

TYC 170–1218–1: A new r-process-enhanced extremely metal-poor star, rich in Th. [★]

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ABSTRACT

Context. Extremely metal-poor (EMP) stars are formed from gas clouds enriched by one or a few supernova explosions belonging to the first stellar generation and this very limited number of sources of metal enrichment is suitable to produce peculiar chemical patterns that give birth to stars with anomalous chemical composition. Among the EMP stars, r-II stars are characterised by an over-abundance of the heavy elements with respect to iron.

Aims. In the search for apparently young, metal-poor stars, we serendipitously selected TYC 170–1218–1, which turned out to be an EMP star, enhanced in neutron capture elements over iron. Our aim is to obtain a detailed chemical inventory for this exceptional object.

Methods. We investigated high-resolution spectra observed with UVES at the VLT telescope and Mike at the Magellan Clay telescope. We derived the abundance of 33 elements using the MyGIsFOS code and an ATLAS 9 model atmosphere.

Results. The star is an EMP with $[\text{Fe}/\text{H}] = -3.52$. It is enhanced in the α elements, as EMP stars usually are. It is an r-II star with $[\text{Eu}/\text{Fe}] = +1.84$ and $[\text{Th}/\text{Fe}] = +1.85$. The star is also poor in carbon with respect to iron. The quality of the spectra was insufficient for us to detect uranium. Kinematically the star belongs now to the Galactic halo, but it joined the Milky Way during the Sequoia accretion event.

Key words. Stars: abundances - Galaxy: abundances - Galaxy: evolution - Galaxy: formation

1. Introduction

Metal-poor (MP) stars are precious witnesses of the early chemical evolution of our Galaxy. The class of extremely metal-poor (EMP) stars that includes all the stars with $-4 \leq [\text{Fe}/\text{H}] < -2.8$ (Bonifacio et al. 2025), has been polluted very little by the chemical elements produced in supernovae, neutron star mergers, and any other event that contributes to the chemical build-up of the early Galaxy. The small number of polluters in the EMP regime is responsible for the large variety of chemical patterns in the heavy elements of EMP stars.

The elements lighter than iron are expected to be produced in the stellar interiors through nuclear fusion reactions, while the elements heavier than the iron peak are synthesised through neutron captures (see e.g. Sneden et al. 2008; Arcones & Thielemann 2023). The neutron captures can occur at different rates depending on the neutron density: *i*) slow, *s* process, that is the time between two neutron captures is longer than the time for β decay of the produced nucleus, for neutron densities of $n \approx 10^5 \text{ cm}^{-3}$; *ii*) intermediate, *i* process with neutron densities in the range of $10^{14} - 10^{16} \text{ cm}^{-3}$; *iii*) rapid, *r* process with neu-

tron densities of $> 10^{23} \text{ cm}^{-3}$ (Cowan & Rose 1977). In both the *i*- and *r*-process, several neutrons can be captured before the nucleus produced by the previous capture has time to β decay. The sites of the *r* process are widely debated (Arcones & Thielemann 2023), the main candidates being neutron star mergers, supernovae, neutrino-driven winds, and jets in highly rotating supernovae. Recently Wanajo et al. (2024) proposed neutron star-black hole mergers as a viable source of both solar-like *r*-process patterns and actinide boost patterns, the latter for a large enough electron fraction (proton number per nucleon), $Y_e > 0.05$, in the dynamical ejecta of the merger.

Europium is an almost pure r-process element ($\sim 95\%$ is from the r-process; (Sneden et al. 2008)) and the fact that in the MP regime $[\text{Eu}/\text{Fe}]$ spans almost 4 dex means that substantially diverse chemical enrichments through the r process characterised the young Universe. Based on the europium abundance, Christlieb et al. (2004) classified MP stars as r-I ($0.3 < [\text{Eu}/\text{Fe}] < 1.0$ and $[\text{Ba}/\text{Eu}] < 0$) and r-II ($[\text{Eu}/\text{Fe}] > 1.0$ and $[\text{Ba}/\text{Eu}] < 0$). The number of EMP r-II stars, according to this classification, is limited, but they are not really rare objects (several tens in the SAGA database, Suda et al. 2008, are available). Another possible classification is provided by Holmbeck et al. (2020) for r-I ($0.3 < [\text{Eu}/\text{Fe}] \leq 1.0$ and $[\text{Ba}/\text{Eu}] < 0$) and r-II

[★] Based on observations made with UVES at VLT 112.25EH.001 and with Mike at the Magellan Clay telescope.

([Eu/Fe] > 0.7 and [Ba/Eu] < 0) stars, but we find it safer, in the discussion of r-II stars, to keep the classification by Christlieb et al. (2004).

The abundances of the radioactive actinide elements (with an atomic number in the range of 89-102) are difficult to derive from the stellar spectra, especially in the MP and EMP regimes, because they have a low abundance, and their absorption lines in the spectrum are often too weak to be detected. Just a few EMP stars with a Th abundance determination are known; the majority of them show [Th/Fe] > 1 (see e.g. Placco et al. 2023) and a subsample of these stars also have a U abundance determination. Clearly an enhancement in Th and U makes it possible to derive their abundances in the EMP regime (see e.g. Hill et al. 2002). The mechanism that produces this enhancement can be the same as the one that makes the star an r-II, but there can be an extra channel (a boost) to enrich the actinides further than with the r process. Th-rich stars are the only MP stars among which it has been possible to measure the abundance of uranium and for which an age estimate was made using the U/Th ratio (see e.g. Ludwig et al. 2010). Since the U/Th production ratio is much less sensitive to the physical conditions under which the r process takes place than the Th/Eu production ratio, it is important, for any star with a Th enhancement, to have a spectrum quality, both in terms of spectral resolution and the signal-to-noise ratio (S/N), sufficient to derive the U abundance. We here investigate high-spectral-resolution spectra of the star TYC 170–1218–1, which is strongly enhanced in all neutron capture elements (making it an r-II star) and also strongly enhanced in Th.

