

Mini Review

# Stellar Evolution Across Cosmic Time: From Cosmic Dawn to Present Day Chemical Fossils

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## Abstract

The formation of the first stars during the Cosmic Dawn initiated the earliest phases of chemical enrichment and radiative feedback that ultimately shaped the subsequent evolution of galaxies and stellar populations throughout the Universe. Current theoretical models predict that primordial star formation was dominated by massive Population III stars formed from metal-free gas, although direct observational confirmation remains challenging because such objects are not expected to survive to the present epoch. Nevertheless, the discovery of extremely metal-poor stars in the Milky Way halo and nearby dwarf galaxies has opened an important observational window into the physical conditions of the early Universe. In this work, we present a focused synthesis connecting early star formation processes to a select population of surviving ultra-metal-poor stars within the Local Group. By examining iron abundances, carbon enhancement, and inferred total metallicities, we argue that the transition from primordial to contemporary star formation is more reliably traced by total metal content than by iron abundance alone. Particular attention is given to the recently identified red giant SDSS J0715-7334, associated with the halo of the Large Magellanic Cloud, whose inferred metallicity falls below  $\log(Z/Z_{\odot}) \approx -4.3$ . Its chemical abundance pattern is consistent with star formation pathways regulated by dust-induced cooling under extremely metal-deficient conditions. These chemically primitive stellar relics provide an important empirical link between the physics of the Cosmic Dawn and the surviving fossil record observed in the Local Universe, with broader implications for interpreting metal-poor stellar populations detected in high-redshift galaxies.

## Introduction

The formation of the first stars during the Cosmic Dawn marked a pivotal transition in cosmic history, initiating the earliest episodes of chemical enrichment and radiative feedback that shaped the subsequent evolution of galaxies. These primordial Population III stars formed from metal-free gas and are generally believed to have been massive and short-lived, enriching their surroundings through supernova explosions and creating the conditions necessary for the formation of later stellar generations. Although Population III stars are not expected to survive to the present epoch, extremely metal-poor stars discovered in the Milky Way and nearby dwarf galaxies preserve a fossil record of the physical processes that operated during the first billion years of cosmic evolution. A central question in modern astrophysics concerns the transition from primordial star formation to the formation of long-lived, low-mass stars. Competing theoretical models suggest that this transition may have been regulated either by fine-structure line cooling from carbon and oxygen or by dust-induced cooling operating at extremely low metallicities. Distinguishing between

these mechanisms requires consideration of total metal content rather than iron abundance alone. In this work, we present a focused synthesis linking theoretical models of early star formation with observational evidence from the most chemically primitive stellar survivors currently known. Particular emphasis is placed on the recently identified star SDSS J0715-7334 in the halo of the Large Magellanic Cloud. By comparing iron abundances, carbon enhancement, and inferred total metallicities, we examine whether total metallicity provides a more reliable tracer of the transition from primordial to contemporary star formation and discuss the implications for interpreting chemically primitive stellar populations in both the local and high-redshift Universe.

### Discussion

Understanding how stars evolved from their primordial origins to the chemically diverse populations observed today remains one of the central problems of modern astrophysics. In the standard cosmological framework, the first stars formed at redshifts  $z \gtrsim 20$  from metal-free gas within minihalos, approximately 200 Myr after the Big Bang, giving rise to massive Population III objects whose short lifetimes rapidly enriched their surroundings through supernova explosions. The lifetimes of stars are strongly mass dependent, approximately following

