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Sensitivity of carbon and oxygen yields to the triple-alpha resonance in massive stars

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ABSTRACT

Motivated by the possible existence of other universes, this paper considers the evolution of massive stars with different values for the fundamental constants. We focus on variations in the triple alpha resonance energy and study its effects on the resulting abundances of ^{12}C, ^{16}O, and larger nuclei. In our universe, the 0^+ energy level of carbon supports a resonant nuclear reaction that dominates carbon synthesis in stellar cores and accounts for the observed cosmic abundances. Here we define ΔE_R to be the change in this resonant energy level, and show how different values affect the cosmic abundances of the intermediate alpha elements. Using the state of the art computational package *MESA*, we carry out stellar evolution calculations for massive stars in the range $M_* = 15 - 40 M_\odot$, and for a wide range of resonance energies. We also include both solar and low metallicity initial conditions. For negative ΔE_R, carbon yields are increased relative to standard stellar models, and such universes remain viable as long as the production of carbon nuclei remains energetically favorable, and stars remain stable, down to $\Delta E_R \approx -300$ keV. For positive ΔE_R, carbon yields decrease, but significant abundances can be produced for resonance energy increments up to $\Delta E_R \approx +500$ keV. Oxygen yields tend to be anti-correlated with those of carbon, and the allowed range in ΔE_R is somewhat smaller. We also present yields for neon, magnesium, and silicon. With updated stellar evolution models and a more comprehensive survey of parameter space, these results indicate that the range of viable universes is larger than suggested by earlier studies.

1. Introduction

Over the past few decades, a detailed paradigm for the evolution of our universe has been developed, and this framework provides a successful explanation for many observed cosmic features (e.g., see [1] for a recent review). Some versions of this theory also argue that our universe could be one portion of a much larger region of space-time, sometimes known as the "multiverse," i.e., our local region could represent one member of a vast collection of other universes [2–7]. Moreover, these alternate universes could have different realizations of the laws of physics. Specifically, the constants of nature, including the strengths of the fundamental forces and the masses of the fundamental particles, could vary from region to region [8–11]. Many authors have studied the effects of these possible variations in the laws of physics and find that only certain ranges for the parameters allow for universes to form cosmic structure and support working stars [12–18]. Related work studies the possible time variations of the laws of physics in our universe [19,20]. Since carbon is generally considered a prerequisite for biology — at least for life in familiar forms — the synthesis of carbon provides an important constraint for habitable universes.

Carbon production in stellar interiors takes place through a rather complicated nuclear process known as the triple alpha reaction [21–23]. Because of the intricate landscape of nuclear binding energies and reaction rates, this process takes place through a resonant reaction, which is enabled by a particular excited state of the carbon nucleus. The resulting reaction rate for carbon production depends sensitively on the value of the resonant energy level (for greater detail, see Section 2 and references therein). As a result, if the laws of physics take different forms in other regions of space-time, the resonance energy level could be different, and the amount of carbon produced would vary accordingly. The objective of this paper is to determine how variations in the triple alpha resonance energy affect the abundances of the alpha elements pro-

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duced in massive stars, with a focus on ^{12}C and ^{16}O. The overall goal is to specify the range in resonance energy, characterized the change ΔE_R (see Eq. (8)), that allows the universe to be viable.

Possible variations to the energy level of the carbon resonance, and their effects on stellar evolution, have been explored previously [24–27]. This paper generalizes earlier work by taking advantage of continuing developments in computational capabilities. This contribution uses the stellar evolution package *MESA* (Modules for Experiments in Stellar Astrophysics), a state of the art coding package that has been recently developed for a host of applications and is publicly available [28,29]. The standard *MESA* package does not include changes to the triple alpha resonance level, so these modifications must be implemented at the code-level. In addition to using an updated stellar evolution code, this work also explores a much larger regime of parameter space. Whereas previous papers were limited to relatively few values for the stellar mass M_* and the resonance energy increment ΔE_R, this work considers much wider ranges for M_* and ΔE_R, along different choices for the stellar metallicity $\mathcal{Z}$ (our results are broadly consistent with earlier work [24–26] for given parameter values). In addition to considering carbon and oxygen, we also compile yields for larger alpha elements (neon, magnesium, and silicon). Altogether, this paper reports the results from $\sim$2400 stellar evolution simulations.

In assessing changes to the triple alpha process, the standard approach, which we also follow, is to vary the energy level of the ^{12}C nucleus, but keep all other parameters the same. At the fundamental level, however, variations in the excited state of nuclei are determined by changes in the strengths of the fundamental forces, especially the strong and electromagnetic interactions [30–34]. In principle, changes in these interaction strengths would affect all nuclear characteristics, including binding energies and reaction rates, not just the energy level of the ^{12}C resonance of interest here. In practice, however, small changes to the resonance energy lead to large changes in carbon production. Because of this extreme sensitivity, we can implement variations to the carbon resonance energy while keeping other nuclear parameters fixed. More specifically, the required changes to the resonance energy are of order 300 keV, whereas the binding energies of the nuclei are much larger and fall in the range 28–92 MeV.