2. Observations and analysis

We analysed one 3000s UVES (Dekker et al. 2000) spectrum of TYC 170–1218–1 observed in the ESO programme 112.25EH.001 (P.I. P. Bonifacio) on the night of December 4 2023. The star was observed in the setting DIC2 437+760, with a slit of 0''.5 in both arms (corresponding to a resolving power of $\sim 70,000$). The spectrum does not show any sign of stellar activity (the profile of H α is regular and no absorption is visible in the core of the Ca II-H and -K lines as shown in Fig. 1). The S/N per pixel is 80 at 400 nm and 100 at 650 nm. The star was targeted because it has a high transverse velocity with respect to the Sun and is in a region of the colour-magnitude diagram that is also populated by MP stars that are apparently young (see Bonifacio et al. 2024, figure 2). Thus the finding that it is an r-II star was serendipitous. The star is contained in the *Gaia* DR3 release (*Gaia* DR3 3116478233336506624; *Gaia* Collaboration et al. 2023) and we used the astrometric and photometric data available.

Recently, we secured three 1200s exposures of TYC 170–1218–1 with Mike at the Magellan Clay 6.5 m telescope on January 31 2026 (P.I. L. Monaco). We used a slit of 0''.7 and 2×2 on-chip binning in both the red and blue arms. This provides a resolving power of 41 500 in the blue arm and 32 500 in the red arm, the bluest orders of the blue arm are slightly undersampled. The blue arm covers the range 334 nm to 499 nm and the red arm the range 484 nm to 915 nm. The three exposures were co-added and the S/N per pixel on the co-added spectrum is 153 at 400 nm and 250 at 650 nm. On March 10 2026, we acquired another spectrum of a 1200s exposure, with Mike, with the same set-up except that the binning was 1×1 . Both the UVES and the two Mike spectra were used to determine the star's radial velocity by template matching using a dedicated synthetic spectrum.

2.1. Kinematics

The radial velocity of TYC 170–1218–1 available in *Gaia* DR3 is $257.46 \pm 0.37 \text{ km s}^{-1}$. The UVES spectrum provides 256.7 km s^{-1} , measured from the spectral range around the IR Ca II triplet, and is therefore similar to the range of the *Gaia* RVs. A model of the terrestrial atmosphere (Lallement et al. 2025) was used to provide a zero point to the measured radial velocity. In the same spectral region and with correction of the zero point, the Mike spectrum of January 31 provides a radial velocity of 256.3 km s^{-1} , while the one of March 10 provides 256.9 km s^{-1} . For both the UVES and the Mike spectrum, we assume an error of 0.5 km s^{-1} dominated by centring the star on the slit, in spite of our zero point correction for the telluric lines. The four radial velocities (**an average Gaia value, one UVES and two Mike**) refer to four different epochs (**2016 Gaia, 2023 UVES, January and March 2026 Mike**) and they show consistency, within the uncertainties.

In order to investigate the star's kinematics, we used the *galpy* code (Bovy 2015), along with its standard potential MW-Potential2014 and the *Gaia* DR3 astrometric parameters and radial velocity. The parallax was zero-point corrected according to the prescriptions of Lindegren et al. (2021).

Figure 2 presents the position of TYC 170–1218–1 (black star) in two widely used kinematic planes: (upper panel) the orbital energy versus the angular momentum and (lower panel) the action diamond. The background population is the 'good-parallax' sample of Bonifacio et al. (2021), where stars are identified as belonging to the halo (blue), the thin disc (red), and the thick disc (green), according to the Bensby et al. (2014) criteria. The shaded green rectangle marks the region where likely Sequoia (Barbá et al. 2019) members are expected to be found according to the criteria defined in Feuillet et al. (2021). As can be seen in Fig. 2, TYC 170–1218–1 belongs to the Galactic halo and more specifically to the Sequoia accretion event. In Fig. 3 the orbit of the star, integrated for the past gigayear, is shown. In the figure, X, Y, and Z are Galactocentric Cartesian co-ordinates, while R is the cylindrical radius, $R = \sqrt{X^2 + Y^2}$. The current position of TYC 170–1218–1 is marked by the filled blue circle, while the position of the Sun is also shown in black.

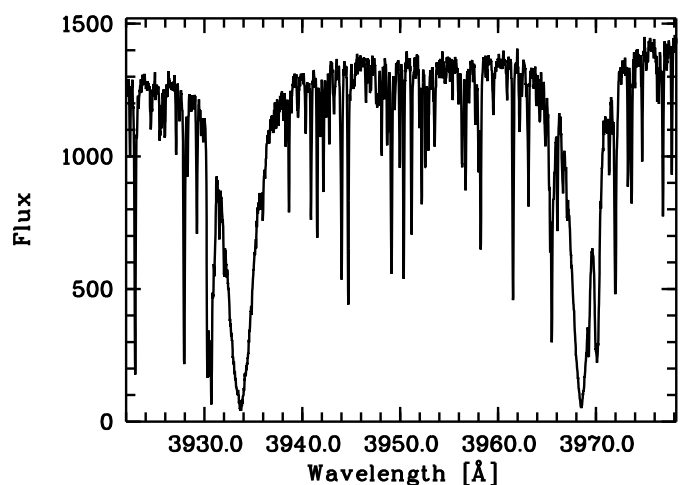


Fig. 1. UVES observed spectrum in the wavelength range of the Ca II-H and -K lines.