$$\tau_* \propto M^{-2.5}$$

such that massive Population III stars exhausted their nuclear fuel within only a few million years, whereas low-mass stars could survive for times comparable to the present age of the Universe [1]. These early episodes of star formation initiated a complex interplay between radiative feedback, chemical enrichment, and gas cooling, ultimately enabling the emergence of long-lived, low-mass stars that persist to the present epoch. For decades, observational access to this early phase was thought to be impossible, as Population III stars are expected to have already disappeared. However, the discovery of extremely metal-poor stars in the Milky Way halo and nearby dwarf galaxies has opened a new observational window into the first billion years of cosmic history. These objects act as chemical fossils, preserving the nucleosynthetic signatures of the earliest supernovae and providing indirect constraints on the physical conditions under which second-generation stars formed. A central theoretical question concerns the minimum metallicity required for low-mass star formation. Two principal cooling mechanisms have been proposed: fine-structure line cooling and dust-induced cooling. Fine-structure cooling arises from atomic transitions of

carbon and oxygen, which can efficiently radiate thermal energy at densities typical of star-forming clouds. This process predicts a critical metallicity threshold of order  $Z_{\text{crit}} \sim 10-3.5 Z_{\odot}$ , above which fragmentation into low-mass objects becomes possible. However, observational studies of extremely metal-poor stars have challenged the universality of this threshold, as many of the most iron-deficient stars exhibit strong carbon enhancement, implying that their total metal content may exceed this limit even when their iron abundance is exceptionally low. Dust-induced cooling offers a distinct and more permissive pathway. In this scenario, trace amounts of dust grains formed in early supernova ejecta can dominate the thermal balance of collapsing gas at high densities. Dust grains efficiently absorb thermal energy from gas through collisions and radiate it in the infrared, enabling fragmentation at metallicities as low as  $Z \sim 10^{-6} Z_{\odot}$ , depending on dust composition and grain size distribution. Unlike fine-structure cooling, this mechanism depends primarily on the dust-to-gas ratio rather than on specific elemental abundances. Distinguishing between these regimes observationally requires moving beyond iron abundance as the sole diagnostic of chemical primitiveness. Stellar abundances are commonly expressed using the logarithmic notation

$$[A/B] = \log_{10} \left( \frac{N_A}{N_B} \right)_* - \log_{10} \left( \frac{N_A}{N_B} \right)_{\odot}$$

where  $N_A$  and  $N_B$  denote elemental number densities relative to hydrogen [2]. Here,  $Z$  denotes the total heavy-element mass fraction in standard astrophysical notation [3]. Total metallicity, which accounts for all heavy elements and dust content, provides a more physically meaningful measure of cooling capability. In this context, stars with simultaneously low iron and suppressed carbon abundances represent particularly stringent tests of star formation theory, as their existence directly constrains the minimum conditions under which low-mass stars can form. In this work, we present a focused synthesis linking early star formation theory with a comparative analysis of the lowest-metallicity stars currently known. By comparing iron abundances, carbon enhancement, and inferred total metallicities, we argue that the transition from primordial to modern star formation may be more reliably traced by total metal content than by iron abundance alone. These results establish a direct observational bridge between the Cosmic Dawn and present-day stellar populations and provide a framework for interpreting ongoing searches for metal-poor stars in both the local and high-redshift Universe. Fine-structure cooling models [4, 5] based on carbon and oxygen line emission predict a critical

metallicity threshold near  $Z_{\text{crit}} \sim 10^{-3.5} Z_{\odot}$  for efficient low-mass star formation. This framework is commonly parameterized using the transition discriminant.

$$D_{\text{trans}} = \log_{10} \left( 10^{[\text{C}/\text{H}]} + 0.3 \times 10^{[\text{O}/\text{H}]} \right),$$

which provides an observational criterion for assessing whether fine-structure cooling can account for the formation of extremely metal-poor stars [5]. However, the increasing number of discoveries of chemically primitive stars with diverse abundance patterns suggests that total metallicity and dust content may provide a more fundamental description of the transition from primordial to contemporary star formation.

