Nucleosynthesis in Stellar Explosions: Type Ia Supernovae, Classical Novae, and Type I X-Ray Bursts

Jordi José[1,a)]

[1]*Dept. Physics, Universitat Politécnica de Catalunya, Av. Eduard Maristany 16, 08019 Barcelona.*

[a)]Corresponding author: jordi.jose@upc.edu
URL: http://www.fen.upc.edu/users/jjose/index.html

Abstract. Nuclear astrophysics aims at understanding the cosmic origin of the chemical elements and the energy generation in stars. It constitutes a truly multidisciplinary arena that combines tools, developments, and achievements in theoretical astrophysics, observational astronomy, cosmochemistry, and nuclear physics: the emergence of high-energy astrophysics with space-borne observatories has opened new windows to observe the Universe, from a novel panchromatic perspective; supercomputers have provided astrophysicists with the required computational capabilities to study the evolution of stars in a multidimensional framework; cosmochemists have isolated tiny pieces of stardust embedded in primitive meteorites, giving clues on the processes operating in stars as well as on the way matter condenses to form solids; and nuclear physicists have measured reactions near stellar energies, using stable and radioactive ion beam facilities. This paper shows provides a comprehensive insight into the nucleosynthesis accompanying stellar explosions, with particular emphasis on thermonuclear supernovae, classical novae, and type I X-ray bursts.

INTRODUCTION

Stars are complex nuclear furnaces. They played (and still do) a key role in the chemical enrichment of the universe, from the ashes of the Big Bang, that contained hydrogen, helium, and traces of lithium, until today, with 82 elements characterized by one or more stable isotopes, including those essential for the emergence of life.

The idea that the chemical elements are synthesized in the stars was developed in the mid 1940s by Hoyle, following early work by Bethe, Gamow, von Weizsäcker, and others in the 1920/30s. The theory was confirmed by the detection of technecium in the spectra of several S stars (i.e., stars that exhibit the presence of s-process elements in their spectra) [1]: in fact, technecium has no stable isotope (the longest lived has a half-life of about $\sim$ 4 Myr), and its discovery proved that nucleosynthesis is still ongoing in the universe. Since then, stellar nucleosynthesis has been firmly established by additional discoveries of other short-lived, radioactive species whose origin could be traced to specific parent stars.

In this paper, we will address the role played by stellar explosions in the synthesis of cosmic elements. White dwarfs and neutron stars, otherwise stellar corpses, can actually be revitalized in the presence of a stellar companion through mass-transfer episodes, giving rise to some of the most fascinating stellar phenomena in the entire universe: type Ia supernovae, classical novae, and X-ray bursts.

TYPE IA SUPERNOVAE

The current supernova taxonomy mostly relies on optical spectroscopic measurements near maximum brightness [2, 3, 4]. Broadly speaking, supernovae are classified in two main groups, distinguished by the absence (type I) or presence (type II) of hydrogen in their spectra. In fact, the lack of hydrogen in the spectra of type Ia (or thermonuclear) supernovae (hereafter, SNIa) puts constraints on the maximum amount of this element that can be present in the expanding atmosphere of the star, about $M_H \leq 0.03 - 0.1\ M_\odot$. A handful of SNIa (e.g., SN 2002ic), however, are anomalous in this regard, and unequivocally exhibit hydrogen emission lines some months post-maximum brightness (suggested to result from the interaction of the supernova ejecta with H-rich, circumstellar material). SNIa are also characterized by a prominent absorption feature near 6150 Å, due to blueshifted Si II, which is absent in the Ib and Ic subclasses (which, instead, are prominent in oxygen and sodium absorption lines). Moreover, types Ib and Ic are distinguished by the presence or absence of strong He I lines (in particular, He I λ5876).