2.2. Stellar parameters and chemical analysis

We derived the stellar parameters by using *Gaia* DR3 photometry and the zero-point corrected parallax, as done by Caffau et al. (2024). The reddening ($A_0 = 0.68$) is from the maps by Vergely et al. (2022). The dereddened colour ($G_{BP} - G_{RP}$)₀, compared to synthetic colours from the KOALA database (Mucciarelli et al. 2026), provided the effective temperature (T_{eff}). The surface gravity ($\log g$) was derived by using the Stefan-Boltzmann law with the distance inferred by the zero-point corrected parallax. The uncertainty in the *Gaia* DR3 photometry is so small (0.003 mag in G and 0.005 mag in ($G_{BP} - G_{RP}$)) to be non-influent in deriving the stellar parameters. The *Gaia* DR3 parallax has a relatively small uncertainty (0.229 ± 0.017) that translates into an uncertainty in $\log g$ within 0.06 dex. This is consistent with the perfect balance of the iron abundance, A(Fe), derived from ionised and neutral Fe lines, once the latter have been corrected for departure from local thermodynamical equilibrium (NLTE). In the case in which the zero-point on the parallax is not applied, the $\log g$ is 0.09 dex smaller. By using the calibration by Mucciarelli et al. (2021), the $\log g$ is 0.02 dex larger and the T_{eff} 48 K hotter. We then assume an uncertainty in T_{eff} of 100 K, twice the difference of T_{eff} from the two methods and 0.1 dex in $\log g$.

We adopted a first guess metallicity of -3 to derive the initial stellar parameters. We then updated the metallicity with the value obtained by MyGIsFOS (Sbordone et al. 2014) in the chemical analysis to update the parameters. A detailed description of our iterative procedure can be found in Lombardo et al. (2021). We initially derived the parameters assuming a mass of $0.8 M_{\odot}$, then we used these parameters to determine the age and the mass with the Bayesian inference code SPINs (Lebreton & Reese 2020; Reese & Lebreton 2020), which provided an estimate of the mass as $0.87 M_{\odot}$. We used SPINs with a flat prior on the age of between 0 and 13.8 Gyr, to avoid unphysical ages larger than the age of the Universe. We used the BaSTI evolutionary tracks enhanced by 0.4 dex in the α elements (Pietrinferni et al. 2021). The input parameters were $\log(T_{\text{eff}})$, $\log(L/L_{\odot})$, and $[\text{Fe}/\text{H}]$. The result is (10 ± 2) Gyr. We then re-ran the procedure with the derived mass. The procedure in deriving the stellar parameters and the mass was iterated. The final stellar parameters (see Table 1) are: T_{eff} of 4581 K, $\log g$ of 1.33, and microturbulence of 2.0 km s^{-1} , from the calibration of Mashonkina et al. (2017).

In a first step of the abundance analysis, we used MyGIsFOS in the standard ‘multi-model’ mode (Sbordone et al. 2014) using synthetic grids computed with SYNTHE (Kurucz 2005) using our grid of ATLAS 12 models (Kurucz 2005) covering metallicities from -4.0 to -0.5 in steps of 0.5 dex, effective temperatures from 4000 K to 5200 K in steps of 200 K, surface gravities from 0.5 to 3.0 in steps of 0.5 dex, and α enhancement from -0.4 to $+0.4$ in steps of 0.4 dex. Conscious that the star has a non-solar-scaled abundance pattern, we switched to the ‘single model’ use of MyGIsFOS as described in Caffau et al. (2024). With the final parameters, we computed with Turbospectrum (Alvarez & Plez 1998; Plez et al. 2025) a grid of synthetic spectra (with a single T_{eff} and $\log g$, and three values of microturbulence of 1, 2, and 3 km s^{-1}) by using an ATLAS 9 model that we computed using the parameters (T_{eff} and $\log g$) selected for the star, 1 km s^{-1} microturbulence, $[\alpha/\text{Fe}] = +0.4$, a metallicity of -3.50 , and the opacity distribution function from the KOALA database. In the grid the pivot abundance value for each element, X, was not the solar scaled value but the A(X) value derived from the first ‘multi-model’ run of MyGIsFOS. The process was iterated, changing the pivot values (and recomputing the grid of synthetic

spectra) up to a difference in the derived abundance and the pivot value inferior to the grid abundance step (0.2 dex). The grid was finally recomputed by putting as a pivot for carbon A(C) the value derived from the fit of the **G-band** (see below). The derived abundances are provided in Table 2. The uncertainty (σ) is the line-to-line scatter. For the elements whose abundance is based on a single line, we attributed an uncertainty of 0.15 dex. In the table we provide the NLTE correction and the reference for it. The lines used are provided in a table in electronic form at the CDS. As a sanity check, we ran MyGIsFOS on the Mike spectrum of January 31, and the results were compatible with those of UVES, within less than 1σ for any abundance. We prefer not to combine the two spectra given the different sampling and resolution. We did not run MyGIsFOS on the Mike spectrum of March 10 that has a lower S/N, due to the shorter exposure time.

The star TYC 170–1218–1 is an EMP, enhanced in α elements, as expected, and it is rich in n-capture elements. What is noticeable is the abundance of Eu and Th that are both strongly enhanced ($[\text{Eu}/\text{Fe}] = +1.84$ and $[\text{Th}/\text{Fe}] = +1.85$ in LTE with Fe from ionised lines). In Fig. 4 one line for each of these two elements is shown. In fact, all elements belonging to the second (Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, and Er) or third (Th) peak have $[\text{X}/\text{Fe}] > 1$ (see Table 2), while the elements of the first peak (Sr, Y, Zr) are just slightly enhanced ($0 < [\text{X}/\text{Fe}] < 1$).