This paper is organized as follows. We start with a brief review of the triple alpha reaction in Section 2, which also shows how changes to the process are implemented. The stellar evolution calculations are presented in Section 3, including a description of numerical considerations, basic evolution for massive stars, the effects of changing the triple alpha resonance energy, and the resulting carbon and oxygen yields over a wide range of parameter space. The abundance of carbon required for a viable universe is addressed in Section 4, along with the possibility that ^8Be can be stable and obviate the need for the triple alpha process. The relationship between the triple alpha resonance energy and the fundamental parameters of particle physics is briefly discussed. The paper concludes, in Section 5, with a summary of our results and a discussion of their implications.

2. The triple alpha reaction

After a star burns through the hydrogen fuel in its central core, which is then composed primarily of helium, the star adjusts its internal structure. The central regions condense so that core becomes hotter and denser. Under these conditions, helium becomes the stellar fuel and leads to the production of heavier elements. Given the tight binding energy of helium nuclei—alpha particles—the natural progression is for the helium nuclei to fuse together to synthesize the so-called alpha elements: carbon, oxygen, and neon. In fact, after hydrogen and helium, these three species are the most abundant elements in our universe [35,36], with magnesium, silicon, and sulfur close behind.

This nuclear chain is complicated by the fact that ^8Be (and all other nuclei with atomic mass number $A = 8$) are unstable in our universe. In the absence of stable ^8Be, which provides a stepping stone on the path to heavier alpha elements, the fusion of helium takes place through the triple alpha reaction [21–23], where three helium nuclei combine to make carbon. The net result of this process can be written in the form

$$3\left(^4\mathrm{He}\right) \to {}^{12}\mathrm{C} + \gamma\,, \tag{1}$$

but intermediate steps are required. In order to facilitate the reaction (1), the stellar core maintains a transient population of unstable ^8Be nuclei [37]. In this setting, the alpha particles fuse to produce ^8Be, which decays back into its constituent alpha particles with a half-life of approximately $\tau_{1/2} \sim 10^{-16}$ s,

$$^4\mathrm{He} + {}^4\mathrm{He} \longleftrightarrow {}^8\mathrm{Be}, \tag{2}$$

The forward reactions occur fast enough that the stellar core maintains nuclear statistical equilibrium (NSE), which determines the abundances of the relevant nuclear species. The resulting transient population of ^8Be is large enough for some of these unstable nuclei to interact during their short lifetimes through the reaction

$$^4\mathrm{He} + {}^8\mathrm{Be} \to {}^{12}\mathrm{C}\,. \tag{3}$$

Given the densities and temperatures of helium-dominated stellar cores, the non-resonant reaction does not take place fast enough to explain the observed carbon and oxygen abundances found in our universe. However, the ^{12}C nucleus has an excited state at an accessible energy so that this reaction can operate in a resonant manner, which increases the reaction rate and allows stars to produce the observed cosmic abundances of carbon. Both the existence and the particular energy level of this excited state were predicted by Hoyle [38], and subsequent laboratory experiments [39] measured the resonance with the anticipated properties (see also the reviews of [40,41]). The relevant excited state has an energy of 7.6444 MeV, and corresponds to a 0^+ nuclear state of the ^{12}C nucleus. Significantly, this energy is somewhat larger than the energy of the alpha particle and the ^8Be nucleus considered as separate particles (see Eq. (3)). The efficacy of carbon production is highly sensitive to the energy of this resonance.

As outlined above, the production of carbon relies, in part, on the intermediate reaction from Eq. (2), even though the product ^8Be is unstable. The reaction rate for this process [21,22,30] depends on the energy difference

$$(\Delta E)_b \equiv E_8 - 2E_4. \tag{4}$$

The ground state energies of ^4He and ^8Be are denoted as E_4 and E_8, respectively. Similarly, the ground state of carbon is denoted here as E_{12} and the excited state (the 0^+ resonance) is $E_{12}^\star$. In the reaction (3), the energy difference between the excited carbon nucleus and the interacting nuclei is then given by

$$(\Delta E)_h = E_{12}^\star - E_8 - E_4. \tag{5}$$

The energy scale E_R of the resonant reaction can then be defined as follows:

$$E_R \equiv (\Delta E)_b + (\Delta E)_h = E_{12}^\star - 3E_4. \tag{6}$$

This energy level has been experimentally measured to be $(E_R)_0 \approx 379.5$ keV. Given the above definitions, the resonant reaction rate $R_{3\alpha}$ for the triple alpha process at temperature T can be written in the form

$$R_{3\alpha} = 3^{3/2} n_\alpha^3 \left(\frac{2\pi\hbar^2}{|E_4|kT}\right)^3 \frac{\Gamma_\gamma}{\hbar} \exp\left[-\frac{E_R}{kT}\right], \tag{7}$$