PROCEEDINGS OF SCIENCE

Classical novae — theory and observations

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Classical nova outbursts are powered by thermonuclear runaways that take place in the H-rich accreted envelopes of white dwarfs in close binary systems. Extensive numerical simulations of such explosions have shown that the accreted envelopes attain peak temperatures between 10^8 and 4×10^8 K, for about several hundred seconds, and therefore, their ejecta is expected to show signatures of a 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. 2-D 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.

11th Symposium on Nuclei in the Cosmos - NIC XI
Heidelberg, Germany
July 19–23 2010

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1.Introduction

Nova problem solved: star expands, and bursts[1]... The conciseness of this text –probably the shortest scientific communication ever-, written by J. Hartmann on occasion of the discovery of the nova RR Pic (1925), reflects the general enthusiasm generated around the characterization of nova explosions. Certainly, much progress has been made in the understanding of such phenomena since the first naked-eye observations of novae by Chinese astronomers (and observers from other ancient empires), more than two millennia ago. But still several key issues remain to be explained.

Etymologically, the term *nova*, from the latin *stella nova* (‘new star’), reflects somewhat the reasons that captivated the interest for such phenomena: the sudden appearance of a luminous object in the sky (at a spot where nothing was clearly visible before), that fades away, back to darkness, in a matter of days to months. Following Duerbeck (2008), the earliest reference to a *stella nova* can be traced back to Plinius, around 75 AD. The text, however, is unclear in what is actually describing: a nova, a supernova, or even a meteor or a comet. In fact, under the Aristotelian dogma of the immutability of the heavens, not many European references to 'new stars' were documented in ancient texts.

Until the astronomical scale distance was not soundly established, both novae and supernovae were associated with the same explosive phenomenon, generically coined as 'nova'. New light was shed into this issue by G.W. Ritchey, H.D. Curtis, H. Shapley, and others, who reported results from serendipitous discoveries of novae in the so-called spiral 'nebulae' (which were actual galaxies) early in the XXth Century. These scattered and heroic efforts were soon followed by systematic nova searches. Indeed, Shapley and Curtis were among the first to question the real distance to spiral nebulae, suggesting their extragalactic nature already in 1917. A major step forward was achieved with nova S Andromedae, discovered and analyzed by the German astronomer Ernst Hartwig in 1885, as well as by the new scale distance of Hubble that placed Andromeda outside the Milky Way. This pushed nova S Andromedae far away, at an incredible distance, and characterized in turn by a huge intrinsic luminosity. Actually, Lundmark and Curtis, in the early 20s, were the first to talk about 'giant novae' in what was known as 'The great debate':

It seems certain [...] than the dispersion of novae in spirals, and probably also in our galaxy may reach at least ten absolute magnitudes, as is evidenced by a comparison of S And with the faint novae found recently in this spiral. A division into two magnitude classes is not impossible.

Soon, it was clear that two different classes of *stellae novae* existed, the most luminous ones corresponding to what today we call supernovae.

[1] “Nova-Problem gelöst. Stern bläht sich auf, zerplatzt.”, J. Hartmann, *AN* **226** (1995), 63.

1.1.Early explanations of the nova phenomenon and breakthroughs

The understanding of the physics that lay behind the nova phenomenon motivated large controversies and vivid discussions. Probably the first explanation that underscored the physical mechanism powering nova explosions appears in Newton's *Principia Mathematica*:

So fixed stars, that have been gradually wasted by the light and vapors emitted from them for a long time, may be recruited by comets that fall upon them; and from this fresh supply of new fuel those old stars, acquiring new splendor, may pass for new stars

Indeed, the concept of revitalization of old stars by *fresh supply of new fuel* (although not by comets!) is at the base of the *thermonuclear runaway* model, in which mass accretion plays a central role.

Observationally, the nova phenomenon has benefited from countless efforts, and particularly, from a number of breakthroughs, such as:

* The first (optical) spectroscopic analysis of a nova (T CrB 1866, Huggins & Miller (1866)

* The discovery of neon ([Ne III] lines at 3869 and 3968 Å) in the spectra of GK Per (Sidgreaves 1901), pointing towards the existence of different nova types (although first calculations of novae in ONe white dwarfs were not performed until 1985, by Starrfield and co-workers).

* The explanation of the observed spectral features as due to ejection of a shell from a star (Pickering 1894).

* The interpretation of the minimum in the DQ Her light curve as due to dust formation (Stratton & Manning 1939).

* The discovery of the binary nature of DQ Her (Walker 1954).

