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Recent advances in the modelling of classical novae and type I X-ray bursts

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Abstract. Classical nova outbursts and type I X-ray bursts are thermonuclear stellar explosions driven by charged-particle reactions. Extensive numerical simulations of nova explosions have shown that the accreted envelopes attain peak temperatures between 0.1 and 0.4 GK, for about several hundred seconds, and therefore, their ejecta is expected to show signatures of significant nuclear activity. Indeed, it has been claimed that novae play some role in the enrichment of the interstellar medium through a number of intermediate-mass elements. This includes ^{17}O, ^{15}N, and ^{13}C, systematically overproduced in huge amounts with respect to solar abundances, with a lower contribution to a number of species with A<40, such as ^{7}Li, ^{19}F, or ^{26}Al. In this review, we present new 1-D hydrodynamic models of classical nova outbursts, from the onset of accretion up to the explosion and ejection phases. Special emphasis is put on their gross observational properties (including constraints from meteoritic presolar grains and potential gamma-ray signatures) and on their associated nucleosynthesis. Multidimensional models of mixing at the core-envelope interface during outbursts will also be presented. The impact of nuclear uncertainties on the final yields will be also outlined. Detailed analysis of the relevant reactions along the main nuclear path for type I X-ray bursts has only been scarcely addressed, mainly in the context of parameterized one-zone models. Here, we present a detailed study of the nucleosynthesis and nuclear processes powering type I X-ray bursts. The reported bursts have been computed by means of a spherically symmetric (1D), Lagrangian, hydrodynamic code, linked to a nuclear reaction network that contains 325 isotopes (from ^{1}H to ^{107}Te), and 1392 nuclear processes. These evolutionary sequences, followed from the onset of accretion up to the explosion and expansion stages, have been performed for two different metallicities to explore the dependence between the extension of the main nuclear flow and the initial metal content. We carefully analyze the physical parameters that determine the light curve (including recurrence times, ratios between persistent and burst luminosities, or the extent of the envelope expansion). Results are in qualitative agreement with the observed properties of some well-studied bursting sources.

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1. Classical novae

Classical novae are stellar explosions that have captivated the interest of astronomers for more than two millennia. They are characterized by a sudden rise in optical brightness (from 8 to 18 magnitudes in 1 or 2 days), with peak luminosities reaching $10^4 - 10^5$ $L_\odot$. In the event, $10^{-4} - 10^{-5}$ $M_\odot$ of nuclear–processed material are ejected into the interstellar medium, at typical velocities > 10^3 km s^{-1}. Nova explosions occur in cataclysmic binary systems, consisting of a compact, white dwarf star (usually, CO- or ONe-rich) and a low mass companion (typically, a K or M dwarf of solar composition, although there is evidence pointing towards more evolved companions in some cases). The system is very close (with orbital periods < 10 – 12 hr), allowing mass transfer episodes caused by Roche Lobe overflow of the main sequence star. Since this flow of hydrogen-rich material carries angular momentum, it forms an accretion disk that surrounds the white dwarf star. Ultimately, a fraction of this material spirals in and piles up on the white dwarf surface (at a rate ~ 10^{-9} -10^{-10} $M_\odot$ yr^{-1}), building up an envelope in semi-degenerate conditions until a thermonuclear runaway (hereafter, TNR) ensues [1-3].

The build up of the envelope is dominated by the operation of both the proton-proton chains as well as the cold CNO cycle, mainly through $^{12}C(p, \gamma)^{13}N(\beta^+)^{13}C(p, \gamma)^{14}N$. Moreover, the dominant nuclear reaction flow, even during the explosive stages, proceeds close to the valley of stability and is dominated by (p,γ), (p,α), and β^+-decays. It is worth noting that neutron and alpha-capture reactions are completely negligible in the physical conditions that characterize a classical nova outburst. Models of nova nucleosynthesis point towards an endpoint around Ca, in agreement with observations of nova shells, with significant overproduction of ^{13}C, ^{15}N and ^{17}O (figure 1), the likely fingerprints of a large number of nova explosions in the overall Galactic history. Explosions hosting CO white dwarfs are also characterized by large overabundances of ^7Li while those occurring on ONe white dwarfs produce a wealth of intermediate-mass elements. Indeed, explosions on massive ONe white dwarfs would overproduce Si-Cl nuclei (figure 1, right panel).

