Postprint: Age Determination of r-Process Enriched Metal-Poor Stars Using Th/U Nuclear Chronometry

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Date: 2025-10-10T00:00:00+00:00

Abstract

Metal-poor stars are stars that formed in the early universe, preserving chemical characteristics imprinted by early nucleosynthesis, thus providing crucial clues for investigating heavy element nucleosynthesis mechanisms and chemical evolution in the early cosmos. Based on Th/U nucleocosmochronology, we analyzed the ages of eight currently known r-process enhanced metal-poor stars: CS31082-001, BD+17°3248, HE1523-0901, CS29497-004, J2038-0023, J0954+5246, J2003-1142, and J2213-5137. The results indicate that these eight r-process enhanced metal-poor stars have ages ranging from 7.4 to 16.9 Gyr, with a mean age of 13.2 Gyr. None of these metal-poor star ages significantly exceed the cosmic age inferred from cosmic microwave background radiation (13.8 Gyr) within their uncertainties, providing independent evidential support for the Big Bang theory. The primary sources of error in estimating metal-poor star ages using Th/U nucleocosmochronology arise from uncertainties in the initial and observed abundances of Th and U elements.

Full Text

Investigating the Ages of R-Process Enhanced Metal-Poor Stars Using Th/U Nuclear Chronometry

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Abstract

Metal-poor stars, formed in the early universe, preserve the chemical signatures of primordial nucleosynthesis and provide crucial clues for understanding heavy element synthesis mechanisms and the chemical evolution of the early cosmos. Using Th/U nuclear chronometry, we analyzed the ages of eight known r-process enhanced metal-poor stars: CS31082-001, BD+17°3248, HE1523-0901, CS29497-004, J2038-0023, J0954+5246, J2003-1142, and J2213-5137. Our results indicate that these stars have ages ranging from 7.4 to 16.9 Gyr, with a mean age of 13.2 Gyr. None of these stellar ages significantly exceed the cosmic age of 13.8 Gyr inferred from cosmic microwave background radiation, providing independent support for the Big Bang theory. The primary source of uncertainty in Th/U nuclear chronometry stems from uncertainties in both the initial and observed abundances of thorium and uranium.

Keywords: Th/U nuclear chronometry; metal-poor star; r-process

1. Introduction

According to nucleosynthesis theory, heavy elements are produced primarily through two neutron-capture processes: the rapid neutron-capture process (r-process) and the slow neutron-capture process (s-process). The r-process is considered the dominant pathway for heavy element synthesis, responsible for producing more than half of all heavy elements in the universe, including all thorium (Th) and uranium (U) [?, ?]. During the r-process, atomic nuclei rapidly capture multiple neutrons to form neutron-rich isotopes. These neutron-rich nuclei are typically unstable and undergo β-decay, increasing their atomic number and producing heavier elements, which can then capture additional neutrons to synthesize even heavier species. The r-process successfully explains both the abundance patterns of r-process heavy elements in the solar system and the observed heavy element abundances in metal-poor stars [?].

The extreme conditions required for the r-process—high temperature, high density, and high neutron flux—are found in only a few astrophysical environments. Extensive simulations have identified two primary sites: (1) core-collapse supernovae and (2) binary neutron star mergers or neutron star-black hole mergers. However, further research has shown that core-collapse supernovae have relatively low neutron densities and can only synthesize some of the lighter r-process elements [?]. In contrast, neutron star mergers eject material rich in free neutrons through tidal disruption, collisional compression, and accretion feedback, enabling the production of substantial quantities of heavy elements via the r-process [?]. Consequently, neutron star mergers are regarded as the ideal site for r-process nucleosynthesis [?].

The first direct evidence for this scenario came with the detection of gravitational waves from the binary neutron star merger GW170817 by the Laser Interferometer Gravitational-Wave Observatory (LIGO) on August 17, 2017 [?]. Subsequent multi-wavelength, multi-messenger follow-up observations revealed an associated gamma-ray burst (GRB170817A) and kilonova emission (AT2017gfo) [?]. Analysis of the kilonova’ s light curve and spectral energy distribution indicated that this single event synthesized approximately 0.05 M of heavy elements [?], with direct spectroscopic evidence for the heavy element strontium [?]. A research team at Peking University further demonstrated that the rates and yields of neutron star mergers can reproduce not only the solar r-process element abundances but also account for the total observed inventory of heavy elements in the Milky Way [?], confirming that neutron star mergers are the primary r-process site and a major source of cosmic heavy elements.