* The systematic studies of novae revealing that binarity is a common property of most cataclysmic variables (novae, in particular; Kraft 1964).

Although the observational picture was firmly established on the basis of ejection from the surface of a star, as stated in the short communication by Hartmann (see Section 1), the explanation of the physics behind the burst had to wait a few decades. Indeed, its thermonuclear origin was first theorized by Schatzmann[2] (1949, 1951), and Cameron (1959) (see also Gurevitch & Lebedinsky 1957, and references therein), while the first hydrodynamic simulation of a nova outburst was performed by W. Sparks in 1969.

1.3.The classical nova *ID card*

The multiple and complementary approaches undertaken in the study of the nova phenomenon –spectroscopic determinations of chemical abundances, photometric studies of the nova light curve, as well as pioneering hydrodynamic simulations-, crystallized in what is known today as the *thermonuclear runaway* model of nova explosions.

Novae have been observed in all wavelengths (but never detected so far in γ-rays). They constitute a very common phenomena (i.e., the second, most frequent type of stellar thermonuclear explosions in the Galaxy after type I X-ray bursts); although just a few, 3 to 5,

[2] Although wrongly attributed to nuclear fusion reactions involving ^{3}He.

are discovered every year (mainly by amateur astronomers), a much higher nova rate, around 30 ± 10 yr^{-1} (Shafter 2002), has been predicted by comparison with the number of events observed in other galaxies. The reason for the scarcity of detections in our Galaxy is the extinction by interstellar dust.

Classical novae occur in short period (1 – 12 hr), stellar binary systems consisting of a white dwarf star and a low-mass main sequence (K-M dwarf) companion (although some evidences of more evolved companions exist). Contrary to type Ia supernovae, in which the white dwarf is fully disrupted by the violence of the explosion, all classical novae are expected to recur, with periodicities of the order of 10^4–10^5 yr (notice, however, that in the thermonuclear explosions that occur in very massive white dwarfs, the so called *recurrent novae*, the expected periodicities range typically between 10 – 100 yr). Both novae and supernovae are characterized by a remarkable energy output, with peak luminosities reaching 10^4 and 10^{10} $L_\odot$, respectively. A basic difference between both explosive phenomena is the amount of mass ejected (the whole star in a thermonuclear supernova versus 10^{-4}–10^{-5} $M_\odot$ in a nova) as well as the mean ejection velocity (> 10^4 km s^{-1} in a supernova, and several 10^3 km s^{-1} in a classical nova).