While SNIa are regularly observed in all types of galaxies, the other supernova classes (i.e., types Ib/c and II) are only spotted in spiral and irregular galaxies. This suggests that SNIa are likely associated with old progenitors, while all the other classes involve much younger stars. The energy released in a SNIa can be inferred from the overall kinetic energy of the expanding ejecta, $E_{kin} \sim 10^{51}$ erg (with characteristic expansion velocities ranging between 5000 and 10,000 km s^{-1}), as well as from the energy integrated over the light curve, $E_{rad} \sim 10^{49}$ erg. Clearly, $E_{kin} >> E_{rad}$, which basically states that what is observed in a SNIa is the fallout from a thermonuclear explosion. Hoyle and Fowler [5] were among the first to propose that such thermonuclear explosions result from ignition of degenerate CO-rich fuel in low-mass stars previously evolved into white dwarfs.

Photometrically, type Ia supernovae are characterized by a dramatic increase in luminosity in about 20 days, reaching a peak value of $L_{peak} \sim 10^{10}$ $L_\odot$. This is followed by a steep decline (by a factor of ~ 20 in luminosity) in ~ 30 days, and later, by a second, somehow smoother decline over a period of ~ 70 days [6, 7, 8]. Peak luminosities depend basically on the total amount of ^{56}Ni synthesized (between 0.1 - 1 $M_\odot$ [9, 10]). During the late stages of the event, the light curve is powered by the radioactive decay chain $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$, with two different slopes attributed to the different half-lives of the decaying species, ^{56}Ni ($T_{1/2}$ = 6.1 days) and ^{56}Co ($T_{1/2}$ = 77.3 days) [11, 12].

About 70% of all observed type Ia supernovae exhibit similar spectral features, peak luminosities, light curve shapes, and characteristic timescales [13, 14]. Such similarities tend to favor a dominant progenitor and explosion mechanism, most likely a 1.4 $M_\odot$ white dwarf, that gets totally disrupted by the explosion (no remnant left). But the increasing number of peculiar supernovae discovered, have raised the interest in other explosion mechanisms. Such differences in the light curves have been attributed to different amounts of ^{56}Ni synthesized in the explosion: since the peak luminosity is proportional to the amount of ^{56}Ni mass synthesized, brighter events are expected when more ^{56}Ni is produced.

Broadly speaking, two basic scenarios have been proposed to explain the origin of the *normal* SNIa: a single-degenerate channel, in which a low-mass star transfers H- or He-rich matter onto a CO white dwarf [15, 16]; and a double-degenerate channel, in which two CO white dwarfs merge as a result of energy and angular momentum losses driven by gravitational wave radiation, with the total mass of the system exceeding the Chandrasekhar limit [16, 17]. Both scenarios present pros and cons. The major drawback faced by the single-degenerate scenario is the complex evolutionary pathway of a CO white dwarf to increase its mass and reach the Chandrasekhar limit. Indeed, state-of-the-art, stellar evolution models predict a maximum mass for a CO white dwarf around 1.1 $M_\odot$. This suggests that, prior to explosion, the star has to gain roughly 0.3 $M_\odot$. This is really challenging. In particular, low mass-accretion rates leading to nova explosions (see Section 3), for which the white dwarf is expected to lose mass, must be avoided. On the other hard, the double-degenerate scenario faces the scarcity of likely candidates detected, that may give rise to a Chandrasekhar-mass explosion after a merging episode in less than the age of the universe.

Back-of-an-envelope estimates suggest that once per century in our Galaxy, and perhaps, 10 per second in the observable universe, a white dwarf gets fully disrupted by a supernova explosion. A thorough comparison of the chemical abundances inferred from high-resolution spectra of SNIa and theoretical predictions based on state-of-the-art simulations has shed light into the physical mechanisms that power such titanic events. In this regard, efforts have focused on understating the nature of the burning front that propagates (and incinerates) throught the star. Arnett [18, 19, 20] pioneered the numerical simulations of C- ignition at the center of the white dwarf star and the development of a supersonic (detonation) burning front. However, those simulations revealed a number of inconsistencies: on one hand, the nucleosynthetic yields predicted by the C-detonation models gave rise to unrealistically high abundances of iron-peak nuclei by existing galactic chemical evolution models; and on the other hand, the low production of intermediate-mass elements (e.g., silicon, sulfur, and calcium) was at odds with the chemical abundance pattern inferred spectroscopically from SNIa ejecta.

