Proc. 14th Int. Symp. on Nuclei in the Cosmos (NIC2016)
JPS Conf. Proc. **14**, 010501 (2017)
https://doi.org/10.7566/JPSCP.14.010501

Nucleosynthesis in Novae

Jordi JOSÉ

Department of Physics, Universitat Politècnica de Catalunya, Barcelona 08019, and Institut d'Estudis Espacials de Catalunya (IEEC-UPC), Barcelona 08034, Spain

E-mail: Jordi.jose@upc.edu

(Received September 10, 2016)

Remarkable progress in our understanding of nova outbursts has been achieved through combined efforts in photometry, spectroscopy and numerical simulations. According to the thermonuclear runaway model, novae are powered by thermonuclear explosions in the H-rich envelopes transferred from a low-mass stellar companion onto a close white dwarf star. Extensive numerical simulations have shown that the accreted envelopes attain peak temperatures ranging between 100 and 400 MK, for about several hundred seconds, hence allowing extensive nuclear processing which eventually shows up in the form of nucleosynthetic fingerprints in the ejecta. Indeed, it has been claimed that novae can play a key role in the enrichment of the interstellar medium through a number of intermediate-mass elements. This includes ^{17}O, ^{15}N, and ^{13}C, plus a smaller contribution in a number of other species (A < 40), such as ^{7}Li, ^{19}F, or ^{26}Al. At the turn of the XXI Century, classical novae entered the era of multidimensional models, which provide new insights into the physical mechanisms that drive mixing at the core-envelope interface. In this paper, we will present an overview on classical nova models, from the onset of accretion up to the explosion and ejection stages, with special emphasis on their gross observational properties and their associated nucleosynthesis. The impact of nuclear uncertainties on the final yields will be discussed.

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 amazed astronomers for more than two millennia. They exhibit a sudden rise in optical brightness, with peak luminosities reaching 10^4 - 10^5 L_{sun}. Nova explosions take place in stellar 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 increasingly reveal more evolved companions). 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 semidegenerate conditions until a thermonuclear runaway (hereafter, TNR) ensues (see refs. [1-4], for recent reviews).

Novae constitute 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, < 5 - 7, are discovered every year, a much higher nova rate, around 30 ± 10 yr^{-1}

has been predicted from extrapolation of galactic and extragalactic data (M31, in particular) [5]. 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 as well as high mass-accretion rates. 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_{sun}, in a thermonuclear supernova versus 10^{-3} - 10^{-5} M_{sun} for a nova).

2. Paving the Road for Nova Explosions

Nova explosions can naturally occur in carbon-oxygen-rich (hereafter, CO) and oxygen-neon-rich (ONe) white dwarfs. The most frequent case involves a CO white dwarf, the remnant of a progenitor star with a mass ≤ 7 - 8 M_{sun} [6], 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, but a value of ~1.1 M_{sun} is obtained when binarity is taken into account [7].

The most important quantity in determining the strength of a nova outburst is the pressure at the core-envelope interface, P_*, which is a measure of the pressure exerted by the layers overlying the burning shell [8,9]. To account for mass ejection, about $P_* \geq 10^{20}$ dyn cm^{-2} are required, for a solar composition envelope. Typical accreted envelope masses range between 10^{-3} - 10^{-7} M_{sun}. Detailed hydrodynamic simulations [10-14] have revealed the 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 ~10^{-7} - 10^{-11} M_{sun} yr^{-1}, have been inferred in cataclysmic variables [15]. Observationally, systems with orbital periods in the range 0.7 < P_{orb} (hr) < 3.3, are characterized by low mass-transfer rates (10^{-10} - 10^{-11} M_{sun} yr^{-1}), while those with larger orbital periods exhibit higher rates (10^{-8} - 10^{-9} M_{sun} yr^{-1}). How these mass-transfer rates translate into mass-accretion rates is however a matter of debate. According to the semianalytic analysis of MacDonald [9], for a given white dwarf mass, there is a maximum value of the mass-accretion rate that leads to nova outbursts. 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. [14] reported mass ejection from models of 1 M_{sun} white dwarfs accreting solar-like material at a rate as high as 10^{-7} M_{sun} yr^{-1} (see ref. [12]