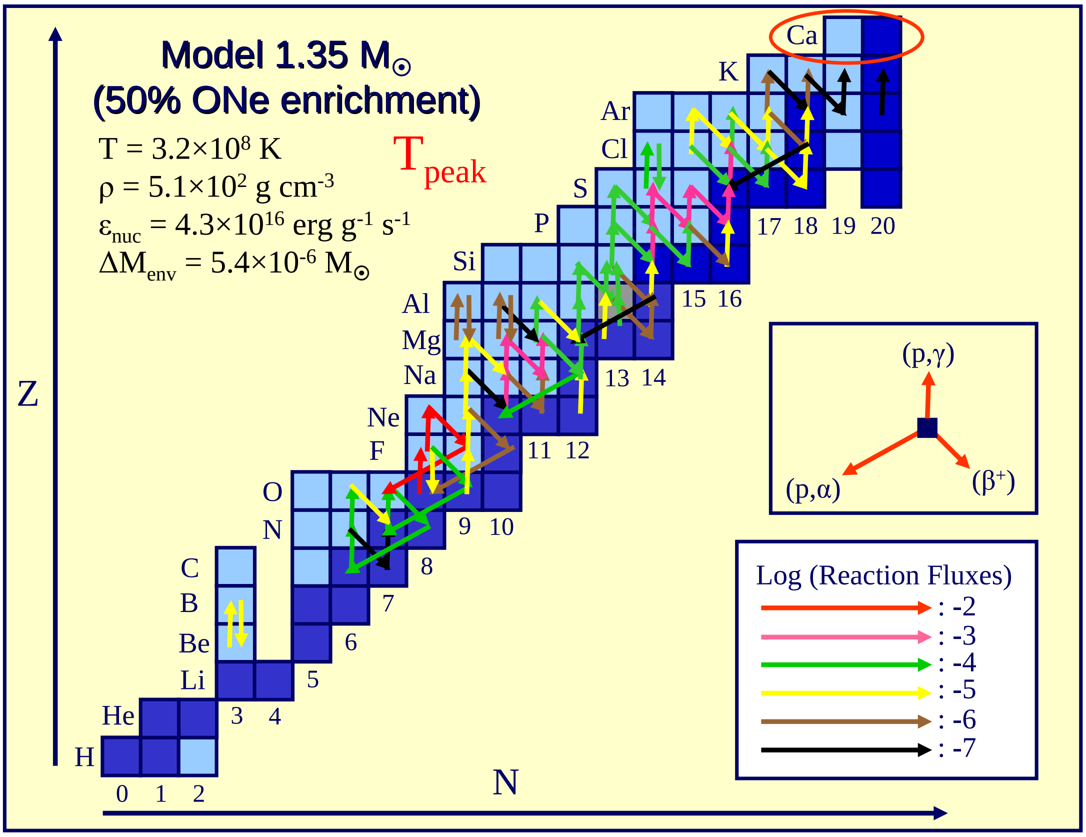


Fig. 1. The main nuclear activity, shown in terms of reaction fluxes (number of reactions per unit volume and time), at T_{peak}, for a nova model of 1.35 $M_\odot$, with 50% ONe enrichment. The dominant nuclear reaction flow proceeds close to the valley of stability and is dominated by (p,γ), (p,α), and β-decays. See text for details.

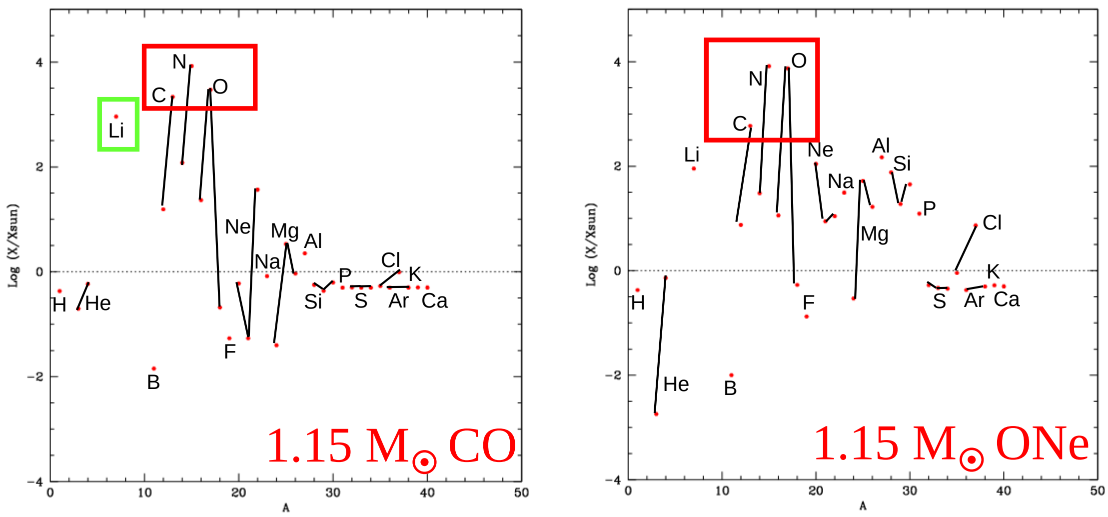
2.The nova nuclear symphony

From the nuclear physics viewpoint, novae are unique stellar explosions: their limited nuclear activity, which involves about a hundred relevant species (A<40) linked through a (few) hundred nuclear reactions, as well as the limited range of temperatures achieved in such explosions (10 – 400 MK), allow us to rely primarily on experimental information (see José, Hernanz & Iliadis 2006).

Contrary to other (related) astrophysical explosive sites, during classical nova outbursts the main nuclear path runs close to the valley of stability, and is driven by (p,γ), (p,α) and β^+ reactions (see Fig. 1). Hence, the contribution from any (n,γ) or (α,γ) reaction (including ^{15}O(α,γ)) becomes negligible. Different studies have focused on the role played by nuclear uncertainties on the overall nucleosynthetic pattern accompanying nova explosions (see, for instance, Iliadis et al. 2002, for a sensitivity study based on 7350 network calculations), which has sparked an extraordinary activity in many nuclear physics labs worldwide. Actually, the list of reactions whose uncertainty has still a strong impact on the nova yields has been dramatically reduced. Indeed, the main interest is focused now on the challenging reactions ^{18}F(p,α)^{15}O, ^{25}Al(p,γ)^{26}Si, and ^{30}P(p,γ)^{31}S. Recent updates on reaction rates at nova conditions have also been presented in this Conference (see, for instance, contributions by A. Parikh [^{33}S(p,γ)], A. Sallaska [^{22}Na(p,γ)], M. Matos [^{31}S(p,γ)], D. Bardayan [^{7}Be(p,γ), ^{17}F(p,γ)], K. Chipps [^{25}Al(p,γ)], C. Herlitzius [^{33}Cl(p,γ)], A. Laird [^{18}F(p,α)], A. Saastamoinen [^{22}Na(p,γ)], N. de Séréville [^{25}Al(p,γ)], and K. Setoodehnia [^{29}P(p,γ)], in these proceedings).