### Cosmic Dawn and the First Stars

The Cosmic Dawn marks the epoch during which the first luminous objects formed from primordial matter, bringing an end to the cosmic dark ages. Following recombination, baryonic gas cooled and collapsed into the gravitational potential wells of dark matter minihalos with characteristic masses of  $10^5$ – $10^6 M_{\odot}$ . In the absence of heavy elements, the primary coolant available to the gas was molecular hydrogen, whose formation was catalyzed by residual free electrons left over from recombination. Cooling through molecular hydrogen enabled gravitational collapse but imposed a temperature floor of several hundred kelvin, corresponding to Jeans masses of tens to hundreds of solar masses. Consequently, theoretical models predict that the first stars were predominantly massive, with characteristic masses substantially larger than those of present-day stellar populations. This top-heavy initial mass function implies that Population III stars were short-lived and highly luminous, producing intense ultraviolet radiation fields that rapidly transformed their surrounding environments. During the epoch of reionization, intense ultraviolet radiation from massive Population III stars generated expanding regions of ionized hydrogen that heated and photoevaporated gas in nearby minihalos, thereby suppressing subsequent star formation in those environments. At the same time, enhanced free-electron fractions in more distant regions could catalyze additional molecular hydrogen formation, thereby promoting cooling and star formation on larger scales.

Following recombination, when the baryonic component decoupled from the radiation field and the cosmic microwave background was released, primordial gas began to cool and collapse into the gravitational potential wells of dark matter minihalos. Chemical enrichment during this phase was highly inhomogeneous. Individual supernova events could dominate the chemical

composition of entire star-forming regions, imprinting distinctive abundance patterns onto the next generation of stars. Consequently, second-generation stars are expected to preserve the nucleosynthetic signatures of one or a small number of progenitor supernovae, making them powerful probes of early stellar populations and primordial enrichment processes. The transition from Population III to Population II star formation was therefore not a smooth global process but a localized and stochastic one governed by the interplay between cooling physics, radiative feedback, and metal mixing. The existence of extremely metal-poor stars in the present-day Universe reflects the survival of objects formed in environments where enrichment remained minimal and subsequent star formation proceeded inefficiently or ceased altogether. These chemically primitive survivors provide some of the most direct observational constraints currently available on the physical conditions that prevailed during the Cosmic Dawn.

### Transition Physics: Cooling and the Low-Mass Threshold

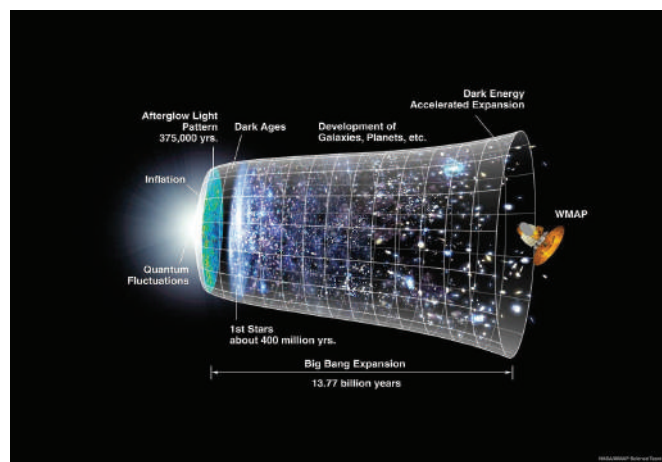
The emergence of long-lived, low-mass stars marks a fundamental transition in cosmic stellar evolution. While the first stars formed from pristine gas in the absence of metals, the present-day stellar population is dominated by low-mass objects whose lifetimes exceed the age of the Universe. Understanding how this transition occurred requires identifying the physical mechanisms that enabled efficient gas fragmentation at progressively lower masses. In primordial environments, cooling is limited primarily to molecular hydrogen and, at higher densities, collision-induced emission. These channels are sufficient to produce Jeans masses of tens to hundreds of solar masses. As a result, Population III stars are predicted to have formed with a top-heavy initial mass function. The appearance of metals fundamentally alters this picture by introducing additional radiative cooling pathways. Two principal mechanisms have been proposed to explain the onset of low-mass star formation: fine-structure line cooling and dust-induced cooling. Fine-structure cooling arises from atomic transitions of carbon and oxygen, which can efficiently radiate thermal energy at densities typical of star-forming clouds. This process predicts a critical metallicity threshold of order  $Z_{\text{crit}} \sim 10^{-3.5} Z_{\odot}$ , above which fragmentation into low-mass objects becomes possible [4, 5]. However, observational studies of extremely metal-poor stars have challenged the universality of this threshold. Many of the most iron-deficient stars exhibit strong carbon enhancement, implying that their total metal content may lie above the fine-structure cooling limit even when their

