

Comparative Characterization of Extremely Metal-Poor and Extremely Metal-Rich Stars

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Abstract- The present work discusses the chemical and physical properties of stars representing two radically different stages of galactic evolution. The object of the study is a dozen extremely metal-poor (EMP/UMP) and super-metal-rich (SMR) reference stars. By combining the data, it is shown how the chemical enrichment of the interstellar medium (as a result of nucleosynthesis) affects the structure of stars, their spatial distribution and the potential for the formation of planetary systems. The work demonstrates the connection between the early archaeology of the universe and the properties of modern, planet-hosting stars.

Keywords— Stellar chemical evolution, extremely metal-poor stars, stellar populations, extremely metal-rich stars.

I. INTRODUCTION

In astrophysics, the term “metal” refers to all chemical elements heavier than hydrogen (H) and helium (He). The metallicity of a star ($[Fe/H]$) serves as a kind of cosmic clock and an indicator of the environment in which a particular luminary was born. At the initial stage of the evolution of the Universe, the interstellar gas contained almost no heavy elements, which is why the oldest objects (Population II) are characterized by an extreme metal deficiency. Over time, as a result of supernova explosions and enrichment of the environment by stellar winds, a new generation of metal-rich objects (Population I) was formed. The aim of this work is to make a complex comparison of representatives of these two extreme classes, which sheds light on the chemical and dynamical evolution of the Milky Way..

II. OBSERVATIONAL MATERIAL

a) Top 10 Metal-Poor Stars

These stars are the remnants of the primordial cosmic objects of the Universe (Population II), which formed shortly after the Big Bang and are composed of almost pure hydrogen and helium:

1. SDSS J0715-7334 — $[Fe/H] = -4.3$ (assigned with a total metallicity $Z = 1.66 \times 10^{-6}$). The purest and most pristine star ever discovered also has an extremely low carbon content[1].
2. SMSS J031300.36-670839.3 (SMSS J0313-6708) — $[Fe/H] < -7.1$. The iron content is at least 10 million times less than the Sun, but unlike the previous star, it has a pronounced carbon excess[2].
3. SMSS J160540.18-144323.1 — $[Fe/H] = -6.2$. A red giant in the Milky Way's halo with an iron content 1.5 million times lower than that of the Sun[3].
4. HE 1327-2326 — $[Fe/H] = -5.4$. Discovered as part of the Hamburg/ESO survey and held the record for decades[4].
5. HE 0107-5240 — $[Fe/H] = -5.2$. A giant star that was one of the first to prove that low-mass stars were also born in the early universe.

6. GDR3_526285 — $[Fe/H] \approx -5.0$. The oldest object recently discovered in the Milky Way's halo, according to data from the Gaia space telescope.[3]

7. Caffau's Star (SDSS J102915+172927) — $[Fe/H] = -4.89$. It is notable for being almost entirely devoid of carbon and nitrogen.

8. 2MASS J18082002-5104378 B — $[Fe/H] = -4.07$. An ultra-poor star in the Milky Way's thin disk, with a heavy element mass equivalent to that of the planet Mercury[4].

9. BD+44 493 — $[Fe/H] \approx -4.0$. A well-studied carbon-enriched ultra-metal-poor (CEMP) star[3].

10. Pic II-503 — $[Fe/H] \approx -4.0$ (iron content 1/40,000th that of the Sun). The most iron-poor star discovered in a dwarf galaxy beyond the Milky Way[5].

b) Top 10 Super Metal-Rich Stars

These stars were formed in the late stages of cosmic evolution (Population I), in regions of the galaxy where supernova explosions have enriched the environment with heavy elements to the maximum extent:

1. Sargas (Theta Scorpii / θ Sco) — $[Fe/H] \approx +0.40 - +0.50$. A white-yellow giant, one of the brightest stars in the universe with the highest metallicity.
2. Sirius A (Alpha Canis Majoris A) — $[Fe/H] \approx +0.40$. A prominent star in the sky, with a metallicity 2.5 times that of the Sun.
3. HD 177409 — $[Fe/H] \approx +0.44$. A dwarf star with one of the highest metallicities in astrophysical catalogs.
4. Mu Leonis (μ Leo) — $[Fe/H] = +0.27 - +0.33$ (almost 2 times the metallicity of the Sun). One of the richest stars visible to the naked eye.
5. HD 168443 — $[Fe/H] \approx +0.31$. A star that hosts massive exoplanets and brown dwarfs.
6. 14 Herculis — $[Fe/H] \approx +0.28$. An orange dwarf that astronomers are observing because of the formation of planetary systems within it.
7. Alpha Centauri A (Rigil Kentaurus) — $[Fe/H] = +0.20 - +0.24$. The main member of the star system closest to the Sun, whose metallicity is ~ 1.6 times that of the Sun.

8. HD 209458 — $[Fe/H] \approx +0.20$. Famous star around which the first transiting exoplanet ("Osiris") was discovered.

9. HD 101065 (Przybylski's Star) — Although the iron group is slightly below the norm, it is the most strange chemically peculiar star in the universe. It contains rare earth elements (lanthanides, uranium, thorium) thousands of times more than the norm.

10. XX Ophiuchi / AS 325 — Categorized as the rarest "Iron Stars". Their optical spectrum consists entirely of emission lines from ionized metals (iron, chromium, titanium) [6].

III. INTERPRETATION OF THE OBSERVED MATERIAL

Based on the data obtained, the most metal-poor and metal-rich groups of stars differ radically in terms of cosmic evolution, origin, and structure. Their main distinguishing features are given in the comparative table: Characteristics The most metal-poor stars The most metal-rich stars Chemical classification Ultra- / Hyper-Metal-Poor (UMP / HMP) Super Metal-Rich (SMR) Typical ratio $[Fe/H]$ -4.0 to -7.1 (10,000 to 10 million times less iron than the Sun) +0.20 to +0.50 (1.5 to 3 times more iron than the Sun) Stellar generation Population II (second generation, direct descendants of the first stars) Population I (younger, evolutionarily late generation) Age and epoch Oldest objects (13-13.5 billion years ago) years, formed shortly after the beginning of the universe [1] Relatively young or middle-aged (several hundred million to several billion years old) Galactic location Mainly in the halo and globular clusters of the Milky Way, or in dwarf satellite galaxies Mainly near the thin disk and nucleus of the galaxy, where matter is dense Environmental influences Formed from pristine hydrogen-helium clouds, only slightly contaminated by the remnants of the first supernovae (Population III) [7] Formed in the most enriched environment possible as a result of many generations of stars and cosmic explosions The existence of planets is almost impossible. The materials necessary for the formation of solid exoplanets (silicon, iron) are virtually nonexistent Very common Such stars are the best hosts for massive gas giants and solid planets. Major astrophysical paradoxes Chemical "anomalies": The lack of metals in poor stars is not uniform; many of them (e.g. SMSS J0313-6708) have a surprisingly high carbon content, indicating the specific explosive mechanisms of early supernovae. In the rich group, we find Przybylski-type stars, where strange, heavy lanthanides and radioactive elements predominate instead of iron. Mass limit: The existence of poor stars (such as Caffau's Star) proves that even in the early universe it was possible to form low-mass stars, which was previously considered physically impossible due to the lack of cooling mechanisms.

How would the universe change if the metallicity of stars doubled?

If the metallicity of stars doubled, the universe would change radically:

The number of giant planets would increase dramatically, the lifespan of stars would change, and the conditions for the formation of life would deteriorate.