Following their synthesis in neutron star mergers, heavy elements are ejected into the interstellar medium, where they become incorporated into subsequent generations of stars. The abundance signatures of these elements are preserved in ancient stellar populations, particularly in r-process enhanced metal-poor stars [?]. These stars, characterized by low metallicity and enhanced r-process element abundances, formed in the early universe and retain the chemical fingerprints of primordial nucleosynthesis, making them invaluable probes of r-process mechanisms and early cosmic chemical evolution. To determine their ages precisely, astronomers employ the Th/U nuclear chronometry method, which exploits the radioactive decay of ^{232}Th (half-life 14 Gyr) and ^{238}U (half-life 4.5 Gyr). By measuring the initial and present-day abundance ratios of these isotopes and applying the laws of radioactive decay, stellar ages can be derived, providing crucial constraints on star formation histories and early cosmic evolution.

Alternative chronometers such as Th/Eu and U/Eu have also been used, but Th and U are produced exclusively via the r-process, whereas europium (Eu) synthesis involves contributions from both the r-process and s-process, introducing significant uncertainties in age calculations. Recent work by a Chinese Academy of Sciences team using the LAMOST telescope identified an r-process enhanced star with extremely high Eu abundance [?], suggesting complex formation and enrichment pathways for Eu. Furthermore, because Th (Z=90) and U (Z=92) are adjacent elements, their abundance ratio is less sensitive to astrophysical and nuclear physics parameters than ratios involving Eu (Z=63), which is separated by nearly 30 atomic numbers. Consequently, Th/U nuclear chronometry provides an independent dating method that does not rely on galactic evolution models and is particularly suitable for age determinations of metal-poor stars [?].

As of September 2024, eight r-process enhanced metal-poor stars with measured Th and U abundances have been discovered: CS31082-001 [?], BD+17°3248 [?], HE1523-0901 [?], CS29497-004 [?], J2038-0023 [?], J0954+5246 [?], J2003-1142 [?], and J2213-5137 [?]. All exhibit extremely low metallicities ([Fe/H] < -2.0), indicating formation in the early universe, and show prominent r-process element absorption features, signifying substantial early r-process enrichment. This paper applies Th/U nuclear chronometry to determine the ages of these eight stars.

2. Research Methods

According to the law of radioactive decay, the number of radioactive nuclei remaining after time t, N(t), relates to the initial number N(0) as:

$$N(t) = N(0)\exp(-\lambda t)$$

where λ is the decay constant. For ^{232}Th and ^{238}U, this becomes:

$$N_{\mathrm{Th}}(t) = N_{\mathrm{Th}}(0)\exp(-\lambda_{\mathrm{Th}} t)$$

$$N_{\mathrm{U}}(t) = N_{\mathrm{U}}(0)\exp(-\lambda_{\mathrm{U}} t)$$

Combining equations (2) and (3) yields the abundance ratio:

$$\frac{N_{\mathrm{U}}(t)}{N_{\mathrm{Th}}(t)} = \frac{N_{\mathrm{U}}(0)}{N_{\mathrm{Th}}(0)}\exp[-(\lambda_{\mathrm{U}} - \lambda_{\mathrm{Th}})t]$$

Taking the base-10 logarithm of both sides gives:

$$\log\left[\frac{N_{\mathrm{U}}(t)}{N_{\mathrm{Th}}(t)}\right] = \log\left[\frac{N_{\mathrm{U}}(0)}{N_{\mathrm{Th}}(0)}\right] - (\lambda_{\mathrm{U}} - \lambda_{\mathrm{Th}})t\log e$$

Rearranging equation (5) provides the age formula:

$$t = \frac{\log\left[\frac{N_{\mathrm{U}}(0)}{N_{\mathrm{Th}}(0)}\right] - \log\left[\frac{N_{\mathrm{U}}(t)}{N_{\mathrm{Th}}(t)}\right]}{(\lambda_{\mathrm{U}} - \lambda_{\mathrm{Th}})\log e}$$

The relationship between half-life $\mathrm{T}_1/_2$ and decay constant λ is $\mathrm{T}_1/_2 = \ln(2)/\lambda$. According to the NuDat3.0 nuclear database, the half-lives of ^{232}Th and ^{238}U are 14.07 Gyr and 4.46 Gyr, respectively. Substituting these values into equation (6) yields the simplified age equation:

$$t = 21.71\left[\log\left(\frac{U}{\mathrm{Th}}\right)_{\mathrm{ini}} - \log\left(\frac{U}{\mathrm{Th}}\right)_{\mathrm{obs}}\right]$$

where t is in Gyr, and (U/Th) and (U/Th) bs represent the initial and observed uranium-to-thorium abundance ratios, respectively.

Applying this method requires knowledge of both the initial and observed U/Th ratios. Bauswein et al. [?] simulated r-process nucleosynthesis in neutron star mergers and found Th/U 1.7, corresponding to log(U/Th) = -0.23. Frebel et al. [?] considered the influence of astrophysical parameters on r-process yields and derived a range of log(U/Th) = -0.22 to -0.30, consistent with Bauswein' s results. For this work, we adopt log(U/Th) = -0.26 ± 0.04.