As pointed out by Nomoto et al. [21, 22, 23], the typical densities at which carbon is expected to ignite near the center of the stars (~ 10^9 g cm^{-3}) favor instead a subsonic (deflagration) burning front, catalysed by the thermal conduction of the degenerate electron gas. A major asset of the pioneering models of Nomoto and collaborators, and of all C-deflagration models in general, was their ability to qualitatively match the chemical abundances inferred from observations (reducing the overproduction of iron while increasing the presence of intermediate-mass elements, such as ^{40}Ca, ^{36}Ar, and ^{32}S). Unfortunately, all C-deflagration models have resulted in a severe overproduction of a number of n-rich isotopes, such as ^{54}Cr and ^{50}Ti, with respect to solar abundances. High-resolution, multipoint ignition simulations that included relevant multidimensional effects (e.g., hydrodynamic instabilities) have proven the failure of C-deflagration models to produce more than 0.7 $M_\odot$ of ^{56}Ni and to power explosions with kinetic energies exceeding 0.7×10^{51} erg, thus unable to account for the most energetic SNIa. Two additional problems associated with C-deflagration models include the absence of chemical stratification in the ejecta and the presence of big clumps of ^{56}Ni in the photosphere around peak luminosity. New generations of explosion models, aimed at reducing the shortcomings of the pioneering C-deflagration models, were developed in the 1990s. To date, the most succesful are the so-called delayed detonation models, in which an early deflagration front that propagates and preexpands the star, subsequently switches into a detonation front [24, 25]. The main uncertainty in these delayed detonation models is the physical mechanism that drives the deflagration-detonation transition.

Nucleosynthesis in Type Ia Supernovae

Nucleosynthesis in SNIa depends critically on the peak temperature achieved and the density at which the explosion initiates. The abundance pattern of the ejecta is the result of five burning regimes: normal and α-rich freeze-out from nuclear statistical equilibrium in the inner regions of the star, and incomplete Si-, O- and C/Ne-burning in the outer layers [23, 26].

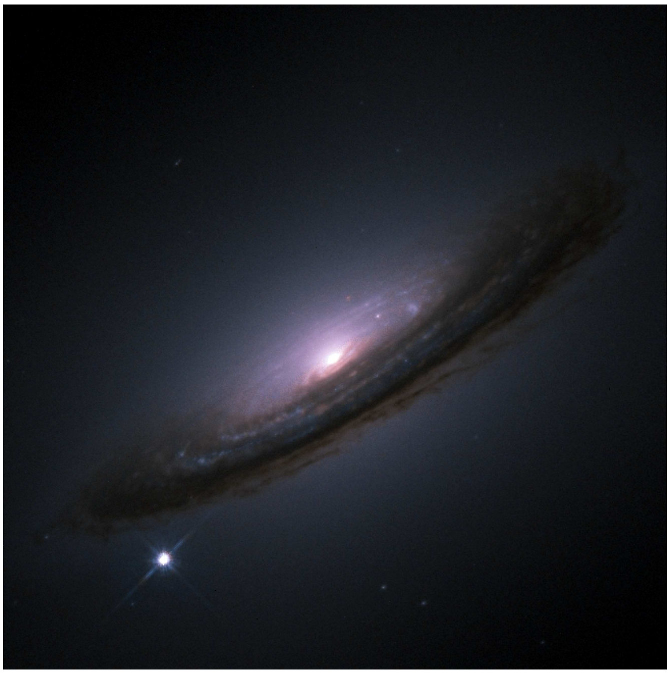

FIGURE 1. Hubble Space Telescope image of the type Ia supernova SN 1994D (the bright star shinning in the left, bottom corner of the image), which exploted in the galaxy NGC 4526. Credit: NASA/ESA, The Hubble Key Project Team and The High-Z Supernova Search Team.