In nova conditions, the early evolution of the TNR is dominated by the operation of both the proton-proton chains as well as the *cold* CNO cycle (mainly through ^{12}C(p,γ)^{13}N(β^+)^{13}C(p,γ)^{14}N). As the temperature increases, the characteristic time for proton captures onto ^{13}N, τ(p,γ)[^{13}N], becomes shorter than its β-decay time, τ(β^+)[^{13}N], 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, or ^{16}O(p,γ)^{17}F. Since such nuclear processes take place in an envelope which operates in semi-degenerate conditions (with a pressure depending only on the density rather than on temperature), the star cannot react to the temperature increase with an expansion. This paves the road for a thermonuclear runaway, in which convection plays a critical role: actually, convective transport (that settles in the envelope when T exceeds $\sim 2\times 10^7$ K), carries a substantial fraction of the short-lived, β^+-unstable nuclei $^{14, 15}$O, ^{17}F (^{13}N), synthesized in the CNO-cycle, to the outer, cooler layers of the envelope (escaping potential p-captures). In fact, as first shown by Starrfield et al. (1972), it is the sudden release of energy from these short-lived species what powers the expansion and ejection stages in a nova outburst. Moreover, the ejecta will likely be highly enriched in the daughter nuclei ^{15}N, ^{17}O, and ^{13}C (see Fig. 2). This basic picture emphasizes the critical role played by the initial ^{12}C content as the main trigger of the TNR. Indeed, ^{12}C(p,γ) not only determines the amount of mass accreted in the envelope, but also the proper pressure at the envelope's base, which in turn, determines the strength of the outburst (i.e., peak temperature, mass and velocity of the ejected shells...).

Models of nova nucleosynthesis point towards Ca as the likely nucleosynthetic endpoint, in agreement with observations of nova shells. In fact, and despite of the problems associated with the modeling of nova outbursts (mainly, the nature of the mixing process and the discrepancy in the amount of mass ejected between models and observations; see Starrfield et al. 1998, and José & Shore 2008), there is, in general, good agreement between the abundance patterns inferred from observations and those derived from numerical hydro calculations.



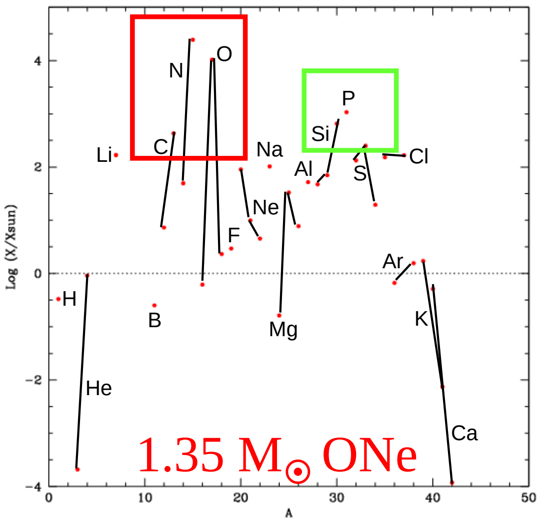


Fig. 2. Main overproduction factors (mean abundances in the the ejecta normalized over solar values) for nova models of 1.15 $M_\odot$ CO, 1.15 $M_\odot$ ONe, and 1.35 $M_\odot$ ONe white dwarfs.

Among the species synthesized during classical nova outbursts, several radioactive nuclei have deserved particular attention as potential gamma-ray emitters (Clayton & Hoyle 1974; Clayton 1981; Leising & Clayton 1987): whereas ^{13}N and ^{18}F may provide a prompt γ-ray output at and below 511 keV (through electron-positron annihilation), ^{7}Be and ^{22}Na (see Gómez-Gomar et al. 1998, Hernanz et al. 1999, and references therein), that decay later, when the envelope is optically thin, may power line emission at 478 and 1275 keV, respectively. ^{26}Al is another important radioactive isotope that can be synthesized during nova outbursts, although only its cumulative emission can be observed because of its slow decay. We refer the reader to Hernanz (2008) for a review of the current theoretical predictions of the gamma-ray output from classical novae and the chances of a nearby future detection using spacecrafts such as INTEGRAL.