iron abundance is exceptionally low. In such cases, carbon itself may provide sufficient cooling to enable low-mass star formation without invoking alternative mechanisms.

Dust-induced cooling offers a distinct and more permissive pathway. In this scenario, even trace amounts of dust grains formed in early supernova ejecta can dominate the thermal balance of collapsing gas at high densities. Dust grains efficiently absorb thermal energy from gas through collisions and radiate it in the infrared, enabling fragmentation at metallicities as low as  $Z \sim 10^{-6} Z_{\odot}$ , depending on dust composition and grain size distribution. Unlike fine-structure cooling, this mechanism depends primarily on the dust-to-gas ratio rather than on specific elemental abundances. The relative importance of these two channels has profound implications for the expected distribution of surviving low-metallicity stars. If fine-structure cooling dominates, one expects the most metal-poor low-mass stars to be preferentially carbon-enhanced. Conversely, if dust-induced cooling operates efficiently, it becomes possible to form stars with both low iron and low carbon abundances, yielding objects with genuinely minimal total metallicity. Distinguishing between these regimes observationally requires moving beyond iron abundance as the sole diagnostic of chemical primitiveness. Total metallicity, which accounts for all heavy elements and dust content, provides a more physically meaningful measure of cooling capability. In this context, stars with suppressed carbon and oxygen abundances represent particularly stringent tests of star formation theory, as their existence directly constrains the minimum conditions under which low-mass stars can form. This theoretical framework establishes the motivation for the comparative analysis presented in the following section. By comparing iron abundances, carbon enhancement, and inferred total metallicities across the most metal-poor stars known, we assess which cooling pathway is most consistent with the empirical record of stellar survivors from the early Universe. A schematic overview of cosmic evolution, highlighting the transition from the cosmic dark ages to the formation of the first stars and galaxies, is shown in Figure 1.

## Meta-analysis of the Lowest-Metallicity Stars

To test the theoretical expectations outlined in the previous sections, we compiled a curated dataset of the lowest-metallicity stars currently known. Our aim is not to produce an exhaustive catalog, but rather to focus on a small number of well-studied objects whose chemical abundances provide stringent constraints on the physical conditions of early star formation.



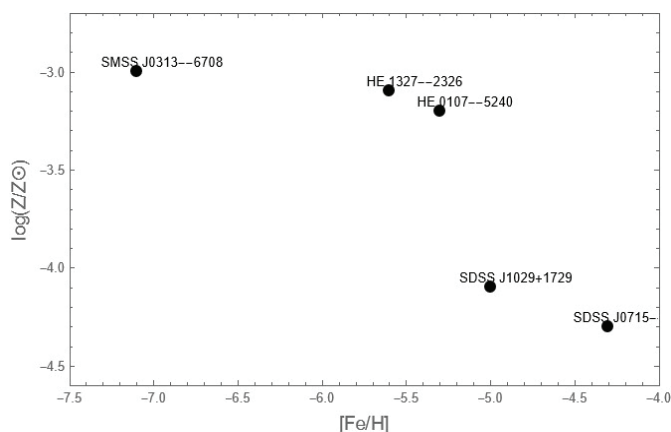
**Figure 1:** Schematic illustration of cosmic evolution from the Big Bang to the formation of the first stars and galaxies.