Unfortunately, the S/N of our UVES spectrum is not sufficient to detect the U II 385.9 nm resonance line. The Mike spectrum in this wavelength region has a slightly lower S/N than the UVES spectrum. Its lower resolution and undersampling prevent the situation from significantly improving with respect to the UVES spectrum. Even the upper limit we provide for U is not significant (see Fig. 5), since it is higher than the measured $[\text{Th}/\text{Fe}]$, while in all stars in which U has been measured $[\text{U}/\text{Fe}] \leq [\text{Th}/\text{Fe}]$. Further observations are needed to elucidate this point.

Carbon was derived by line profile fitting on the **G-band** (see Fig. 6) and provided $A(\text{C}) = 4.02$, which is lower than expected due to the mixing related to the stellar evolution. In fact, according to Placco et al. (2014), a depletion of about 0.5 dex is expected due to the evolution of this star, while the star has a ratio $[\text{C}/\text{Fe}]$ of almost -1 dex. We were not able to get any insight into the $^{12}\text{C}/^{13}\text{C}$ ratio because the **G-band** is too weak.

3. Discussion

The star TYC 170–1218–1 is: (1) rich in n-capture elements, (2) rich in the actinide element Th, and (3) poor in carbon. Both these two chemical situations are particularly rare. In the EMP regime, just a few stars, the large majority of them more evolved than TYC 170–1218–1, are known with such a low $[\text{C}/\text{Fe}]$. It may be tempting to make the hypothesis that the r-II nature and the low $[\text{C}/\text{Fe}]$ are linked. In fact, some C-poor EMP stars have been analysed by Hansen et al. (2018); they are all more metal-rich, mainly more evolved, and the majority are not so low in $[\text{C}/\text{Fe}]$ as TYC 170–1218–1. The very MP star 2MASS J17045729+3720576 (Bandyopadhyay et al. 2024), an r-II according to Holmbeck et al. (2020) and an r-I according to Christlieb et al. (2004), is even more C-poor than TYC 170–1218–1. These facts may suggest that poor C content is somehow related to the production of r elements. Indeed the spectra of C-poor stars are easily analysed: no or very few CH and CN features contaminate the observed spectra, making easy to derive abundances of heavy elements. We then expect a bias

Table 1. Parameters of TYC 170–1218–1.

<i>Gaia</i> DR3 ID	NAME	T _{eff} K	log g [c.g.s]	VTURB kms ⁻¹	[Fe/H] dex	log(<i>L/L</i> _⊙)	σ _L
311647823336506624	TYC 170–1218–1	4579	1.35	2.01	-3.52	2.63	0.06

Table 2. Abundances of TYC 170–1218–1. For [X/Fe], the iron abundance [Fe/H] is from neutral lines when the abundance A(X) is based on neutral lines, from Fe II lines when A(X) is from ionised lines.

Element	Z	ion	N lines	A(X) _⊙	A(X)	σ	[X/H]	[X/Fe]	NLTE cor	Ref. NLTE
C	6	0		8.50	4.02	0.15	-4.48	-0.96		
Na	11	0	2	6.30	3.24	0.20	-3.06	0.47	-0.35	Alexeeva et al. (2014)
Mg	12	0	5	7.54	4.57	0.13	-2.97	0.55	0.24	Bergemann et al. (2017)
Al	13	0	1	6.47	2.25	0.15	-4.22	-0.69	~ 0.4	Andrievsky et al. (2008)
Si	14	0	1	7.52	4.14	0.15	-3.38	0.14	0.03	Bergemann et al. (2013)
S	16	0	1	7.16	4.62	0.15	-2.54	0.98	-0.20	Takeda et al. (2005)
K	19	0	1	5.12	2.12	0.15	-3.00	0.52	-0.20	Andrievsky et al. (2010)
Ca	20	0	15	6.33	3.22	0.08	-3.11	0.41	0.20	Mashonkina et al. (2017)
Sc	21	1	3	3.10	-0.21	0.01	-3.31	-0.05		
Ti	22	0	9	4.90	1.68	0.07	-3.22	0.30		
Ti	22	1	30	4.90	1.93	0.09	-2.97	0.29	0.03	Sitnova et al. (2016)
V	23	0	3	4.00	0.23	0.16	-3.77	-0.24		
Cr	24	0	8	5.64	1.95	0.06	-3.69	-0.17	0.56	Bergemann & Cescutti (2010)
Mn	25	0	6	5.37	1.61	0.08	-3.76	-0.23	0.59	Bergemann & Gehren (2008)
Fe	26	0	131	7.52	4.00	0.09	-3.52	0.00	0.21	Mashonkina et al. (2011)
Fe	26	1	13	7.52	4.26	0.09	-3.26	0.00		
Co	27	0	7	4.92	1.45	0.09	-3.47	0.05	0.84	Bergemann et al. (2010)
Ni	28	0	6	6.23	2.78	0.09	-3.45	0.08		
Zn	30	0	2	4.62	1.54	0.02	-3.08	0.44	0.15	Sitnova et al. (2022)
Sr	38	1	2	2.92	0.57	0.03	-2.35	0.91	0.04	Mashonkina et al. (2022)
Y	39	1	8	2.21	-0.44	0.09	-2.65	0.60		
Zr	40	1	7	2.62	0.21	0.11	-2.41	0.85		
Ba	56	1	4	2.17	0.21	0.25	-1.96	1.30	-0.02	Mashonkina & Belyaev (2019)
La	57	1	30	1.14	-0.77	0.10	-1.91	1.35		
Ce	58	1	72	1.61	-0.51	0.09	-2.12	1.14		
Pr	59	1	11	0.76	-1.15	0.09	-1.91	1.34		
Nd	60	1	112	1.45	-0.36	0.10	-1.81	1.45		
Sm	62	1	58	1.00	-0.65	0.07	-1.65	1.61		
Eu	63	1	5	0.52	-0.90	0.07	-1.42	1.84	0.23	Mashonkina (2000)
Gd	64	1	23	1.11	-0.53	0.06	-1.64	1.62		
Dy	66	1	14	1.13	-0.36	0.12	-1.49	1.76		
Er	68	1	6	0.96	-0.64	0.12	-1.61	1.65		
Lu	71	1	2	0.12	-1.12	0.02	-1.24	2.02		
Hf	72	1	1	0.87	-0.98	0.15	-1.85	1.40		
Th	90	1	2	0.08	-1.33	0.11	-1.41	1.85	0.15	Mashonkina et al. (2012)
U	92	1	1	-0.52	< -1.8		< -1.28	< 2.24		