The sensitivity of the predicted SNIa nucleosynthesis to variations of both thermonuclear reaction and weak interaction rates involved in the explosion, for a pure C-deflagration model and a delayed-detonation model have been investigated by Parikh et al. [27]. Postprocessing calculations with a network containing 443 species (n to ^{86}Kr) were performed with temperature and density versus time profiles extracted from the hydrodynamic simulations. All thermonuclear reaction and weak interaction rates were individually varied by a factor of ten, up and down. Several million, postprocessing calculations were performed to recalculate the yields accordingly, which were subsequently compared with those obtained with standard, recommended rates. The study revealed that out of the 2305 nuclear interactions included in the network, only the uncertainties affecting $\sim$ 50 reactions have a real impact on the yield of any species present in the star with $\geq 10^{-8}$ $M_\odot$, by a factor of $\geq$ 2, most notably ^{12}C(α, γ), ^{12}C+^{12}C, ^{20}Ne(α, p), ^{20}Ne(α, γ), and ^{30}Si(p, γ). Moreover, from the study of 658 weak interaction rates, only variations of the stellar ^{28}Si$(\beta^+)^{28}$Al, ^{32}S$(\beta^+)^{32}$P, and ^{36}Ar$(\beta^+)^{36}$Cl rates have a significant effect on the final yields in any of the models adopted.

CLASSICAL NOVAE

Classical novae (hereafter, CN) are another type of stellar explosion that takes place in a binary system, consisting of a white dwarf (usually, CO- or ONe-rich) and a low-mass main sequence (or a more evolved) companion. They show a sudden increase in optical brightness (in 1 - 2 days), reaching peak luminosities in the range between 10^4 - 10^5 $L_\odot$. Binary systems leading to nova outbursts are very close, with orbital periods < 15 hr, allowing mass- transfer episodes caused by Roche Lobe overflow of the secondary 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 mildly degenerate conditions until a thermonuclear runaway ensues [28, 29].

Nova explosions occur quite regularly in the Universe. In fact, they constitute the second, most frequent type of stellar thermonuclear explosions in the Galaxy after type I X-ray bursts (see Section 4), with an estimated occurrence of 30 ± 10 yr^{-1} [30]. However, detection of Galactic CN from Earth is hampered by interstellar extinction from dust, and only a fraction, 5 - 10, are discovered per year. Neither the white dwarf nor the binary system are destroyed by a nova explosion. Therefore, and in sharp contrast to SNIa, CN are expected to recur, typically after 10^4 - 10^5 yr. However, it is worth noting that the subclass of recurrent novae (by definition, novae that have been observed in outburst more than once) undergoes an explosion after 1 - 100 yr, likely implying very massive white dwarfs (close to the Chandrasekhar limit) and high mass-accretion rates. Whether the whole range of recurrence times follows a nearly continuous sequence, from the short values that characterize recurrent novae to the long values predicted for classical novae (i.e., 1 - 10^5 yr), is still a matter of debate. Another important difference between CN and SNIa is the velocity of the ejecta (> 10^4 km s^{-1} in SNIa, several 10^3 km s^{-1} in CN), as well as the amount of mass ejected (the whole star, ~ 1.4 $M_\odot$, in a thermonuclear supernova versus 10^{-7} - 10^{-3} $M_\odot$ for a nova).

As mass-accretion is established, and material piles up on top of the white dwarf, compressional heating rises the temperature of the envelope and nuclear reactions ensue. 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 in the accreted envelope. Convection distributes 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. The strength of the resulting nova outburst depends critically on four parameters: the mass and initial lumininosity (or temperature) of the white dwarf that hosts the explosion, and the metalliticity and mass-trasfer rate from its stellar companion. 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; see Section 4).