These stars represent the most chemically primitive survivors of the early Universe and serve as direct empirical probes of the transition from primordial to modern star formation. Traditionally, the chemical primitiveness of stars has been assessed primarily through their iron abundance, expressed as  $[Fe/H]$ . While this metric is observationally convenient, it does not necessarily reflect the total metal content of a star, particularly in cases where individual elements such as carbon or oxygen are strongly enhanced. As discussed in Section 3, cooling efficiency depends on the overall metal and dust content rather than on iron alone. We therefore emphasize total metallicity,  $Z$ , as the physically relevant quantity for evaluating star formation pathways. Table 1 summarizes key

**Table 1:** Representative sample of the lowest-metallicity stars known.

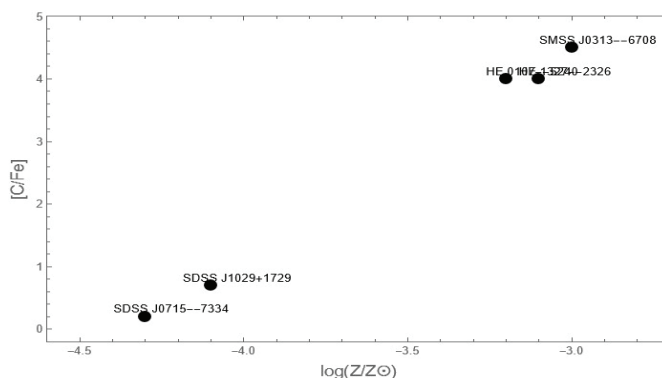
Star	[Fe/H]	[C/Fe]	$\log(Z/Z_{\odot})$	Environment
SMSS J0313-6708	-7.1	4.5	-3.0	MW halo
HE 1327-2326	-5.6	4	-3.1	MW halo
HE 0107-5240	-5.3	4	-3.2	MW halo
SDSS J1029+1729	-5.0	0.7	-4.1	MW halo
SDSS J0715-7334	-4.3	< 0.2	< -4.3	LMC halo

Abundance parameters for a representative subset of the most metal-poor stars known to date. The sample includes classical ultra-metal-poor stars in the Milky Way halo, as well as the recently discovered object SDSS J0715-7334 associated with the halo of the Large Magellanic Cloud [6]. For each star, we list iron abundance, carbon enhancement, and an estimate or upper limit on total metallicity inferred from available elemental measurements. A comparison of iron abundance with total metallicity reveals a striking pattern. Several of the most iron-deficient stars, such as SMSS J0313-6708 and HE 1327-2326, exhibit extreme carbon enhancement, resulting in total metallicities significantly higher than their iron abundances alone would suggest. These stars therefore lie above the canonical fine-structure cooling threshold despite their extraordinarily low [Fe/H] values. In contrast, SDSS J0715-7334 [6] displays both low iron and suppressed carbon, yielding one of the lowest total metallicities currently known for any star.



**Figure 2:** Iron abundance versus total metallicity for the lowest-metallicity stars known.

Carbon-enhanced stars occupy a regime of elevated total metallicity despite extremely low [Fe/H], while SDSS J0715-7334 lies in a distinct region characterized by both minimal iron and minimal carbon. The plotted abundances are compiled from literature sources [4-6]. This distinction is illustrated in Figure 2, which plots [Fe/H] against  $\log(Z/Z_{\odot})$  for the stars in our sample. While most objects cluster along a trend in which carbon enhancement elevates total metallicity, SDSS J0715-7334 occupies a distinct region characterized by exceptionally low total metallicity. This position makes it a uniquely powerful constraint on star formation theory, as its existence cannot be easily explained by fine-structure cooling alone.