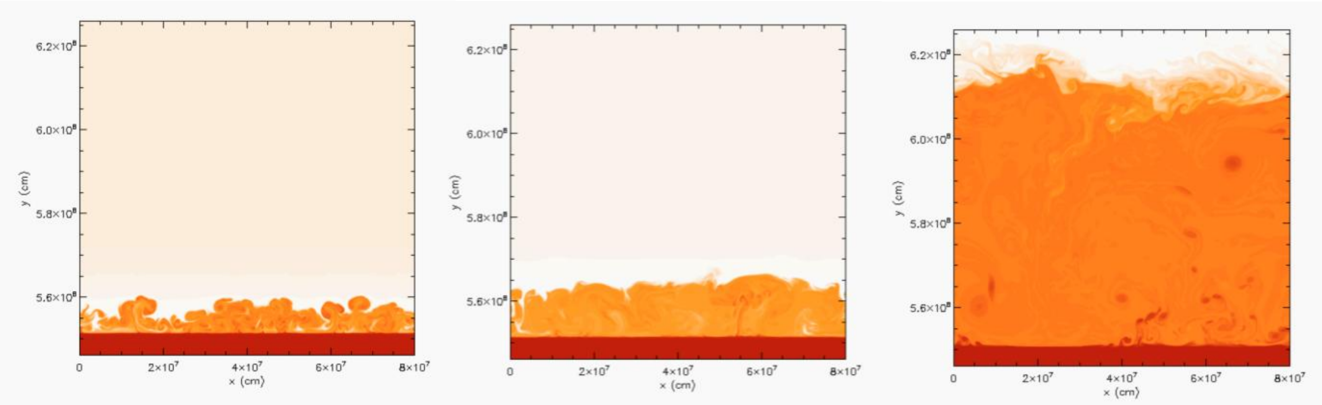


Fig. 3. Two dimensional simulations of mixing at the core-envelope interface during a nova outburst in a CO white dwarf. Adapted from Casanova et al. (2010).

3.Multidimensional studies of the nova outburst

Observations show that even when the accreted material is approximately solar, the ejecta accompanying classical novae is highly enriched in metals: in average, CO-rich novae show a mean metallicity of about Z~0.25, while ONe-rich novae are characterized by Z~0.5. Because of the moderate peak temperatures achieved in these explosions, it is unlikely that such metallicity enhancements could result from thermonuclear processing of solar-like material. Instead, mixing at the core-envelope interface has been proposed as the likely explanation. Several mixing mechanisms have been proposed, including multidimensional processes. Two independent, two-dimensional studies (Glasner et al. 1997; Kercek et al. 1998), based upon the same 1-D initial model, reached totally different conclusions about the strength of the runaway and its capability to power a fast nova. The origin of these differences was carefully analyzed in Glasner et al. (2005), who concluded 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, another 2-D simulation, performed with the hydrodynamic code FLASH has been performed. The results, reported in Casanova et al. (2010), show that a shear flow at the core-envelope interface drives mixing through Kelvin-Helmholtz instabilities. Large convective eddies develop close to the core-envelope interface, with a size comparable to the height of the envelope, mixing CO-rich material from the outermost layers of the underlying white dwarf into the accreted envelope. The mean metallicity achieved in the envelope, Z ~0.30, is in agreement with observations of CO nova ejecta. More details can be found in Casanova et al., in these proceedings.

4.Presolar nova 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) (a concept already suggested by Cameron in 1973), 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, ^{22}Ne was attributed to in situ ^{22}Na decay, a clear imprint of a classical nova explosion). Indeed, Clayton and Hoyle pointed out several isotopic signatures (large overproduction of ^{13,14}C, ^{18}O, ^{22}Na, ^{26}Al or ^{30}Si), that may help in the identification of such nova candidate grains. Twenty-five years later, most of these signatures still hold, in view of our current understanding of nova explosions, except ^{14}C, bypassed by the main nuclear path in novae, and ^{18}O, slightly overproduced by novae although grains nucleated in this environment are expected to be much more anomalous in ^{17}O.