Even though numerical simulations have confirmed that envelopes with solar metallicity can give rise to explosions resembling *slow novae* [31, 32], only envelopes with CNO-enhanced abundances (in the range $Z_{CNO} \sim 0.2$ - 0.5) can reproduce the *gross* observational properties of a *fast nova* [33, 34]. The origin of such 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 attributed to thermonuclear processes driven by CNO breakout. Instead, mixing at the core-envelope interface is a more likely explanation. Several mixing mechanisms have been proposed and explored to date, including diffusion-induced mixing, shear mixing at the disk-envelope interface, convective overshoot-induced flame propagation [35], or mixing by gravity wave breaking on the white dwarf surface [36, 37], but none has proven fully successful.

Promising results have been obtained when relaxing the constraints imposed by spherically symmetric models. Indeed, multidimensional simulations of mixing at the core-envelope interface during nova outbursts have shown that Kelvin-Helmholtz instabilities can naturally lead to self-enrichment of the accreted envelope with core material, at levels that agree with observations. In particular, pioneering 3-D simulations [38, 39] have provided hints on the nature of the highly fragmented, chemically enriched and inhomogeneous nova shells, observed in high-resolution 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.

Nucleosynthesis in Classical Nova Outbursts

From a nuclear physics viewpoint, the early stages of the thermonuclear runaway that characterize a nova outburst are dominated by 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. 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, which constitute the main contribution of novae to the Galactic abundances.

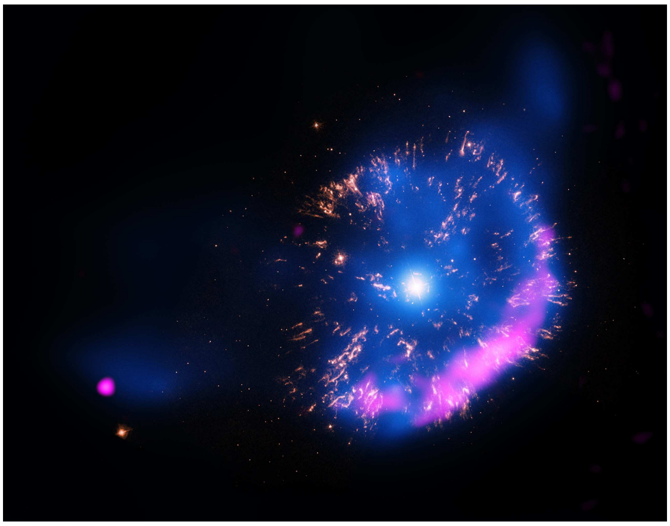

FIGURE 2. Image of GK Persei (Nova Persei 1901) and its ejecta, obtained by combining X-ray data from the Chandra X-Ray Observatory (blue), optical data from the Hubble Space Telescope (yellow), and radio data from the National Science Foundations Very Large Array (pink). Credit: X-ray: NASA/CXC/RIKEN/D.Takei et al.; Optical: NASA/STScI; Radio: NRAO/VLA.

The main nuclear path in nova outbursts runs close to the valley of stability, and is driven by proton-capture reactions and β^+-decays. Novae are *unique* stellar explosions, since their nuclear activity, limited to about a hundred relevant species (with mass number, 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 [40]. The key role played by nuclear reactions has motivated different studies aimed at identifying the most critical reactions whose uncertainty has the largest impact on nova nucleosynthesis (see, for instance, Ref. [41], for a detailed sensitivity study). Many of the important reactions identified have been re-evaluated in recent years. In fact, only the uncertainties associated to the reactions ^{18}F(p, α)^{15}O, ^{25}Al(p, γ)^{26}Si, and ^{30}P(p, γ)^{31}S still have a strong impact on nova nucleosynthesis.

Several species synthesized during classical nova outbursts may 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. The contribution of novae to the Galactic content of ^{26}Al, however, is expected to be small (i.e., ~20% [42]).