**Figure 3:** Carbon enhancement as a function of total metallicity for representative ultra-metal-poor stars.

Most objects exhibit strong carbon enhancement despite extremely low iron abundances, whereas SDSS J0715-7334 displays suppressed carbon abundance at the lowest inferred total metallicity. The plotted abundances are compiled from literature sources [5, 6]. The relation between carbon enhancement and total metallicity for the ultra-metal-poor stars considered in this study is illustrated in Figure 3. Taken together, these results demonstrate that the lowest iron abundance does not necessarily correspond to the lowest total metallicity. Many of the most iron-deficient stars remain substantially enriched in carbon and oxygen, implying that their cooling histories were governed by total metal content rather than by iron abundance alone. Truly primitive stellar survivors are therefore characterized by simultaneously low iron and suppressed carbon abundances. The rarity of such objects suggests that low-mass star formation at extremely low metallicity was possible but highly inefficient, consistent with theoretical expectations for dust-induced fragmentation. The existence of SDSS J0715-7334 in this regime provides a particularly important empirical constraint on models of early star formation and establishes a direct observational link between the chemical conditions of the Cosmic Dawn and the surviving stellar fossil record observed in the Local Group.

## Case Study: SDSS J0715-7334

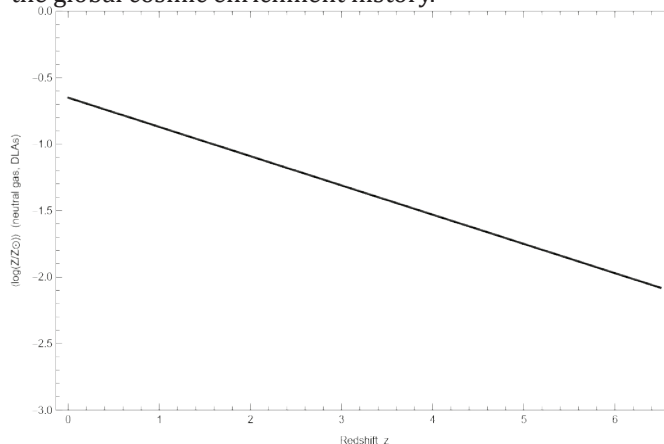
The star SDSS J0715-7334 [6] represents one of the most chemically primitive stellar objects currently known and provides an important empirical constraint on models of early star formation. Identified in the course of large spectroscopic surveys and subsequently analyzed in detail, this red giant exhibits both extremely low iron abundance

and a striking absence of carbon enhancement. Its chemical properties distinguish it sharply from the majority of previously known ultra-metal-poor stars. Spectroscopic analysis yields an iron abundance of approximately  $[\text{Fe}/\text{H}] \approx -4.3$ , placing SDSS J0715-7334 among the most iron-deficient stars observed. Unlike many comparably metal-poor objects, however, it shows no significant carbon enhancement relative to iron; its upper limit on  $[\text{C}/\text{Fe}]$  is close to the solar carbon-to-iron ratio. Consequently, its absolute carbon abundance remains extremely low. As a result, its inferred total metallicity falls below  $\log(Z/Z_{\odot}) \approx -4.3$ , making it among the lowest- $Z$  stars currently known. This combination of low iron and suppressed carbon is exceptionally rare and places SDSS J0715-7334 in a distinct chemical regime. Kinematic analysis indicates that the star is associated with the halo of the Large Magellanic Cloud rather than the Milky Way. This finding is significant, as it demonstrates that chemically primitive stellar survivors are not confined to the Galactic halo but can also persist in satellite systems with different star formation histories.