for models of very luminous white dwarfs). It is also worth noting that Yaron et al. have computed nova models with very low mass-accretion rates, 5×10^{-13} M_{sun} yr^{-1}. In turn, Glasner and Truran [10] have explored the possibility of CNO-breakout in novae, in the context of low luminosity white dwarfs accreting matter at low rates, 10^{-11} M_{sun} 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 (see, however, ref. [14]). 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. Ref. [16] 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 pressures are achieved, which translate into more violent outbursts (similar effects have been described elsewhere; see, for instance, refs. [11-14, 17]). 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. Note that if the white dwarf is initially too luminous, the ignition shell is not highly degenerate when the thermonuclear runaway develops and a mild runaway without mass ejection may occur.

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, 3/2 kT, is smaller than the Fermi energy [3]. Complete degeneracy is, for instance, 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 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. Degeneracy is lifted very early in the runaway (as soon as the temperature at the base of the envelope achieves 30 MK; see ref. [3] for details).

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 (in sharp contrast to type I X-ray bursts).

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 [18,19], only envelopes with CNO-enhanced abundances (in the range Z_{CNO} ~ 0.2 - 0.5) can reproduce the gross observational properties of a fast nova

[20,21]. 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 (see Sect. 3.2, for 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., refs. [22-25]), in which the envelope's history relies on the time evolution of the temperature (T) and density (ρ) in a single layer (usually, the envelope base). Such thermodynamic quantities are often calculated by means of semianalytic 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, has been widely used in the past to overcome the strong time limitations that arise when large nuclear reaction networks are 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 [26]. 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., ref. [27]). 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 semianalytic models directly coupled to a nuclear reaction network. An example of this category can be found in Coc [28], which is based on the semianalytic model of MacDonald. 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 receeds from its surface, are completely ignored.

So far, the state-of-the-art in nova nucleosynthesis relies on 1D hydrodynamic models (e.g., refs. [11-14,29,30]). 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 have been succesfully 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 [31] was the first to address localized TNRs on the surface of white dwarfs by means of semianalytic 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. The first studies that addressed this question in the framework of multidimensional nova simulations were performed by Glasner et al. [32,33]: 2D simulations were performed with the code VULCAN, an arbitrary Lagrangian Eulerian (ALE) code with capability to handle both explicit and implicit steps. 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 km × 5 km. The evolution of an accreting 1 M_{sun} 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 100 MK. Such 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 instabilites (a mechanism that bears a clear resemblance to the convective overshooting proposed by Woosley [34]). The efficient dredge-up of CO material from the outermost white dwarf layers accounts for a 20%-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, 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 (and 3D) simulations were published, shortly after, by Kercek et al. [35,36], providing qualitatively similar results but somewhat less violent outbursts (i.e., longer TNRs with lower peak temperatures and ejection velocities) caused by large differences in the convective flow patterns: whereas in Glasner et al., 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. Kercek et al. concluded that CO mixing *must* take place prior to the TNR, in sharp contrast with the main results reported by Glasner et al. 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.

Confirmation of the feasibility of this mixing scenario was provided by a set of independent 2D simulations [37,38], 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. 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 [39,40]. These structures, vortices and filaments, will undergo a similar fate down to approximately the Kolmogorov scale. In this framework, a pioneering 3D simulation of mixing at the core-envelope interface during nova explosions [41] 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 techniques, they may represent a real signature of the turbulence generated during the thermonuclear runaway. Similar results have also been recently obtained in the framework of 3D models of mixing for ONe-rich substrates [42].

