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Structure and stability of primordial stars

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Abstract: For decades large-scale cosmic structures have been modeled as the gravitational amplification of small-density perturbations of the cosmological recombination epoch of the Big Bang. In astrophysics, cosmological nucleosynthesis is considered responsible for the production of the pristine gas, which should be found in the first-generation stars in the form of hydrogen and helium as the main constituents. In the later type of second-generation stars, hydrogen is converted into helium by the CN-cycle reactions, in which heavier elements are produced. These elements are believed to enrich the intergalactic medium by possible star bursts at the last stages of evolution.

Stability criteria in the stellar evolutionary models pointed out that first-generation stars should be massive and live long enough for the nucleosynthesis of the natural elements, heavier than hydrogen and helium. Initially, they were expected to be very faint and blue to be observed spectroscopically. Nowadays, more and more metal-deficient star observations, made possible by the new era of space telescopes, are interpreted as the discovery of a primordial footprint of the initially pure gas. These new data are combined with the astrophysical models to review the predictability, mass, and chemical composition with regard to stability and existence of the first-generation stars.

Key words: Nucleosynthesis, first-generation stars, abundance, mass, stability

1. Introduction

In the past several decades different scenarios were developed in order to explain the present large-scale cosmic structure as the amplification of small-density fluctuations right after the Big Bang. First observations of such anisotropies in the cosmic microwave background defined these initial conditions at the epoch of 370,000 years [1]. Late discovery of very high red shift ($z \approx 10$) distant galaxies by means of large ground-based telescope observations reveals the cosmic structure at the reionization epoch, several hundred million years after the Big Bang [2]. At that time, the very first stars are thought to have formed by radiative cooling, when the initially pristine cosmic gas had enough hydrogen and helium produced from the proton and neutron collisions. Thus, understanding the structure and evolution of these very first stars (herein, POP III.1 type) is very important as producers of the chemical abundances of elements discovered in our galaxy today. Besides their composition, debates are still continuing concerning their mass and stability, which would finally affect their age. In this context, different cosmological scenarios predict the POP III.1 type stars to be very massive, ranging from 10^2 to 10^3 solar masses, $M_\odot$ (see, e.g., [3]). This result turns out to be consistent with the fragmentation models of the primordial clouds [4].

On the other hand, stellar evolution models assume that, when stars arrive at the zero-age main sequence

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This paper is dedicated to the memory of Prof Dr Dilhan Eryurt Ezer.

(ZAMS) stage, nuclear burning of hydrogen via the p-p chain and helium burning by the triple-alpha reactions start to operate in their interiors. From their pioneering work of solar and stellar evolution models, Ezer and Cameron [5] showed that intermediate mass 20 ($M_\odot$) POP III.1 type stars already reach characteristic central temperatures (T_C around 10^8 K) suitable for the production of enough C^{12} from the operation of the triple-alpha reactions. Compared to the later POP III.2 type stars containing heavier elements, principal energy production at the ZAMS stage of the first-generation stars is not by the p-p chain but rather the CN-cycle. The POP III.1 stars should also be more compact then the second-generation POP III.2 stars, in which the ZAMS radiation is in the UV part of the spectrum. The helium abundance predicted by the solar evolution models also favored the idea that the first stars should contain only hydrogen (X = 0.80) and helium (Y = 0.20) by parts, with almost no other heavier elements (Z = 0), to be consistent with the actual Sun (Y = 0.23). Afterwards, it was accepted that in normal stars of the same mass, hydrogen is converted into helium by the CN-cycle reactions, as they already contain the necessary heavy elements produced by the primordial nucleosynthesis. Nuclear burning in the interiors would have a destabilizing effect in the outer parts, leading to mass loss after a certain limit. We can revise the historical theoretical stability analysis as follows:

1. Ledoux [6] demonstrated the existence of a critical mass below which stars are pulsationally stable against adiabatic oscillations on the main sequence. For normal stars containing about 2% of heavy elements, Schwarzschild and Härm [7] established this mass limit around 60 $M_\odot$.

2. Extending the above studies to massive POP III.1 type first-generation stars (100 $M_\odot$ to 200 $M_\odot$), İbrahim et al. [8] assumed that C^{12} already accumulated by the triple-alpha reactions was sufficient to trigger the CN-cycle for synthesizing heavier elements. The growing importance of the radiation pressure in these stars was also taken into account and pulsationally stable critical mass was established as 123 $M_\odot$.