against CEMP r-I or r-II stars, but we do not expect such a bias against r-I and r-II for C-normal stars.

In Fig. 7 the [C/Fe] ratio versus the surface gravity for TYC 170–1218–1 is compared to a more metal-rich ($\langle [Fe/H] \rangle = -1.76$) stellar sample selected for their high radial-velocity by Caffau et al. (2025). All but one star in this sample are likely mixed, so that [C/Fe] < 0 is expected. Two stars stand out for having a very low [C/Fe] ratio: RVS740 with [Fe/H] = -2.86 and [C/Fe] = -0.98; RVS718 with [Fe/H] = -1.65 and [C/Fe] = -1.63. The stars in the EMP reference sample of Cayrel et al. (2004) have metallicities similar to TYC 170–1218–1, but no star is so low in [C/Fe] (Spite et al. 2005). The stars in Hansen et al. (2018) are all more metal-rich than TYC 170–1218–1 ($-3.12 < [Fe/H] < -0.7$), but some of them are in fact almost as low as TYC 170–1218–1 in [C/Fe].

One can always invoke extra mixing, above what is normally observed above the **red giant branch (RGB)** bump, to explain this extremely low C abundance, yet this hypothesis is not supported by anything else, observationally or theoretically.

Known r-II stars show some diversity in their abundance patterns; this can be seen in Fig. 8, where the pattern of HE 2252–4225 (actinide boost according to the definition of Mashonkina et al. 2014) is compared to that of TYC 170–1218–1. The [X/Fe] ratios for the elements Ca to Zn are by and large comparable. The two patterns for heavy elements ([X/Fe]) are offset by about 0.5 dex, TYC 170–1218–1 being higher in [X/Fe]. The elements C to K again also show a surprising diversity. In Fig. 9, we compare the [X/Fe] ratios in TYC 170–1218–1 with those of the prototype actinide boost star CS 31082–001 (Cayrel et al. 2001; Hill et al. 2002). This plot shows some striking similarities, namely

among the n-capture elements, in particular Th, and also some clear differences among the light elements, in particular carbon, which is underabundant by almost 1 dex with respect to iron in TYC 170–1218–1, while in CS 31082–001 it is depleted as expected by the evolutionary state of this star. From Fig. 8 and Fig. 9, one concludes that the chemical pattern in heavy elements for two r-II stars defined as actinide boost (HE 2252–4225 and CS 31082–001) are quite different. This diversity is a strong motivation for having as many details as possible on the chemical pattern of these r-rich stars, to be able to solve the quest on where and when the n-capture (and the actinide) elements are formed.

Not many Galactic EMP stars (about 20 the SAGA database Suda et al. 2008) have a A(Th) determination, and only a subsample of them has $[\text{Th}/\text{Fe}] > 1$; they are mainly centred at a higher metallicity than TYC 170–1218–1 ($[\text{Fe}/\text{H}] \sim -3$). Of these, only three stars have a metallicity around -3.5 : SMSS J200322.54–114203.3 (Yong et al. 2021) with $[\text{Fe}/\text{H}] = -3.57$ and $[\text{Th}/\text{Fe}] = 2.2$; SPLUS J142445.34–254247.1 (Placco et al. 2023) with $[\text{Fe}/\text{H}] = -3.41$ and $[\text{Th}/\text{Fe}] = 2.12$; CS 30315–029 (Siqueira Mello et al. 2014) whose $[\text{X}/\text{Fe}]$ ratios for the n-capture elements are much lower than for TYC 170–1218–1.

The chemical pattern of TYC 170–1218–1 is similar to what has been derived for other stars. In fact, the abundance ratios $[\text{X}/\text{Fe}]$ are similar to: SMSS J200322.54–114203.3 Yong et al. (2021), CS 29497–005 (Christlieb et al. 2004), CS 31081–001 (Hill et al. 2002), HE 1219–0312 (Roederer et al. 2009), RAVE J203843.2–002333 (Placco et al. 2017), and CS 29529–0089 (da Silva & Smiljanic 2025). None of these stars is poor in carbon, though.

As the number of known actinide boost¹ and r-II stars increases, the diversity among them also increases. In the case of TYC 170–1218–1, it is the low carbon abundance that is at odds with the majority of the observed stars. Also the difference in the pattern of heavy elements between TYC 170–1218–1 and other r-II stars is evident.

