Impact of Nuclear Reaction Rate Uncertainties on Nova Models

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We have, for the first time, determined the effect of nuclear reaction rate uncertainties on nova model predictions by *simultaneously* considering uncertainties in *all* relevant reaction rates. Our unique Monte Carlo approach enables a robust determination of uncertainties of nuclear origin in predictions of synthesized abundances, including radioisotopes which may be observable. This technique also enables us to identify which reactions most influence the production of each isotope, thereby guiding future measurements.

1. Motivation

The sensitivity of nova model predictions of energy generation and element synthesis to selected reaction rates has been demonstrated in numerous studies (e.g., [1]). It is crucial to guide experimental programs to measure essential rates, especially those involving proton-rich radioactive nuclei [2], by determining which nuclear reactions have the largest impact on predictions of nova outburst simulations. The correlations between *all* reaction rates and *all* synthesized isotopes should be considered. Additionally, progress in probing the nova phenomena can be made by determining statistically robust uncertainties on predictions of synthesized abundances, enabling meaningful comparisons with observations. This is especially true for long-lived radioactive nuclei such as ^{18}F and ^{22}Na, the observation of which may provide stringent constraints on nova models [3]. We have addressed these issues with a Monte Carlo approach to nova nucleosynthesis calculations where - for the first time - uncertainties in *all* input nuclear reaction rates are considered simultaneously. While this approach has been used with great success in the analysis of Big Bang nucleosynthesis [4], it has not previously been applied to other thermonuclear burning scenarios.

2. Nova Nucleosynthesis Calculations

The temporal evolution of the isotopic composition in novae was followed using a nuclear reaction network [5] containing 169 isotopes from hydrogen to ^{54}Cr with nuclear reaction rates drawn from REACLIB [6]. In this study, we focus on nova explosions occurring on a 1.25 $M_{\odot}$ ONeMg white dwarf (WD), representative of a very prevalent class of novae. We assume an initial composition which is solar mixed with 50% by mass oxygen, neon and magnesium as done in Politano et al. [7] to simulate the mixing of the envelope material with the WD material. We utilized a post-processing approach where the nucleosynthesis is decoupled from the hydrodynamics of the burst. We determined that the reaction variations did not appreciably change the nuclear energy generation nor, therefore, the temperature and density history of the explosion, so this approach was valid. To investigate the extent to which nuclear reaction uncertainties translate into abundance variations, we use a Monte Carlo technique which assigns a different, uncorrelated, random enhancement factor to *each* reaction rate in the simulation. The nucleosynthesis is calculated with these modified reaction rates, the results stored, and the process repeated with different enhancement factors. These factors are distributed according to the log-normal distribution, necessary for quantities like reaction rates which are manifestly positive [8]. Our use of this distribution is a significant improvement over previous calculations. We have assigned uncertainties of $\sim 50\%$ to rates whose measurement would require radioactive ion beams, a factor of 2 for rates calculated by Hauser-Feshbach methods, and $\sim 20\%$ for all other non-weak rates. These are typical of those reactions that are best determined in their class. Beta-decay rates are given their measured uncertainties [9]. After 10000 iterations of the network with these rate enhancement factors, the mean values and 90% confidence limits are determined from the distribution of abundance predictions.

3. Results

In this paper, we present results from the innermost zone of a 1.25 $M_{\odot}$ WD nova model, though the method can examine the impact on entire outburst models. Even with our modest uncertainties, many of the abundant metals have a ratio of their upper and lower 90% confidence limits that differ by a factor of 2 or larger, such as ^{16}O (factor of 2.7), ^{17}O (2.7), ^{18}O(3.3), and ^{30}Si (5.6). The predicted abundances of radionuclides also have large 90% confidence limits, such as ^{18}F (3.3), ^{26}Al (3.6), and ^{22}Na (3.6, Figure 1.A). Our confidence limits are the first statistically robust uncertainties determined for nova nucleosynthesis. They also have important implications for determining the sensitivity of orbital observatories (e.g., INTEGRAL) for detection of gamma rays from novae.