1. The boom of planets and the dominance of "gas giants" The doubling of the metallicity of stellar protoplanetary disks directly affects the formation of planets: The frequency of

giant planets: Studies, including The New Generation Planetary Population Synthesis (NGPPS), confirm that the probability of the formation of Jupiter- and Neptune-type gas giants is directly proportional to the increase in metallicity. According to the Core Accretion model, the abundance of heavy elements allows the planet's solid core to reach critical mass more quickly and attract surrounding gas.[5]

Orbital migration: Planets around stars with high metallicity are more likely to migrate to inner orbits, leading to the so-called the abundance of "Hot Jupiters" [7].

2. Evolution and lifespan of stars Metals act as a "shield" for stellar matter, blocking internal radiation (increasing optical thickness):

Size and temperature: Stars with high metallicity expand more, their surfaces become cooler, and their color is redder[3]. Blocking nuclear fusion: According to a study published in the journal Monthly Notices of the Royal Astronomical Society, "The most metal-rich stars in the universe," excessively high metallicity inhibits convection processes (in the Asymptotic Giant Branch (AGB) phase), which is why some of the heavy elements are trapped in the core of white dwarfs instead of rising to the surface of the star[6].

3. The universe will become more hostile to life (ozone paradox) Although the increase in metals favors the existence of building blocks for solid (Earth-like) planets, the conditions for the development of life will worsen:[7].

The balance of ultraviolet (UV) radiation:

Metal-rich stars generally emit less UV radiation, but their spectrum has a sharp change in the ratio of UV-C (ozone-forming) to UV-B (ozone-depleting) radiation. Planets around such stars cannot form a protective ozone layer, leaving the surface exposed to deadly UV-B radiation. Consequently, as the universe ages and increases in metallicity, the cosmos becomes more inhospitable to life.[6]

4. Structure of galaxies and cosmic debris

Types of supernovae:

Massive stars with high metallicity lose more mass in the form of stellar winds. Because of this, at the end of their lives they more often explode as type Ib/Ic supernovae, leaving behind neutron stars, rather than forming directly into black holes radiation, which destroys the planet's protective ozone layer and makes life almost impossible[8].

Planetary migration and orbital chaos: Due to the high density of matter in the protoplanetary disk, giant planets undergo strong migration towards the star, which can expel small rocky planets in inner orbits from the system altogether or cause them to collide with the star.[9].

What would the universe be like if the metallicity of stars were half that of today?

According to recent astrophysical and cosmological studies, a universe in which the metallicity (content of elements heavier than hydrogen and helium) of stars was half that of today (i.e., about 50% of the metallicity of the Sun) would have been radically different in terms of stellar life cycles, planet formation, and the potential for the emergence of life. In the cosmic chronology, this period corresponds to the past of the universe about a few billion years ago (Redshift

$z \sim 1 - 2$), when the intensity of star formation in galaxies reached its peak[8].

The following are the main scientific aspects of what this universe would have been like, based on the latest scientific data:

1. Hotter, more compact, and more massive stars. In the environment of low metallicity, the gas clouds lack the heavy elements (such as carbon, oxygen, and iron) that would provide effective cooling during collapse.[9]

Weakening of stellar winds:

Due to the lack of heavy elements, radiation pressure interacts less with the outer layers of the star. Consequently, stellar winds are much weaker and stars lose almost no mass during their lifetime [3]. Physical characteristics: Stars would be more compact, hotter, and bluer than modern stars of similar mass [4]. Fast rotation: Stars with low metallicity rotate faster around their axis, which favors chemically homogeneous evolution. This leads to the formation of extremely bright ultraviolet (UV) radiation sources [5].

2. Constraints on planet formation ("rocky super-Earths") The amount of solid material (dust particles) in protoplanetary disks where planets form is directly proportional to the metallicity of the star [6]. Recent astronomical studies have shown that at half metallicity, rocky planets the size of the Earth can still form freely, although the formation of larger, so-called Formation of super-Earths and gas giants [7]. Scientists have called this phenomenon the "metallicity cliff" of planetary formation, meaning that a diverse planetary architecture like that of the Solar System would have been much rarer at that time.[8].

