15}N ratios, high ^{30}Si/^{28}Si, and close-to-solar ^{29}Si/^{28}Si; and high ^{26}Al/^{27}Al and ^{22}Ne/^{20}Ne ratios for some of the grains. But in order to quantitatively match the grain data, one had to assume mixing of the material newly synthesized in the nova outburst with more than ten times as much unprocessed, isotopically close-to-solar, material before grain formation. One possible source of dilution might be mixing between the ejecta and the accretion disk, or even with the outer layers of the stellar companion. Concerns about the likely nova paternity of these grains have been raised (Nittler & Hoppe 2005), after three additional micron-sized SiC grains were isolated from the Murchison meteorite with similar trends, but also with additional imprints (mainly non-solar Ti features), from which a supernova origin cannot be excluded. The presence of Ti in these grains, an element slightly above the canonical nucleosynthetic endpoint predicted for novae (Ca), has once more raised the issue of the possibility that other nuclear channels, like the CNO-breakout, may take place in nova outbursts under special circumstances. This, for instance, has been investigated in the context of slow white dwarf accretors in cataclysmic variables (Glasner & Truran 2009), or in very-low metallicity systems (such as for primordial novae; see José et al. 2007). Identification of many more nova candidate grains is needed to shed light into this question.

5. Outlook

Recent developments in computer science are now providing modelers with the required capabilities to study novae in a truly multidimensional framework. Pioneering 2D and 3D simulations are beginning to shed light into the nova mixing problem and detailed multidimensional simulations of the expansion and ejection stages are likely to become available soon.

Moreover, the emergence of high-energy astrophysics with space-borne observatories has opened new windows to observe novae, from a new panchromatic perspective. Detection of unambiguous γ-ray signatures from a close enough event would provide unprecedented constraints on the predicted nucleosynthesis accompanying nova outbursts.

Cosmochemistry, in turn, is helping in the analysis of tiny pieces of stardust embedded in primitive meteorites, giving clues on the processes operating in novae. We expect to increase the inventory of presolar nova grains, likely within the oxide and A+B groups.

Finally, nuclear physicists are determining reaction rates at (or close to) stellar energies, through combined efforts with stable and/or radioactive ion beams and theoretical modeling, at the required precision for nova explosions. Soon, all nuclear interactions of interest for novae would have been determined experimentally.

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