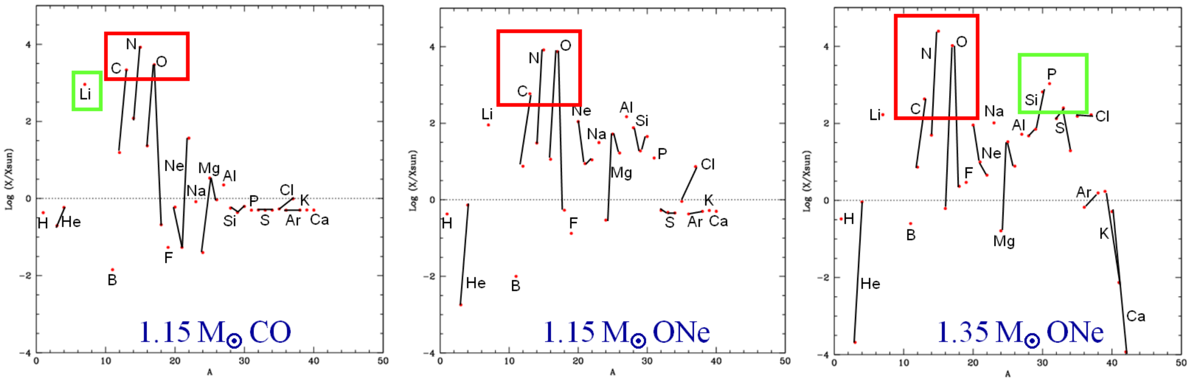

Figure 1. Overproduction factors, relative to solar abundances, obtained in three classical nova models involving 1.15 $M_\odot$ CO, 1.15 $M_\odot$ ONe and 1.35 $M_\odot$ ONe white dwarfs. Calculations have been performed with the 1-D *Shiva* code [4], using updated nuclear reaction rates [5].

Crude comparisons have shown, in general, good agreement between the abundance patterns inferred from observations and those derived from numerical simulations, once the stream of matter transferred from the companion is *conveniently* pre-enriched in metals, in an attempt to mimic the mixing process that should naturally occur at the core-envelope interface. Unfortunately, there is a lack of consensus concerning the nature of such mixing process, required to account for the non-solar patterns inferred in the ejecta, with metallicities around 0.3 (CO) and 0.5 (ONe), but as high as 0.86 in some extreme cases. Recent theoretical efforts have focused on multidimensional simulations in an attempt to circumvent the mixing length theory of convection usually adopted in 1-D simulations. So far, two independent 2-D studies [6,7], based upon the same initial 1-D model, led to nearly opposite conclusions about the strength of the runaway and its capability to power a fast nova. The origin of these differences was carefully analyzed [8], suggesting that the early stages of the explosion, prior to the onset of the TNR – when the evolution is almost quasi-static – are extremely sensitive to the outer boundary conditions. To disentangle the existing controversy, 2-D simulations have been recently performed with the hydrodynamic code FLASH [9, 10]: results show that a shear flow at the core-envelope interface drives mixing through Kelvin-Helmholtz instabilities. The conservation of vorticity imposed by the adopted 2-D geometry induces large convective eddies close to the core-envelope interface, with a size comparable to the height of the envelope, that mix CO-rich material from the outermost layers of the underlying white dwarf into the accreted envelope (figure 2). The metallicity enrichment achieved in the envelope, Z ~0.30, is in agreement with the values inferred in the ejecta of CO novae. 3-D simulations aimed at describing more realistically how mixing at the core-envelope interface and convection develop are currently being computed by the Barcelona group.