The presence of such an object in the LMC halo suggests that pockets of extremely low-metallicity gas survived in multiple environments during the early stages of galaxy assembly. The detailed abundance pattern of SDSS J0715-7334 is consistent with enrichment by a single or small number of core-collapse supernovae with progenitor masses of order 20–40  $M_{\odot}$ . The absence of strong carbon enhancement disfavors enrichment by faint supernovae or mixing-and-fallback explosions, which are commonly invoked to explain carbon-rich ultra-metal-poor stars. Instead, the observed chemical signature is more naturally explained by relatively normal supernova yields diluted into a very small mass of gas. From the perspective of cooling physics, SDSS J0715-7334 is broadly consistent with dust-induced star formation at extremely low metallicity. Given its minimal carbon and oxygen content, fine-structure line cooling alone may have been insufficient to enable efficient fragmentation in its parent gas cloud. The existence of a long-lived, low-mass star in this regime is therefore consistent with a scenario in which dust grains supplied the dominant cooling channel at high densities, allowing collapse and fragmentation even when total metal content was extremely low. More broadly, SDSS J0715-7334 serves as a critical benchmark for interpreting claims of chemically primitive stellar populations in high-redshift galaxies. Its total metallicity lies below that inferred for many galaxies observed at  $z \gtrsim 7$ , indicating that star formation can persist at levels well below current extragalactic detection limits. As such, this object provides a local calibration point for the physical meaning of “pristine” in both nearby and distant astrophysical contexts.

### Implications for High-Redshift “Pristine” Claims

Figure 4 places these local chemical fossils in the context of the global cosmic enrichment history.



**Figure 4:** Cosmic enrichment history of neutral gas traced by damped Ly $\alpha$  absorbers (DLAs) showing the decline of the cosmological mean metallicity with increasing redshift.

The curve is based on the empirical fit [7], and the local chemical fossil SDSS J0715-7334 is shown for comparison. The results presented in the preceding sections have direct implications for the interpretation of metal-poor stellar populations in high-redshift galaxies. Recent observations with the James Webb Space Telescope (JWST) have reported the detection of galaxies at redshifts  $z \gtrsim 7$  whose spectral properties suggest extremely low metallicities, raising the possibility that Population III or nearly pristine star formation may be observable at cosmological distances. However, translating such observations into physical constraints on star formation requires careful consideration of what is meant by “pristine” in an observational context. In extragalactic studies, metallicity estimates are typically inferred from integrated nebular emission lines, such as oxygen and hydrogen recombination features. These diagnostics are sensitive primarily to a small subset of elements and may not capture the full metal or dust content of the underlying star-forming gas. As demonstrated by the local stellar fossil record, low iron or weak oxygen emission does not necessarily imply minimal total metallicity. Carbon enhancement or dust enrichment can significantly elevate cooling efficiency even when traditional metallicity tracers appear suppressed. The existence of SDSS J0715-7334 provides an important local calibration point for interpreting chemically primitive systems at high redshift. Its inferred total metallicity lies below that estimated for many of the most metal-poor galaxies currently detected at high redshift, yet it formed a long-lived, low-mass star. This suggests that star formation can proceed under chemical

conditions substantially more primitive than those currently accessible through extragalactic observations and that weakly enriched systems may, in some cases, mimic genuinely pristine environments when observed through integrated spectral diagnostics alone.

Our results therefore suggest that claims of Population III or near-primordial star formation based solely on low inferred metallicity should be interpreted with caution. Without independent constraints on carbon abundance, dust content, or detailed chemical patterns, it remains difficult to distinguish between truly metal-free star formation and dust-mediated second-generation star formation. In this sense, the local stellar fossil record currently provides some of the most stringent empirical constraints on primordial star formation physics available from observations. Looking forward, the framework developed here offers clear predictions for future surveys. If dust-induced cooling dominates the formation of the first low-mass stars, then the rarest and most informative stellar fossils should be those with simultaneously low iron and suppressed carbon abundances. Next-generation spectroscopic surveys targeting the faint outskirts of the Milky Way, the Magellanic Clouds, and ultra-faint dwarf galaxies should therefore prioritize the identification of such chemically minimal objects. In parallel, improved modeling of dust formation and survival in early supernovae will be essential for interpreting both local and high-redshift observations within a unified physical framework.