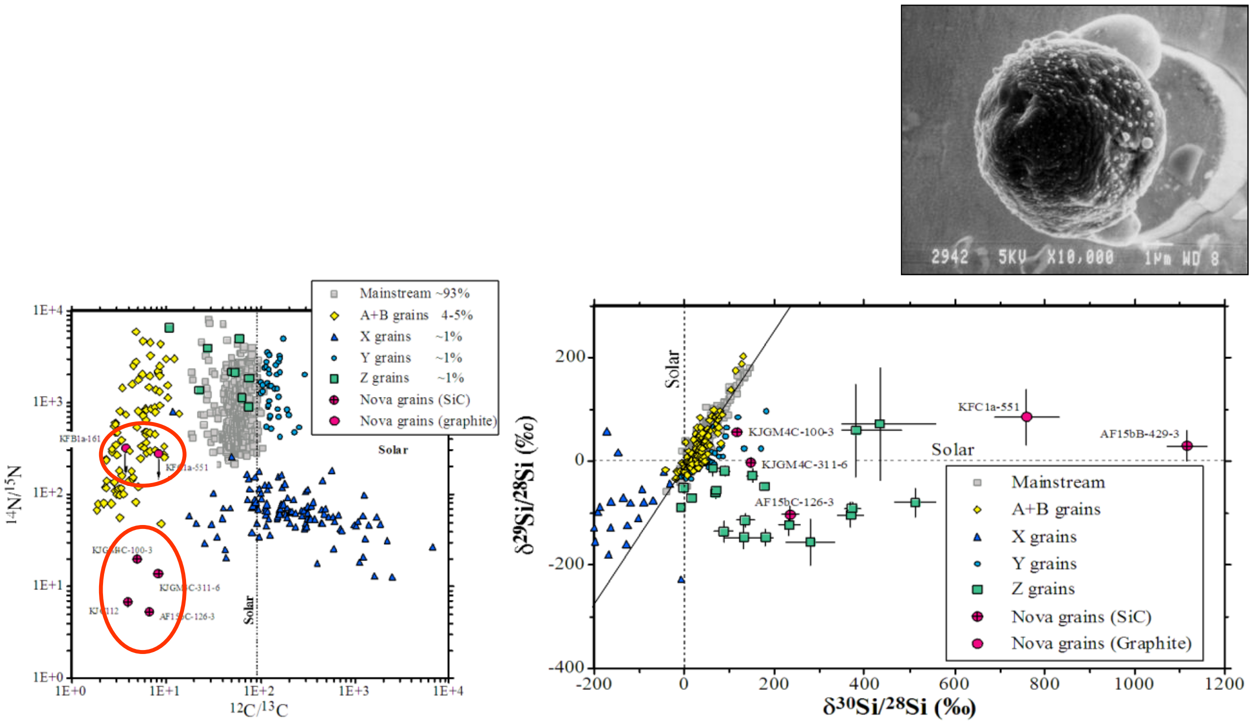


Fig. 4. Upper panel: The nova candidate graphite grain KFC1a-511 after Secondary Ion Mass Spectrometry (SIMS). Lower panels: Carbon and nitrogen isotopic ratios (left) and silicon excesses (deviations from solar in permil; right) for the different SiC grain populations.

A major step forward in the discovery of presolar nova candidate grains was achieved by Amari et al. (2001) (see also Amari 2002), 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 a mixing process between material newly synthesized in the nova outburst and 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. Preliminary 3-D SPH simulations of the interaction between the nova ejecta and the companion star can be found in Campbell et al., in these proceedings.

Concerns about the likely nova paternity of these grains have been raised (Nittler & Hoppe 2005), after three additional micron-sized SiC grains were also isolated from the Murchison meteorite with similar trends (in particular, low ^{12}C/^{13}C and ^{14}N/^{15}N

ratios), but with additional imprints (mainly non-solar Ti features), from which a supernova origin cannot be excluded. Recently, more nova candidate grains (oxides) have been identified (see Gyngard et al., in these proceedings).
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). But as fully supported by observations, *standard* classical novae do not seem to undergo an efficient CNO-breakout (notice for instance, that after the recent revision of the nuclear reaction network used by Starrfield et al. (2009), the Arizona group is not anymore claiming such possibility, even for the most extreme outbursts resulting from massive white dwarfs).

Acknowledgments

This paper summarizes the progress in our understanding of the nova phenomenon. Many researchers have contributed to one or different aspects of the work presented here. I'm particularly indebted to S. Amari, A. Calder, S.W. Campbell, J. Casanova, A. Coc, E. García-Berro, F. Gyngard, M. Hernanz, C. Iliadis, L. Nittler, S. Shore, and E. Zinner.

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