We also determine the correlation between small variations of *all* relevant reaction rates and *all* synthesized isotopes in the outburst. Figure 1.B. shows a representative result - the distribution of the predicted ^{22}Na abundance with the variation in the ^{22}Na(p,γ)^{23}Mg reaction rate. A linear fit shows that in this case the negative correlation is statistically significant – the slope is more than a hundred standard deviations different from zero. We have determined a prioritized list of reactions that most influence the production of radioisotopes that may be observable tracers of novae. For ^{18}F, the critical reactions are (in order of importance) ^{17}O(p,γ)^{18}F, ^{17}F(p,γ)^{18}Ne, ^{16}O(p,γ)^{17}F, ^{18}F(p,α)^{15}O, and ^{17}O(p,α)^{14}N. For ^{22}Na, the most important reactions are: ^{22}Na(p,γ)^{23}Mg, ^{20}Ne(p,γ)^{21}Na, ^{23}Na(p,α)^{20}Ne, ^{23}Na(p,γ)^{24}Mg, and ^{21}Na(p,γ)^{22}Mg. For ^{26}Al, the most important reactions are ^{23}Mg(p,γ)^{24}Al, ^{26}Al(p,γ)^{27}Si, ^{23}Na(p,γ)^{24}Mg, ^{23}Na(p,α)^{20}Ne, ^{20}Ne(p,γ)^{21}Na, ^{25}Mg(p,γ)^{26}Al, and ^{25}Al(p,γ)^{26}Si. Radioactive beams are required to study a number of

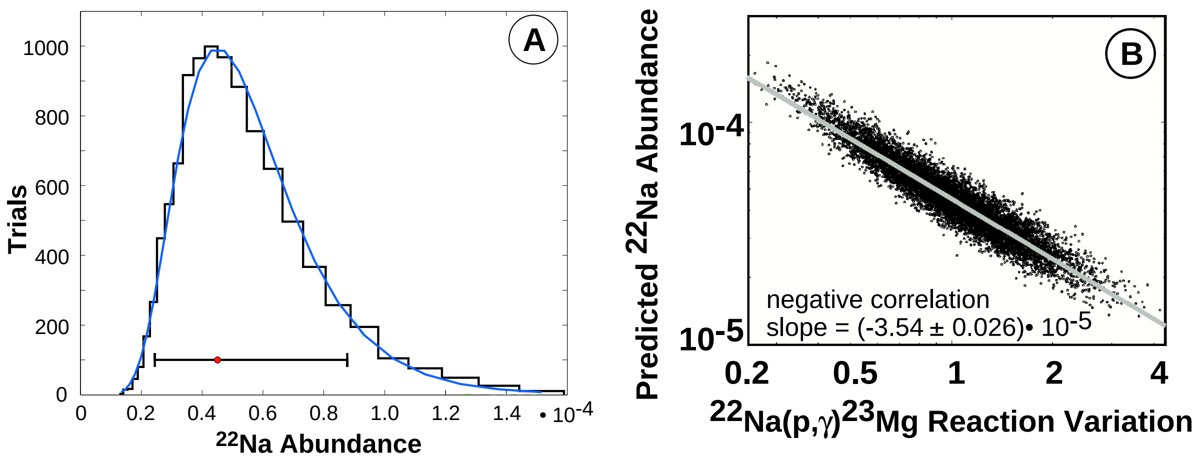

Figure 1. (A). Distribution of the predicted ^{22}Na abundances in the Monte Carlo simulation. The curve is a fit to a log-normal distribution, and the mean abundance and 90 % confidence levels from the are shown by the horizontal bar. (B). Distribution of the predicted ^{22}Na abundance with the multiplicative factor in the ^{22}Na(p,γ)^{23}Mg reaction rate are shown with a linear fit.

these reactions, and our calculations can be used to set priorities for these measurements.

In summary, we have utilized a Monte Carlo approach to nova nucleosynthesis calculations where - for the first time - uncertainties in *all* input nuclear reaction rates are considered simultaneously. This enables us to determine robust uncertainties in nova model predictions as well as the most important reaction rates for future measurements.

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