There is, in general, good agreement between the abundance patterns inferred from observations and those derived from numerical simulations, with a predicted nucleosynthetic endpoint around Ca. However, the specific chemical abundance pattern spectroscopically inferred yields only atomic values, so comparison with theoretical predictions is rather limited. Better perspectives 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 [43]. Since the pioneering studies of dust formation in novae by Clayton and Hoyle [44], efforts devoted to the identification of putative nova grains have mainly relied on the search for low ^{20}Ne/^{22}Ne ratios. Since noble gases (e.g., 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 identification of presolar nova candidate grains was achieved by Amari [45], 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; and high ^{26}Al/^{27}Al and ^{22}Ne/^{20}Ne ratios for some of the grains. More recent efforts in this area include the first identification of a CO nova graphite grain extracted from the the primitive meteorite LaPaz Icefield 031117 [46] and the identification of 18 presolar grains with measured isotopic signatures consistent with a CO nova origin, based on a Monte Carlo technique, that involves the random sampling over the most important nova model parameters [47].

A final word of warning regarding nucleosynthesis predictions for nova outbursts. In the era of multidimensional simulations, one may be tempted to rule out results based on 1D models. However, multidimensional models are extremely time consuming. The only nova simulations performed to date in 2D and 3D relied on 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, to approximately account for the energetics of the explosion, and therefore, no reliable nucleosynthesis predictions can be made.

TYPE I X-RAY BURSTS

X-ray bursts (hereafter, XRBs) have been discovered much more recently than novae and supernovae, since a major fraction of their energy output is emitted in X-rays, and hence, detection requires the use of space observatories (they are optically faint objects). More than 100 Galactic low-mass X-ray binaries that exhibit such bursting behavior have been found since the independent discovery by Babushkina et al. [48], Grindlay et al. [49], and Belian, Conner, and Evans [50]. These events, that bear a clear resemblance to CN, take place in even more compact stellar remnants: neutron stars (with a mass up to 2 - 3 $M_\odot$, and a very small diameter, 20 to 30 km only), resulting from type II supernova explosions of stars more massive than 10 $M_\odot$ (even though they can also form in other astrophysical scenarios, as in the accretion-induced collapse of a white dwarf). The companion is frequently a main-sequence star or a red giant. As for CN, XRBs are recurrent events, but XRBs are characterized by a much shorter recurrence periods, ranging from hours (even minutes!) to days.

XRBs are also characterized by a sudden increase in brightness, reaching $L_{peak} \sim 10^4 10^5$ $L_\odot$ after a very fast rise (in $\sim 1\ \ 10$ s). Their light curves are usually described by the so-called, α parameter, or ratio of the persistent over burst luminosities, $\alpha = L_{persistent}/L_{burst} \sim 100$. The overall energy output in a typical XRB is E $\sim 10^{39}$ erg, released over 10 - 100 s.

A major challenge in the modeling of XRBs is associated with the lack of observational nucleosynthetic constraints. It is unclear whether a typical XRB results in mass ejection because of the extremely large escape velocities from a neutron star surface. Indeed, the energy required to escape from the strong gravitational field of a neutron star of mass M and radius R is G M m_p/R $\sim$ 200 MeV/nucleon, whereas the nuclear energy released from thermonuclear fusion of solar-like matter into Fe-group elements is only $\sim$ 5 MeV/nucleon. However, numerical simulations for suitable values of the mass-accretion rate reveal a dramatic photospheric radius expansion in models characterized by large envelope masses. The high pressures and densities achieved at the envelope base lead to strong bursts, characterized by short periods of super-Eddington luminosities, accompanied by mass-loss episodes through radiation-driven winds, as inferred from some bursting sources [51, 52, 53, 54]. The origin of these radiation-driven winds is explained by the fact that the radiation flux difusing outward from the burning regions may exceed the local Eddington limit in the outer, cooler layers of the star, and, therefore, hydrostatic equilibrium is broken in those layers.