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, ^{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 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 ~ 2×10^7 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 by 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 [20]. Moreover, the synthesis of these short-lived species during the outburst translates 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, together with the moderate temperatures achieved during the explosion (10 – 400 MK), allow us to rely primarily on experimental information [43]. 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 [26]. 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, spectroscopic abundance determinations yield only atomic values, so comparison with theoretical predictions is rather limited in this regard.

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 [44]. Since the pioneering studies of dust formation in novae by Clayton and Hoyle [45], 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. A major step forward in the discovery of presolar nova candidate grains was achieved by Amari et al. [46], who reported 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, together with high ^{26}Al/^{27}Al and ^{22}Ne/^{20}Ne ratios for some grains. But in order to quantitatively match the grain data, one had to assume mixing of the material newly synthesized in the 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 [47], 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 (core-collapse) supernova origin cannot be excluded. Fourteen new submicron- to micron-sized ^{13}C- and ^{15}N-enriched presolar SiC grains from Murchison have also been recently reported [48]. In some of these grains, both nova and supernova origins are viable because explosive H-burning in the two stellar sites could result in quite similar proton-capture isotopic signatures. Other recent advances in this area include the first identification of a CO nova graphite grain [49] and new insights into the production of C-rich dust in CO novae [50] based on updated stellar evolution calculations of the low-mass progenitor star.

Acknowledgment

This work has been partially supported by the Spanish MINECO grant AYA2014–59084–P, by the E.U. FEDER funds, and by the AGAUR/Generalitat de Catalunya grant SGR0038/2014.

References

[1] S. Starrfield, C. Iliadis and W. R. Hix: *Classical Novae* (Cambridge Univ. Press, Cambridge, 2008) 2nd ed., p. 77.
[2] S. Starrfield, C. Iliadis and W. R. Hix: Publ. Astron. Soc. Pacific **128** (2016) 051001.
[3] J. José: *Stellar Explosions. Hydrodynamics and Nucleosynthesis* (CRC/Taylor & Francis, Boca Raton, FL, 2016).
[4] J. José and S. N. Shore: *Classical Novae* (Cambridge Univ. Press, Cambridge, 2008) 2nd ed., p. 121.
[5] A. W. Shafter: *Classical Nova Explosions* (AIP, Melville, NY, 2002) 2nd ed., p. 467.
[6] L. G. Althaus, A. H. Córsico, J. Isern and E. García-Berro: Astron. Astrophys. Rev. **18** (2010) 471.
[7] P. Gil-Pons, E. García-Berro, J. José, M. Hernanz and J. Truran: Astron. Astrophys. **407** (2003) 1021.
[8] M. Y. Fujimoto: Astrophys. J. **257** (1982) 752.
[9] J. MacDonald: Astrophys. J. **267** (1983) 732.
[10] S. A. Glasner and J. W. Truran: Astrophys. J. **692** (2009) L58.