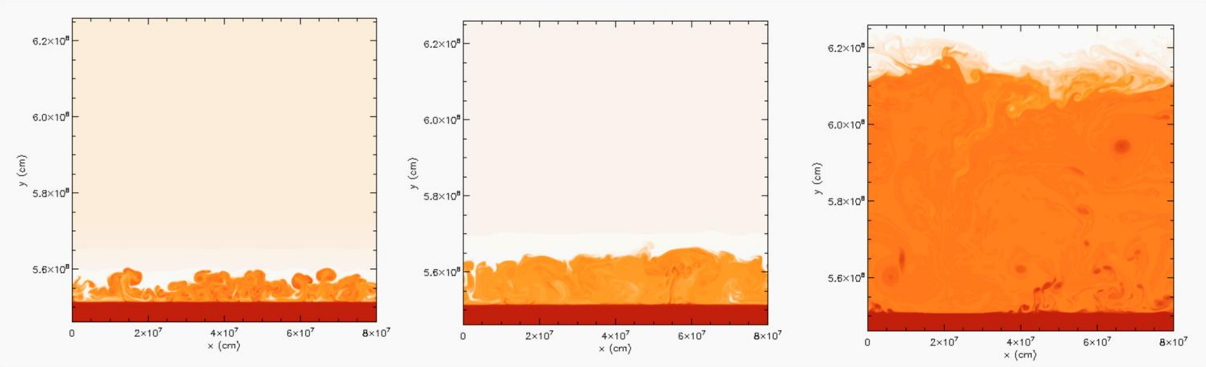

Figure 2. Snapshots of the development of Kelvin-Helmholtz instabilities shown in terms of the ^{12}C mass fraction (in logarithmic scale; darker regions correspond to higher CO mass fractions). Times correspond to 235 s (left panel), 279 s (central panel) and 498 s (right panel) since T at the core-envelope interface reaches ~10^8 K. The mean CNO mass fraction at the end of the simulations reaches ~0.30, by mass. Adapted from [9].

Unfortunately, spectroscopic determinations rely only on atomic abundances. Better nucleosynthesis constraints could be achieved through the pioneering detection of specific γ-ray signatures (such as the lines at 1275 keV –^{22}Na–, 478 keV –^{7}Li–, 511 keV or the continuum down to 20-30 keV –both from electron-positron annihilation powered mainly by ^{13}N and ^{18}F [11]) or from laboratory analyses of presolar grains of a putative nova origin [12,13].

Finally, it is worth mentioning that most of the reactions important for novae (i.e., proton-induced reactions) have been (or will be soon) measured directly in the laboratory, or rely on experimental information. Usual reaction rate uncertainties, typically less than 30% are sufficiently accurate for quantitative nova model predictions [1]. ^{18}F(p,α), ^{25}Al(p,γ), and ^{30}P(p,γ) are probably the most outstanding examples of reactions whose uncertainties in nova conditions must yet be improved. In that sense, nova nucleosynthesis predictions are today limited by uncertainties in the hydrodynamic description of those events rather than by nuclear physics uncertainties.

2. Type I X-ray bursts

With a neutron star as the underlying compact object hosting the explosion, temperatures and densities in the accreted envelope reach during type I X-ray bursts $T_{peak} > 10^9$ K, and $\rho \sim 10^6$ g cm^{-3}. Hence, nucleosynthesis studies require the use of hundreds of isotopes, up to the SnSbTe mass region [14] (or beyond [15]), linked through thousands of nuclear interactions.

The main nuclear reaction flow is driven by the *rp-process* (rapid proton-captures and β^+-decays), the 3α-reaction, and the *αp-process* (a sequence of (α,p) and (p,γ) reactions), and is expected to proceed far away from the valley of stability, merging with the proton drip-line beyond A = 38 [13-18]. The existence of a nucleosynthetic endpoint in XRB is still a matter of debate, since recent studies [19,20] suggest that the SnSbTe-mass region is maybe harder to reach.