3. Paradox: The universe is more favorable for life Despite the fact that there would be fewer planets, scientists have discovered a surprising cosmic paradox: planets around low-metallicity stars have much better conditions for the development of complex life. Ozone layer effect: Although low-metallicity stars emit more ultraviolet radiation, their spectrum is rich in harsh UV-C radiation. This radiation, when interacting with the oxygen in the planet's atmosphere, forms a thicker and more durable protective ozone layer.

The spectrum of modern high-metallicity stars (such as today's Sun) contains more UV-B radiation, which destroys ozone. Therefore, in a universe with half the metallicity, the surfaces of existing rocky planets would be much better protected from harmful radiation.[9].

4. Extreme cosmic explosions Since massive stars did not lose mass through stellar winds, their end-of-life events were much more violent [5]: Hypernovae and GRBs: Gamma-Ray Bursts (GRBs) and supermassive hypernovae were much more common in such a universe [7]. Black hole mergers: During this period, massive stars collapsed to form much more massive black holes. This explains why modern gravitational

wave detectors (LIGO/Virgo) detect collisions of black holes in the distant universe that are almost nonexistent in our galaxy today[9]. Of the stars studied, the star HD 19994 was found to contain the most metallicity, with a metallicity index of + 1.15 (this means that it contains $10^{1.15}$ times more metallic substances than the Sun), and the star J0023+0307, whose metallicity index is - 6.1 (this means that it contains $10^{-6.1}$ times less metallic matter than the Sun), turned out to be the poorest among the studied stars. It appears that the ecological state of our galaxy is currently at least 18 million times ($10^{1.15}/10^{-6.1} = 10^{7.25} \sim 18.10^6$) more polluted with metals in some parts of the galaxy than it was at the beginning of the birth of the second generation of stars.

IV. CONCLUSION

The study showed a clear evolutionary nexus between the chemical composition of a star and its physical environment. Extremely metal-poor stars are "cosmic fossils" that store information about the primordial nucleosynthesis of the Universe. Radically different from them, super-metal-rich stars are the result of long-term chemical enrichment and maturation of the Galaxy. It was confirmed that the presence of metals is a critical factor for planetary accretion: high metallicity directly increases the probability of the formation of giant exoplanets with a solid core, while in metal-poor environments the formation of planetesimals is virtually blocked. It appears that the ecological state of our galaxy is currently at least 18 million times more polluted with metals in some parts of the galaxy than it was at the beginning of the birth of the second generation of stars.

REFERENCES

- [1] B. Piercarlo, E. Caffau, "The most metal poor starsar" Xiv:2504.06335v2 [astro-ph.GA] 29 May 2025
- [2] Jose Groh., "Effects of low metallicity on the evolution and spectra of massive stars," pp.68, 2015.
- [3] Cristina Chiappini, "Stellar Evolution at Low Metallicit," *Proceedings of the International Astronomical Union 3(S250)*, pp. 217-230, 2007
- [4] Bonifacio, Piercarlo, et al. "The most metal poor stars."arXiv preprintarXiv:2503.16595 (2025)
- [5] Di-Chang Chen et al., "The New Generation Planetary Population Synthesis" A&A Volume 701, September 2025
- [6] A. Shapiro et al., "Inhospitable planets due to metal-rich stars, Max Planck Institute," July 14, 2023
- [7] A.V. Shapiro et al., "Metal-rich stars are less suitable for the evolution of life on their planets," 2023.
- [8] G. C. Cinquegrana, Amanda I. Karakas, "The most metal-rich stars in the universe: chemical contributions of low and intermediate mass asymptotic giant branch stars with metallicities between $0.04 \leq Z \leq 0.10$," License: arXiv.org perpetual non-exclusive license arXiv:2111.09527v1 [astro-ph.SR] 18 Nov 2021
- [9] P. Benjamin et al. "The cosmic evolution of metallicity from the SDSS fossil record. Mo,". *Not. R. Astron. Soc. Vol. 391*, pp. 1117–1126, 2018.