[11] D. Prialnik and A. Kovetz: Astrophys. J. **445** (1995) 789.
[12] M. M. Shara, O. Yaron, D. Prialnik, A. Kovetz and D. Zurek: Astrophys. J. **725** (2010) 831.
[13] S. Starrfield, J. W. Truran, M. C. Wiescher and W. M. Sparks: Monthly Not. Royal Astron. Soc. **296** (1998) 502.
[14] O. Yaron, D. Prialnik, M. M. Shara and A. Kovetz: Astrophys. J. **623** (2005) 398.
[15] J. Patterson J.: Astrophys. J. Suppl. **54** (1984) 443.
[16] E. Schwartzman, A. Kovetz and D. Prialnik: Monthly Not. Royal Astron. Soc. **269** (1994) 323.
[17] J. José and M. Hernanz: Meteoritics Planet. Science **42** (2007) 1135.
[18] W. M. Sparks, S. Starrfield and J. W. Truran: Astrophys. J. **220** (1978) 1063.
[19] D. Prialnik, M. M. Shara and G. Shaviv: Astron. Astrophys. **62** (1978) 339.
[20] S. Starrfield, J. W. Truran, W. M. Sparks and G. S. Kutter: Astrophys. J. **176** (1972) 169.
[21] S. Starrfield, J. W. Truran and W. M. Sparks: Astrophys. J. **226** (1978) 186.
[22] W. Hillebrandt and F.-K.Thielemann: Astrophys. J. **255** (1982) 617.
[23] M. Wiescher, J. Görres, F.-K. Thielemann and H, Ritter: Astron. Astrophys. **160** (1986) 56.
[24] A. Weiss and J. W. Truran: Astron. Astrophys. **238** (1990) 178.
[25] S. Wanajo, M.-A. Hashimoto and K. Nomoto: Astrophys. J. **523** (1999) 409.
[26] C. Iliadis, A. Champagne, J. José, S. Starrfield and P. Tupper: Astrophys. J. Suppl. **142** (2002) 105.
[27] W. R. Hix, M. S. Smith, S. Starrfield, A. Mezzacappa and D. Smith: Nuclear Physics **A718** (2003) 620.
[28] A. Coc, R. Mochkovitch, Y. Oberto, J.-P. Thibaud and E. Vangioni—Flam: Astron. Astrophys. **299** (1995) 479.
[29] J. José and M. Hernanz: Astrophys. J. **494** (1998) 680.
[30} S. Starrfield, C. Iliadis, W. R. Hix, F. X. Timmes and W. M. Sparks: Astrophys. J. **692** (2009) 1532.
[31] M. M. Shara: Astrophys. J. **261** (1982) 649.
[32] S. A. Glasner and E. Livne: Astrophys J. **445** (1995) L149.
[33] S. A. Glasner, E. Livne and J. W. Truran: Astrophys J. **475** (1997) 754.
[34] S. E. Woosley: *Nucleosynthesis and Chemical Evolution* (Geneva Observatory:Sauverny, 1986), p. 1.
[35] A. Kercek, W. Hillebrandt and J. W. Truran: Astron. Astrophys. **337** (1998) 379.
[36] A. Kercek, W. Hillebrandt and J. W. Truran: Astron. Astrophys. **345** (1999) 831.
[37] J. Casanova, J. José, E. García-Berro, A. C. Calder and S. N. Shore: Astron. Astrophys. **513** (2010) L5.
[38] J. Casanova, J. José, E. García-Berro, A. C. Calder and S. N. Shore: Astron. Astrophys. **527** (2011) A5.
[39] S. Pope: *Turbulent Flows* (Cambridge Univ. Press, Cambridge, 2000).
[40] S. N. Shore: *Astrophysical Hydrodynamics. An Introduction* (Wiley,Weinheim, 2007).
[41] J. Casanova, J. José, E. García-Berro, S. N. Shore and A. C. Calder: Nature **478** (2011) 490.
[42] J. Casanova, J. José, E. García-Berro and S. N. Shore: Astron. Astrophys. (2016) in press.
[43] J. José, M. Hernanz and C. Iliadis: Nucl. Physics **A777** (2006) 550.
[44] R. D. Gehrz, J.W. Truran, R. E. Williams and S. Starrfield: Publ. Astron. Soc. Pacific **110** (1998) 3.
[45] D. D. Clayton and F. Hoyle: Astrophys. J. **203** (1976) 490.
[46] S. Amari, X. Gao, L. Nittler, E. Zinner, J. José, M. Hernanz and R. Lewis: Astrophys. J. **551** (2001) 1065.
[47] L. R. Nittler and P. Hoppe: Astrophys. J. 631 (2005) L89.
[48] N. Liu, L. R. Nittler, C. M. O.'D. Alexander, J. Wang, M. Pignatari, J. José and A. Nguyen: Astrophys. J. **820** (2016) 140.
[49] P. Haenecour, C. Floss, J. José, S. Amari, K. Lodders, M. Jadhav, A. Wang and F. Gyngard: Astrophys. J. **825** (2016) 88.
[50] J. José, G. M. Halabi and M. F. El Eid: Astron. Astrophys. (2016) in press.