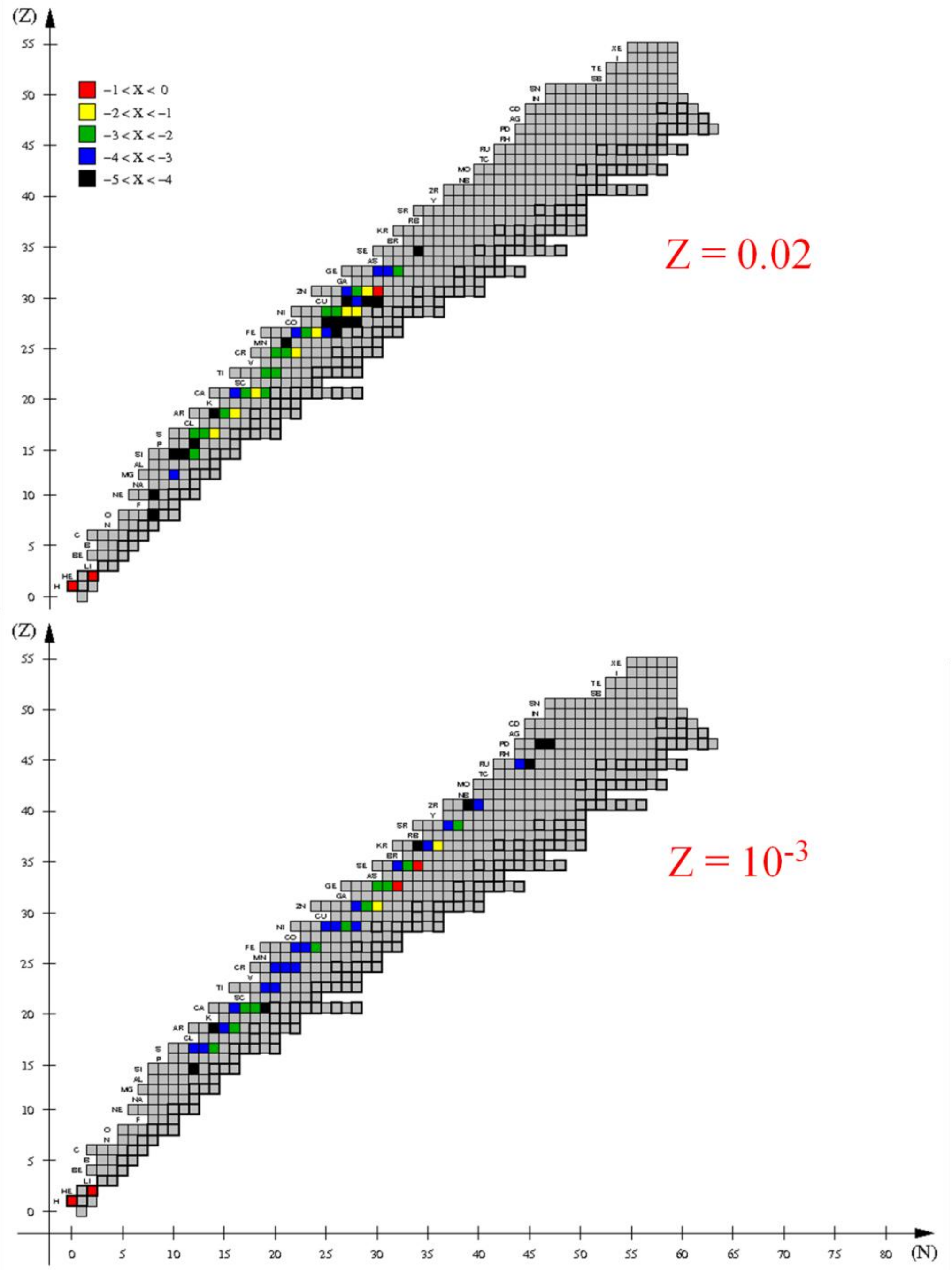

Figure 3. Main nuclear activity at peak temperature during the first burst, shown in terms of the most abundant species at the innermost envelope shell, for two different XRB models. Color legends indicate different ranges of mass fractions (in logarithmic scale). Calculations have been performed with the 1-D hydrodynamic code SHIVA, and involve 1.4 $M_\odot$ neutron stars, accreting mass at rate 1.8 × 10^{-9} $M_\odot$ yr^{-1}. The composition of the accreted material is assumed to be solar-like (Z = 0.02; upper panel), or metal-deficient (Z =0.001 = $Z_\odot/20$; lower panel). Adapted from [18].

Most of the reaction rates used in XRB nucleosynthesis calculations lack experimental information and often rely on theoretical Hauser-Feschbach estimates. Recent studies [21, 22] have led to the identification of the key reactions whose uncertainty most deeply influences the predicted XRB nucleosynthesis: this is a very limited subset (~40 reactions), with the most influential ones being ^{65}As(p, γ) and ^{61}Ga(p, γ). Mass measurements around waiting point nuclei are also required to improve our current nucleosynthesis predictions [22]. This includes ^{62}Ge, ^{66}Se, ^{70}Kr, ^{84}Nb, ^{85}Mo, ^{86,87}Tc, ^{96}Ag, ^{97}Cd, and ^{103}Sn (since ^{65}As, ^{69}Br and ^{106}Sb have been recently measured [23, 24]). Better precision for the experimentally-known masses of ^{71}Br, ^{83}Nb, and ^{86}Mo may be also required as these are known to only ±568, 315, and 438 keV, respectively. Finally, mass measurements of ^{66}Se ($t_{1/2}$ = 33 ms) as well as spectroscopy of ^{66}Se are also needed to improve our knowledge of the important ^{65}As(p, γ) reaction rate in XRBs.