In the top panel of Fig. 10, the abundances of TYC 170–1218–1 are compared to the hot and cold models (Wanajo 2007; Siqueira Mello et al. 2013). The difference in the radioactive Th is due to its decay since the formation of the star. In the lower panel, we show the comparison with the solar r-process abundances from Thielemann & Cowan (2026). The fact that the solar Th/Eu ratio (almost identical to the solar r-process ratio, since both elements are essentially formed by the r process) is so close to the value found in TYC 170–1218–1 is remarkable, considering the age difference between the two stars. This implies that at the origin the Th content in TYC 170–1218–1 was much higher. For 23 r-II stars (according the definition by Christlieb et al. 2004) from the literature and TYC 170–1218–1, the $A(\text{Th}) - A(\text{Eu})$ varies from -0.84 to 0.04 ($A(\text{Th}) - A(\text{Eu}) = -0.43$ in TYC 170–1218–1) with $\langle(A(\text{Th}) - A(\text{Eu}))\rangle = -0.48 \pm 0.21$, to be compared to the solar value of -0.44 . These very or extremely MP stars are supposed to be much older ($\sim 6 - 9$ Gyr) than the Sun. Their Th has decayed more than for the Sun. It is reasonable to think that for the stars with a slightly sub-solar or an over-solar $A(\text{Th}) - A(\text{Eu})$, Th have been produced by an extra channel with respect to the r process.

¹ The number of actinide boost stars depends on the definition adopted for actinide boost.

4. Conclusions

The three main results of our investigation are: *i*) to firmly establish that star TYC 170–1218–1 is a neutron-capture rich and Th rich star; *ii*) that it is very poor in carbon, more than what can be justified by a depletion due to standard mixing and more than what is normally observed above the RGB bump; *iii*) that it belongs to the Sequoia accretion event, and thus was formed in an external galaxy and not in the Milky Way. The extremely low carbon abundance could be explained by some extra mixing; however, it is interesting to consider the possibility that the star was initially formed with a low carbon abundance, which was further depleted during the evolution of the star.

Being able to determine the U abundances in all r-II stars would be extremely important for our understanding of the actinide production mechanism. Stars such as HE 2252–4225 are too faint for the currently available telescopes, but U measurement may become achievable once the ANDES spectrograph on the ELT is available (Marconi & Andes Consortium 2025). However, TYC 170–1218–1 is bright enough that further eight hours of integration with UVES or another high-resolution spectrograph on an 8 m class telescope should allow its U abundance to be determined, provided its $[\text{U}/\text{Fe}]$ is the similar to that of CS 31082–001. This is a reasonable expectation, since their $[\text{Th}/\text{Fe}]$ are almost the same.

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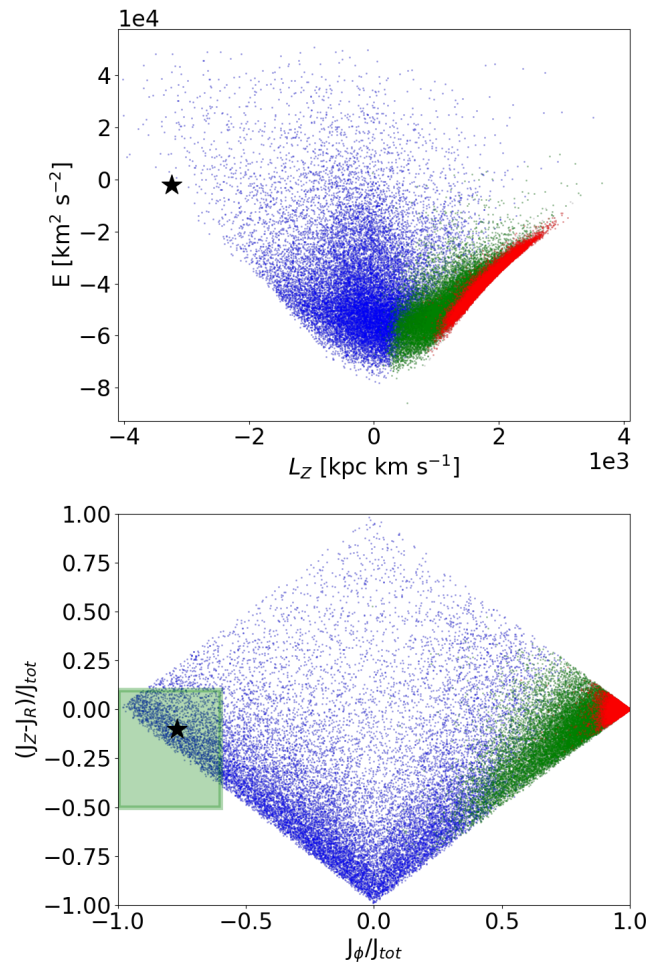


Fig. 2. Position of TYC 170–1218–1, (filled black star) in the energy, E , versus angular momentum, L_z (top panel), plane and in the action diamond plane, namely the difference in the vertical and radial actions ($J_z - J_R$) versus the azimuthal action, J_ϕ (equal to the vertical component of the angular momentum, L_z), all normalised to the total action, defined as $J_{tot} = |J_\phi| + J_R + J_z$. Stars from the ‘good-parallax’ sample of Bonifacio et al. (2021) are also shown for comparison and divided into halo (blue), thin disc (red), and thick disc (green) stars. The shaded green rectangle marks the region where likely Sequoia members are expected to be found.