### Conclusion

In this work, we have presented a focused synthesis linking the physics of early star formation during the Cosmic Dawn to a small but decisive set of surviving ultra-metal-poor stars in the Local Group. By emphasizing total metallicity rather than iron abundance alone, we have shown that the most chemically primitive stellar survivors are not necessarily those with the lowest  $[\text{Fe}/\text{H}]$ , but rather those with simultaneously suppressed abundances of carbon and other cooling agents. Our meta-analysis demonstrates that many of the most iron-deficient stars known are, in fact, significantly enriched in carbon, placing their total metallicities above the canonical fine-structure cooling threshold. In contrast, SDSS J0715-7334 occupies a unique chemical regime characterized by both low iron and low carbon, yielding the lowest total metallicity currently measured for any star. Its existence provides a direct empirical constraint on the minimum conditions required for low-mass star formation. The chemical and

kinematic properties of SDSS J0715-7334 are broadly consistent with scenarios in which dust-induced cooling played an important role in enabling fragmentation at extremely low metallicity.

This result supports theoretical models in which even trace amounts of dust produced by early supernovae can regulate the transition from primordial, massive star formation to the long-lived, low-mass stellar populations that dominate the present-day Universe. More broadly, this study highlights the power of local stellar fossils as physical laboratories for early-Universe astrophysics. While high-redshift observations offer invaluable insights into the first galaxies, the detailed chemical information preserved in nearby ultra-metal-poor stars provides some of the most stringent empirical tests of primordial star formation theories currently available. Future surveys that systematically target chemically minimal stars in the outskirts of the Milky Way, the Magellanic Clouds, and ultra-faint dwarf galaxies will play a central role in refining our understanding of how the first generations of stars shaped cosmic evolution. Ultimately, the evolution of stars from the Cosmic Dawn to the present age is encoded not only in distant galaxies, but also in a handful of ancient survivors orbiting our own. These objects represent the closest and most direct empirical link to the birth of starlight in the Universe.

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# Digital Journal of Science (DJS)

## Declaration of Interests

The author declares no competing financial or non-financial interests.

## Declaration of Generative AI and AI-Assisted Technologies

During the preparation of this work, the author used generative AI tools, including ChatGPT, DeepSeek, and Perplexity, for reasoning and drafting support. After using these services, the author reviewed, edited, and verified all content as needed and takes full responsibility for the accuracy and integrity of the publication.

## Ethics, Consent to Participate and Consent to Publish

Not applicable.

## Author Contributions

The author collected data regarding the Length of Day (LOD) from popular science literature by Isaac Asimov, George Gamow, and Carl Sagan. Following the NASA press release on the Silver Jubilee Anniversary of the Moon landing (20 July 1994), reporting that the Moon has receded by approximately 1 m in the preceding 25 years, the author reanalyzed the Earth–Moon system and presented the results at the 82nd Session of the Indian Science Congress (Jadavpur University, Kolkata, 1995). Subsequently, the author presented the Kinematic Model of the Earth–Moon system at the World Science Congress (Houston, 2002). In 2004, at the 35th Scientific Assembly of COSPAR, the author presented a new perspective on the birth and evolution of the Solar System and exoplanetary systems. In 2012, at the 39th Scientific Assembly (Mysore, India), the paper “Iapetus sub-satellite revisited and it reveals the celestial body formation in the Primary-Centric Framework” (B03-0011-12) was presented.

In 2017, at CELMEC VII (Rome), the advanced Kinematic Model of the Earth–Moon system was presented and subsequently published in the *Journal of Geography and Natural Disasters*, demonstrating a close match between observed and theoretical LOD curves. Further related studies on the Earth–Moon system and its habitability were published in JMTCM. Subsequent work extended the Primary-Centric Framework to stellar and exoplanetary systems, including stars near Sagittarius A\*,

the 51 Pegasi system, the WASP-12 system, and several other exoplanetary systems, which are currently under peer review. The present paper continues this research program by applying the framework to early stellar evolution and chemically primitive stellar systems.

## Data Availability

The data underlying this article are available within the article and in its online supplementary material. All figures in this paper were generated by the author using published observational data and empirical relations.

## Clinical Trial Registration

Not applicable.

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