3. Eryurt-Ezer and Kızıloğlu [9] studied the evolution and structure of intermediate-mass POP III.1 stars (5, 7, and 9 $M_\odot$) from the threshold of stability through helium exhaustion. The 5 $M_\odot$ star was shown to be stable against radial vibrations by Kırbıyık [10].

4. Vibrational instability of low-mass POP III stars with various masses ranging between 1 and 5 $M_\odot$ and initial compositions X = 0.75 for metal-free (Z = 0) or metal-poor cases (Z between 0.01% and 0.02%) were studied by Sonoi and Shibahashi [11]. In their pioneering work, they elaborated the nonradial g-mode instability triggered by the ε-mechanism of the triple-alpha burning of ^{3}He. They showed that this type of instability indeed occurs for POP III low-mass stars for $M < 1\ M_\odot$ with no metals. The upper limit depends on metallicity with an extreme value of 5 $M_\odot$ reached among the above cases. Since the e-folding time (10^7 years) of instability is short compared to the star's life timescale, it should be stabilized during the evolution of the star. On the other hand, if the amplitude grows nonlinearly, it may result in mixing the matter in the stellar interior and affect the nucleosynthesis studies.

5. For pure He stars, stable mass is evaluated as 9 $M_\odot$ [12] and that for pure hydrogen stars is 280 $M_\odot$ [13].

6. Stabilities of various very massive primordial stars of 120–500 $M_\odot$ with different Z values have been evaluated and compared with that of normal stars [14]. It was concluded that instabilities of the ZAMS may not essentially lead to mass loss, as they evolve more rapidly off the main sequence than their counterpart POP III.2 stars. Thus, very massive first-generation stars should indeed contribute to the nucleosynthesis of the galaxy by mass ejection at the end of their evolution.

7. İbrahim [15] investigated, as a PhD thesis, the structure and pulsational stability of two intermediate mass ($10M_\odot$ to $20M_\odot$) first-generation type POP III.1 stars, consisting of the primordial matter ($X = 0.80$, $Y = 0.20$, $Z = 0$) on arrival at the ZAMS. It was shown that energizing of pulsations by the nuclear energy sources in the cores of these stars is much smaller than the radiative damping processes (pulsational damping time 430 years and 99 years, respectively). This result supported Silk's hydrodynamic stability considerations [16] that the very early stars with primordial composition should have formed with masses greater than 20 $M_\odot$. These two first-generation stars had surface temperatures of around 4×10^4 to 6×10^4 K at the ZAMS, which means that if galaxies containing these stars were formed at one-tenth of the present age of the universe (around 14 billion years), then the radiation emitted from them with the effective temperatures of the order of 10^4 K would be redshifted by a factor of 10, reducing the temperature by the same amount to the present time. With these considerations, we would expect that if these stars ever existed, they would probably appear as very faint and extremely blue objects today, hence difficult to observe spectroscopically. However, space telescope observations provide exciting discoveries not imagined before. For example, according to Cayrel [17], the most promising candidates of first-generation stars are the very metal-poor stars HE 0107-5240 [18] and HE 1327-2326 [19] found by the Subaru telescope. Even though their masses and distances are not yet known, various scenarios exist about their origin [20,21].

More recently, from direct abundance measurements, scientists reported [22] observations of neutral hydrogen with no heavier metals in a quasar of redshift 7. This corresponds to a time about 700 million years after the Big Bang, when the earliest stars began synthesizing elements. They interpreted this as the first observation of a possible massive population star formation site, after the heavy elements were brought to the low-mass stars at later times (POP III.2).

The most promising discovery is the one made by the 200 Fermi scientists of NASA. Using the gamma-ray space telescope Fermi, they measured the high-energy gamma ray blasts emitted by 150 blazars (giant black holes) some 10 billion years ago [23]. By screening the extragalactic background light from all stars, they claimed to have measured starlight from the supermassive first-generation stars just about 4 billion years after the Big Bang.

2. Comments

Hence, considering the points stated above, we can also "safely conclude" that, if first-generation stars were formed as intermediate or supermassive objects [24], they should be able to arrive at the main sequence with no mass loss by radial oscillations up to hundreds of solar masses ($M_\odot$), but be very faint to observe spectroscopically.

Hopefully, more and more discoveries seem to point toward potential candidates for the very first stars [25,26]. When the James Webb Space Telescope is orbiting around the Sun in 2018, we can expect closer observations of the young universe.

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