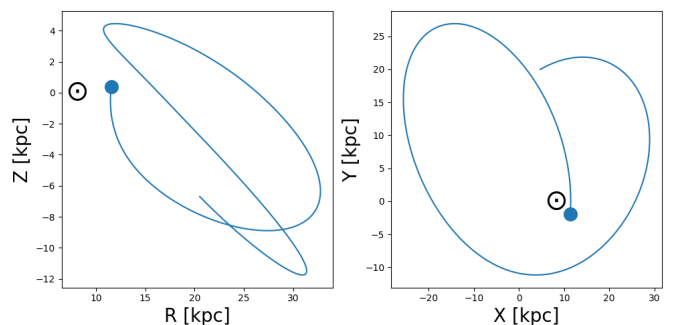


Fig. 3. Orbit of TYC 170–1218–1, integrated for one gigayear in the past. The positions of our target (filled blue circle) and the Sun (black solar symbol) are marked.

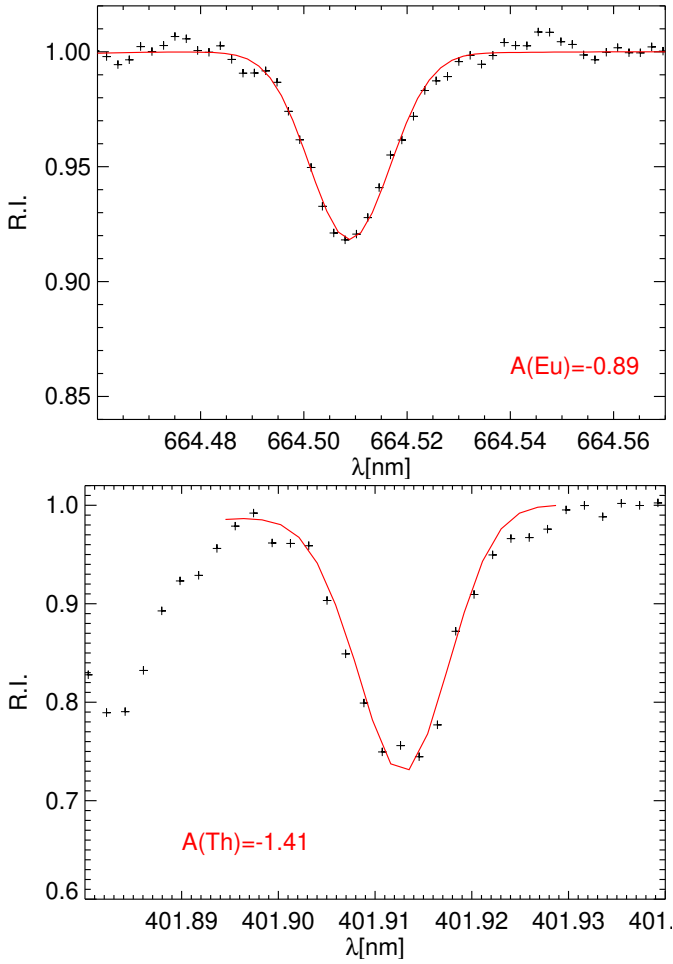


Fig. 4. UVES spectrum (black crosses) compared to the best fit profile (solid red) in the region of: (upper panel) the 664.5 nm Eu II line and (lower panel) the 401.9 nm Th II line.

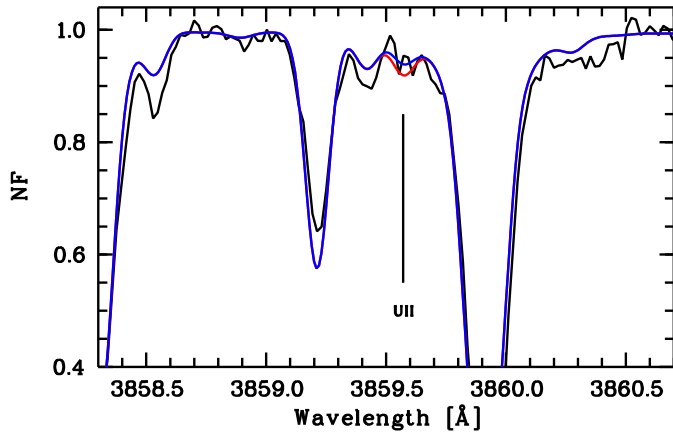


Fig. 5. UVES spectrum (solid black) in the region of the U II line at 385.9571 nm compared to synthetic spectra with $A(U)=-1.8$ (solid red) and $A(U)=-2.0$ (solid blue).

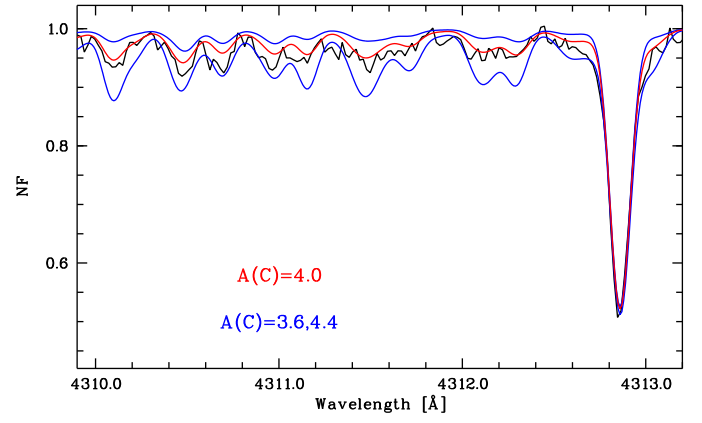


Fig. 6. UVES spectrum (solid black) in the region of the G-band compared to synthetic spectra.