Several attempts to link the extension of the nuclear path in XRBs with the metallicity of the accreted material have been published in recent years [16, 18]. In particular, we will summarize here the main conclusions reached from two sets of hydrodynamic models of type I XRBs, containing 324 species and 1392 nuclear processes [18]. In the first one, a 1.4 $M_\odot$ neutron star accretes material of solar composition from its stellar companion at a rate 1.75×10^{-9} $M_\odot$ yr^{-1}. Recurrence times between bursts of ~5 hours, peak temperatures of about $(1.1- 1.3)\times10^{9}$ K, and ratios between persistent and burst luminosities, α, in the range ~ 30−40 (with $L_{peak} \sim (4 - 8)\times10^{38}$ erg s^{-1}), have been obtained for the 4 bursts computed in this model. These values are qualitatively in agreement with those determined in the XRB sources [25] GS 1826-24 [τ_{rec}= 5.74±0.13 hr, α=41.7±1.6], 4U 1323-62 [τ_{rec}=5.3 hr, α=38±4], or 4U 1608-52 [τ_{rec}=4.14–7.5 hr, α=41–54]. Morever, the moderate peak temperatures achieved in this model restrict most of the nuclear activity to mass ~60, and hence, no large concentrations in the SnSbTe-mass region are found Figure 3, upper panel), in agreement with results reported previously [16,17]. This model also yields a very small post-burst abundance of ^{12}C, below the threshold amount required to power *superbursts* ($X[^{12}C]_{min} > 0.1$; see [26]).

A second set of bursts have been computed assuming now that the stream of material transferred from the companion onto the neutron star is metal-deficient, with $Z = Z_\odot/20 = 0.001$. Longer recurrence times of ~9 hours, peak temperatures of about $(1.3-1.4)\times10^{9}$ K, and ratios between persistent and burst luminosities of $\alpha \sim 20-30$ (with $L_{peak} \sim 10^{38}$ erg s^{-1}) have been obtained in the 5 bursts computed in this model, values that are also in agreement with those measured in the XRB sources [25] 1A 1905+00 [τ_{rec}=8.9 hr], 4U 1254-69 [τ_{rec}=9.2 hr], or XTE J1710-281 [τ_{rec}=8.9 hr, α=22–100]. These results reveal a clear dependence of burst properties on the metallicity of the accreted material: the smaller the metal content, the larger the recurrence time (and the smaller the α). In turn, explosions in metal-deficient envelopes are characterized by lower peak luminosities and longer decline times, in agreement with the pattern described in [16]. This, together with the longer exposure times to high temperatures (driven by a slower decline phase), cause an extension of the main nuclear path towards the SnSbTe-mass region (figure 3, lower panel).

A debated aspect of the nucleosynthesis predicted during X-ray bursts is their role as nuclear factories of the Galactic light p-nuclei ^{92,94}Mo and ^{96,98}Ru [14]. Two main aspects have to be considered here: first, the synthesis of those nuclei during XRBs is questionable since detailed hydrodynamic simulations show that the abundances of many species synthesized during the bursts decrease remarkably towards the outer envelope layers, because of limited convective transport. This shows the limitations posed by one-zone nucleosynthesis calculations (like those used in [14]), in which the chemical species synthesized in the innermost layers are, by default, assumed to represent the whole (chemically homogeneous) envelope. Indeed, the mass fractions of these p-nuclei, drop by more than an order of magnitude in the outer envelope layers (as compared with the values achieved at the innermost shells). The resulting overproduction factors are several orders of magnitude smaller than those required to account for the origin of these problematic nuclei [19], in sharp contrast with the results obtained in one-zone calculations [14]. And second, ejection from a neutron star is energetically unlikely: notice, for instance, that matter accreted onto a neutron star of mass M and radius R releases $GMm_p/R \sim 200$ MeV nucleon^{-1}, whereas only a few MeV nucleon^{-1} are released from thermonuclear fusion. However, it has been suggested that radiation-driven winds during photospheric radius expansion *may lead* to the ejection of a tiny fraction of the envelope. Unfortunately, this idea has not been properly addressed through detailed calculations.

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