3. Results and Analysis

Figure 1 [Figure 1: see original paper] presents the heavy element abundance patterns of the eight metal-poor stars, with the solid black line representing solar r-process abundances. The abundance patterns of all eight stars closely follow the solar r-process distribution, confirming that they experienced significant early r-process enrichment and are suitable candidates for Th/U chronometry.

Figure 2 [Figure 2: see original paper] displays the metallicities and observed U/Th abundance ratios. The log(U/Th) bs values range from -1.1 to -0.6. Three stars—BD+17°3248, CS29497-004, and J2213-5137—have large observational uncertainties of $±$0.30 dex, while CS31082-001 shows the smallest uncertainty at $±$0.11 dex.

Using the Th/U chronometry age formula, we calculated ages for all eight stars, as shown in Figure 3 [Figure 3: see original paper]. The shaded region indicates the uncertainty range due to the initial abundance (U/Th) , while error bars represent uncertainties from the observed ratio (U/Th) bs. For a given initial ratio, stellar age correlates linearly with the observed log(U/Th) bs, with older stars showing more negative values. The derived ages span 7.4 to 16.9 Gyr, with a mean of 13.2 Gyr. The adopted initial abundance ratio of log(U/Th) = -0.26 ± 0.04 introduces an age uncertainty of 0.9 Gyr. However, uncertainties from observed abundances dominate the total error budget. CS31082-001 exhibits the smallest age uncertainty (2.4 Gyr), while CS29497-004 shows the largest (7.2 Gyr). These results demonstrate that precise abundance measurements of Th and U in r-process enhanced metal-poor stars are essential for reducing age uncertainties, as are high-precision r-process simulations for constraining initial abundances.

Figure 4 [Figure 4: see original paper] presents the final age determinations with error bars incorporating both initial and observational uncertainties. Among the eight stars, CS29497-004 is the oldest at 16.9 ± 8.0 Gyr, while J2003-1142 is the youngest at 7.4 ± 5.2 Gyr. CS31082-001 has the most precise age determination at 14.8 ± 3.3 Gyr. No clear correlation emerges between stellar age and metallicity [Fe/H]. Table 1 summarizes the age calculations for all eight stars.

Figure 4 also compares the stellar ages with the cosmic age inferred from cosmic microwave background radiation. Since substantial time must elapse from the Big Bang to the formation of these ancient stars, their ages should be younger than the universe itself. As an independent dating method, Th/U chronometry can thus constrain the lower limit of the cosmic age and provide crucial evidence for the Big Bang theory. The figure shows that all eight r-process enhanced metal-poor stars have ages consistent with the CMB-derived cosmic age of 13.8 Gyr [**?**], providing independent support for the standard cosmological model.

We compared our results with those of Wu et al. [**?**], who used r-process nucleosynthesis simulations to estimate ages for six of these stars (excluding the more recently discovered J2003-1142 and J2213-5137). As shown in Figure 5

[Figure 5: see original paper], the ages derived from Th/U chronometry agree well with Wu et al.' s simulation-based results. Our work extends the analysis to include J2003-1142 (7.381 ± 5.210 Gyr) and J2213-5137 (15.197 ± 7.164 Gyr), providing age estimates for these newly identified r-process enhanced stars.

4. Summary and Discussion

Using Th/U nuclear chronometry, we have determined the ages of eight known r-process enhanced metal-poor stars: CS31082-001, BD+17°3248, HE1523-0901, CS29497-004, J2038-0023, J0954+5246, J2003-1142, and J2213-5137. Analysis of their heavy element abundances reveals observed U/Th ratios log(U/Th) bs ranging from -1.1 to -0.6. Applying the Th/U chronometric age formula yields ages of 7.4–16.9 Gyr, with a mean age of 13.2 Gyr. These results are consistent with the age estimates obtained by Wu et al. [**?**] using r-process nucleosynthesis simulations.

Th/U nuclear chronometry provides an independent dating method that avoids uncertainties associated with galactic evolution models. By determining the ages of ancient stars, this technique effectively constrains the lower limit of the cosmic age. Our results show that the ages of r-process enhanced metal-poor stars do not exceed the CMB-derived cosmic age of 13.8 Gyr, offering independent evidence in support of the Big Bang theory.

We have identified two primary sources of uncertainty in Th/U chronometry: (1) the initial Th/U abundance ratio, and (2) the observed Th/U abundance ratio. For most stars, uncertainties from observed abundances substantially exceed those from initial abundances. Therefore, precise spectroscopic measurements of Th and U in r-process enhanced metal-poor stars are critical for reducing age uncertainties. Additionally, high-precision r-process nucleosynthesis simulations are needed to better constrain the initial Th and U abundances and further improve age determinations.

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