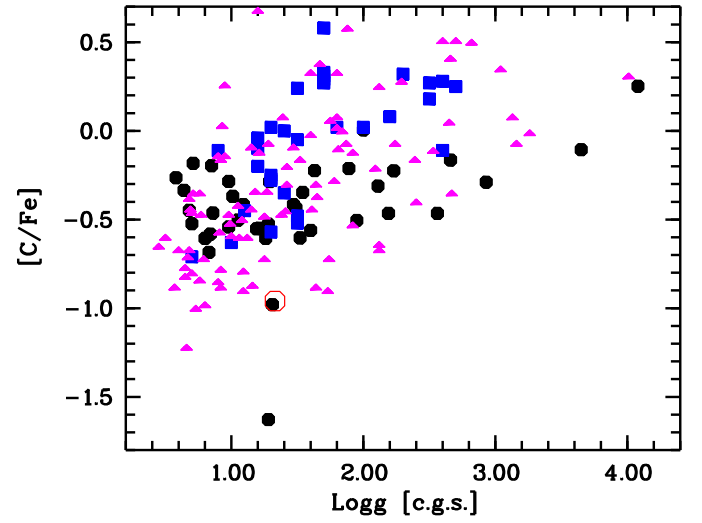


Fig. 7. [C/Fe] ratio of TYC 170–1218–1 (open red) compared with a sample of MP stars (filled black circles Caffau et al. 2025), a sample of EMP stars (filled blue squares Cayrel et al. 2004), and the sample from Hansen et al. (2018, filled pink triangles).

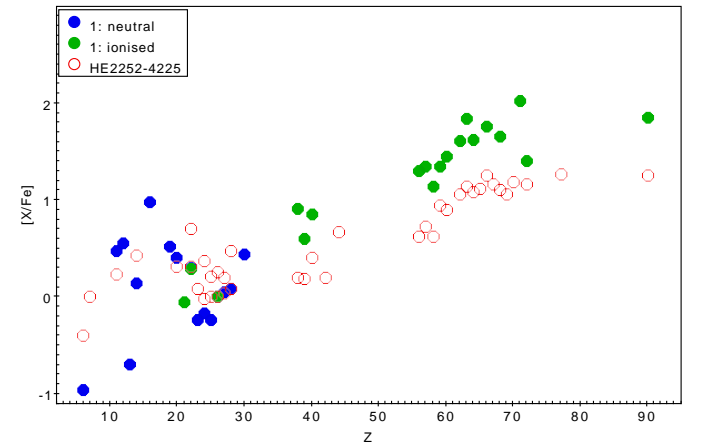


Fig. 8. Abundances of TYC 170–1218–1 compared to HE 2252–4225 (Mashonkina et al. 2014).

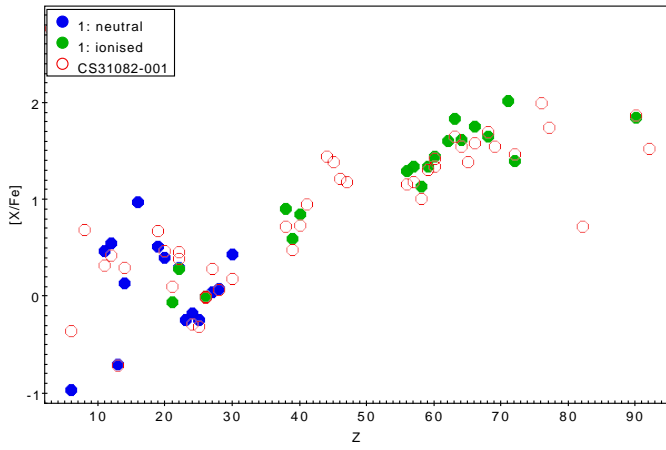


Fig. 9. Abundances of TYC 170–1218–1 compared to CS 31082–001 (Hill et al. 2002).

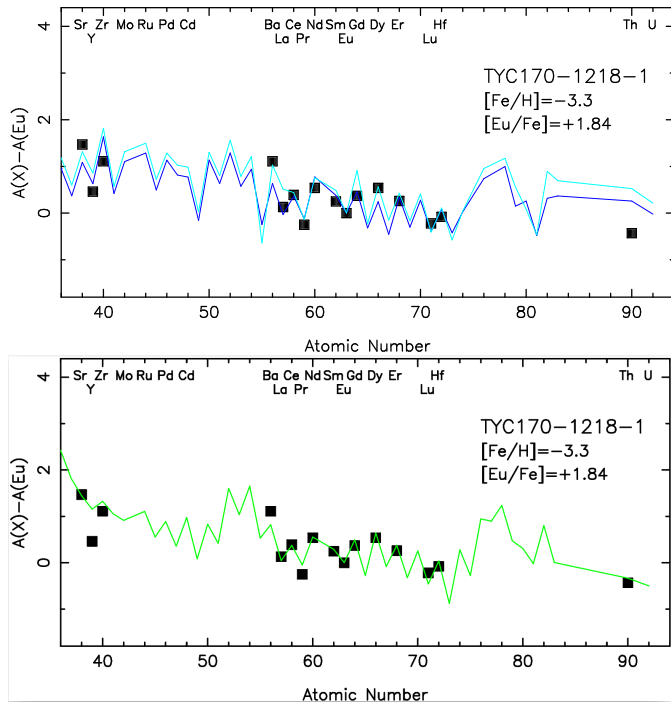


Fig. 10. $A(X)-A(\text{Eu})$ in TYC 170–1218–1 compared to: (upper panel) the model of Wanajo Siqueira Mello et al. (2013) computed for two different temperatures (solid blue cold model and solid cyan hot model); (lower panel) the distribution of the solar r process (Thielemann & Cowan 2026).