A number of efforts aimed at providing observables from XRBs have been undertaken in recent years. Preliminary determinations of gravitationally-redshifted absorption lines were reported by Cottam et al. [55] on the basis of high-resolution spectra of 28 XRBs detected from the source EXO 0748-676 after 335 ks of observations with the XMM-Newton X-ray satellite. The work tentatively identified lines of Fe XXVI (during the early phase of the bursts), Fe XXV, and perhaps O VIII (at later stages). But no evidence for such spectral features was found neither during the analysis of 16 bursts observed from GS 1826-24 [56], nor from another series of bursting episodes detected from the original source after 600 ks of observations [57, 58]. It is, however, worth noting that another study identified strong absorption edges in two XRBs exhibiting strong photospheric expansion. The spectral features were attributed to Fe-peak elements with abundances about 100 times solar, which may suggest the presence of heavy-element ashes in the ejected wind [59]. This issue clearly deserves further theoretical and observational work.

Nucleosynthesis in Type I X-Ray Bursts

During accretion onto neutron stars, the stronger surface gravity (as compared with that of a white dwarf) gives rise to larger temperatures and densities in the accreted envelopes, typically an order of magnitude larger than in a typical nova outburst (see pioneering models by Woosley and Taam [60], Maraschi and Cavaliere [61], and Lewin and Joss [62]). As a result, detailed nucleosynthesis studies rely on several hundreds of isotopes and thousands of nuclear interactions. Until recently, because of computational limitations, most simulations of X-ray bursts were performed in the framework of reduced nuclear reaction networks. Schatz et al. [63, 64] have pioneered very detailed nucleosynthesis calculations, with a detailed reaction network up to the SnSbTe mass region, but using a simple one-zone approach. More recently, hydrodynamic simulations, coupling detailed hydrodynamic stellar models in one-dimension with an extended nuclear reaction network have been performed [65, 66, 67]. All these studies have shed light into the main nuclear reaction flow in XRBs, which turns out to be driven by the rp-process (rapid p-captures and β^+-decays), the 3α-reaction, and the αp-process (a sequence of (α,p) and (p,γ) reactions), and proceeds away from the valley of stability, even merging with the proton drip-line beyond A = 38.

Most of the reaction rates used in XRB nucleosynthesis studies rely on theoretical estimates obtained from statistical models, and therefore may be affected by significant uncertainties. Efforts to quantify the impact of such nuclear uncertainties have been undertaken by different groups. For instance, Parikh et al. [68, 69] used two different approaches. First, the effect of individual reaction-rate variations was analized in the framework of postprocessing calculations for different temperature and density versus time profiles. An extensive nuclear network containing 606 isotopes (ranging from H to ^{113}Xe), was used to this end. Only a handful of reactions, out of the 3551 nuclear processes considered, resulted in a significant impact on the final yields, when their nominal rates were varied by a factor of 10, up and down. This included mostly proton-capture reactions, such as ^{65}As(p, γ)^{66}Se, ^{61}Ga(p, γ)^{62}Ge, ^{96}Ag(p, γ)^{97}Cd, ^{59}Cu(p, γ)^{60}Zn, ^{86}Mo(p, γ)^{87}Tc, ^{92}Ru(p, γ)^{93}Rh, or ^{102,103}In(p, γ)^{103,104}Sn, as well as a few α-capture reactions like ^{12}C(α, γ)^{16}O, ^{30}S(α, p)^{33}Cl, or ^{56}Ni(α, p)^{59}Cu. The study also identified some reactions affecting energy production, when individually varied within a factor of 10. This has to be taken as a warning of the limitations of postprocessing techniques, since a self-consistent analysis would require computationally intensive hydrodynamic simulations capable of self-adjusting both the temperature and the density of the stellar envelope. Similar results were obtained in a second, Monte Carlo approach, in which all reaction rates were varied simultaneously by a random factor. Indeed, all reactions flagged as important in the Monte Carlo simulations were previously identified in the individual reaction-rate variation study. When not too restrictive conditions were applied to the Monte Carlo studies, a total agreement on the results obtained with both techniques was achieved.

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