

Chemo-Dynamical Abundance Analysis of the Very Metal-Poor Halo Star HE 2315–4240

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Abstract: Learning about the chemical evolution of the universe is crucial to understanding the formation of the first stars and structure formation in the early universe. To find out how elements are produced via nucleosynthesis and how their relative amounts have evolved with time, abundance trends of stars with different metallicities can be established and compared. In this study, we present a spectrum of a very metal-poor star, HE 2315–4240, with $[\text{Fe}/\text{H}] = -2.9$ based on a Magellan/MIKE high-resolution visual light spectrum. The star has a radial velocity of $+41.9 \text{ km s}^{-1}$, an effective temperature of 5200 K, a surface gravity of 2.2 dex, and a microturbulence of 1.6 km s^{-1} . The α -elements and the iron peak elements agree well with the abundance trends of other metal-poor halo stars. The low abundance of $[\text{Sr}/\text{Ba}]$ and $[\text{C}/\text{Fe}]$ supports the idea that HE 2315–4240 is accreted and formed in a dwarf galaxy. The value of $[\text{Ba}/\text{Eu}]$ suggests the operation of a limited r-process. The abundance pattern of $[\text{Mg}/\text{Fe}]$ and $[\text{Si}/\text{Fe}]$ in HE 2315–4240 and its metallicity indicated that the star formed from gas enriched by a Type II supernova of a massive Pop III star. The abundance pattern fits Population III supernova yields moderately. The star's kinematic behavior shows that the star has a retrograde orbit and is moving away from the galactic center and out of the galactic disk. This means that although the star is located in the halo of the Milky Way, it didn't form in the Milky Way but rather formed in a small dwarf galaxy that was later absorbed by the Milky Way.

Keywords: Stars: individual (HE 2315–4240), metal-poor stars, stellar kinematics, nucleosynthesis, chemical evolution, Galactic halo

1. Introduction

The universe started off as a dense and hot fireball 13.8 billion years ago as it exploded with the Big Bang. As the universe expanded, it rapidly cooled down. In the process, hydrogen and helium began to form from the subatomic building blocks. The elements after the first few minutes of the Big Bang were 75% hydrogen, 25% helium, and trace amounts of lithium. No other heavier elements were made because the universe was not hot enough to fuse even heavier elements. However, at the present time, the heavier elements make up 2% of the universe [1]. As a result, the first stars that formed in the universe contained only hydrogen and helium and no heavier elements. They provided the first light in the universe, which had been dark until then. Also, those first stars were metal-free—without all elements that are heavier than hydrogen and helium [2].

They were very massive, around 100 times the mass of the Sun, since metal-free gas poorly cools and

clumps to form smaller stars. A massive star has a short life-time. That led to the first stars having lifetimes of only a few million years. Then they exploded as the first supernovae. During their lifetimes, elements heavier than hydrogen and helium were fused in their cores to produce energy. Elements up to iron were made, which were all spilled into the surrounding gas upon explosion. Additional elements, up to zinc, were also created during the explosion [3].

The pristine gas left over from the Big Bang was then polluted with these new elements from the supernova explosions. From that chemically enriched gas, the next generation of stars formed [4]. Since the gas had a different chemical composition, it was possible to form stars with all masses, which was different than before. Stars with masses similar to the Sun or even less could form for the first time, as could all the masses in between. Lower masses imply that stellar lifetimes are progressively longer. Stars with less mass than the Sun have a lifetime of more than 10 billion years. Stars born as part of the second generation of stars in the universe can thus still be alive if they have masses less than the mass of the Sun and around 0.6 to 0.8 solar masses. Many of these stars are now found on the so-called “red giant branch” in the Hertzsprung-Russell diagram, which is the last major evolutionary phase of a low-mass star. Those first low-mass stars were not metal-free anymore. As a result, these ancient stars are called “metal-poor stars.” They have a metal content, or “metallicity,” that is lower than one-tenth that of the Sun’s metallicity, which is given as the iron abundance $[Fe/H] = 0$. The bracket notation refers to “with respect to the Sun”. Zero is the baseline, and stars with less metals have negative values in $[Fe/H]$ [3]. The metals observed in these surviving stars today are not made by the star itself. Instead, metal-poor stars preserve the chemical composition of the birth gas cloud from which they formed through collapses due to gravity. Being on the red giant branch, those stars have not started to dredge up matter from their interiors to their surfaces through mixing processes. As a result, the chemical composition of metal-poor stars can be studied with telescopes and spectroscopy to reconstruct the composition of the gas clouds at different times. This allows astronomers to reconstruct the chemical evolution of the universe with the help of stars with different metallicities. Using the oldest, most metal-poor stars, they help us learn how stars and even galaxies formed in the early universe and about the physical and chemical properties of the early universe [5].

These metal-poor stars also trace heavier elements. But it remains unclear if heavy elements were formed in the first stars and dispersed into the interstellar medium through supernovae, if exotic supernovae were required, or if other objects such as merging neutron stars were required. Elements heavier than iron are synthesized only through neutron-capture processes onto seed nuclei, such as iron, for example in supernova explosions or other explosive events [6].

The oldest, most metal-poor stars have unique properties, such as appearing bluer than metal-rich stars because metals absorb shorter wavelengths of light, so metal-poor stars emit more blue than red light because they in fact absorb less blue light than more normal, more metal-rich stars. That also makes them look hotter and more luminous than metal-rich stars [7].

Over the last three decades, huge spectroscopic surveys and many observations have resulted in the discovery of many metal-poor stars, and their spectra have been analyzed in detail. The star SMSS J0313–6708 [8], with an iron abundance (a proxy for the overall metallicity) of $[Fe/H] < -7$, is one of the most pristine and oldest stars known. Astrophysicist Anna Frebel made this and many other important discoveries about ancient stars in the Milky Way’s halo and in dwarf galaxies. All these stars date back to the earliest phase of the universe, when only little of the heavier elements had been produced. Many of her discoveries are actually relatively brighter and closer stars, all still in the Milky Way and left over from that early time.

Despite the discoveries made, metal-poor stars remain rare and extremely hard to find. In addition, some

metal-poor stars in dwarf galaxies are very faint and need to be observed for around 10 hours [9]. But individual exposures with the telescope can only last for about an hour to avoid increased background noise caused by energetic cosmic rays hitting the detector. This means that nothing fainter can be observed with current telescopes.

The goal of this project is to analyze one of such metal-poor stars, named HE 2315–4240, originally discovered in the Hamburg/ESO survey, to help study element production and their astrophysical sites in the early universe.

2. Observations and Measurements

In order to analyze and understand a star, observations have to be made through a telescope. The spectrum of a star recorded from telescope observation can serve to understand the star's chemical composition from the strengths of absorption lines as well as its geocentric velocity from the line positions, which tell how fast it is moving away from Earth.

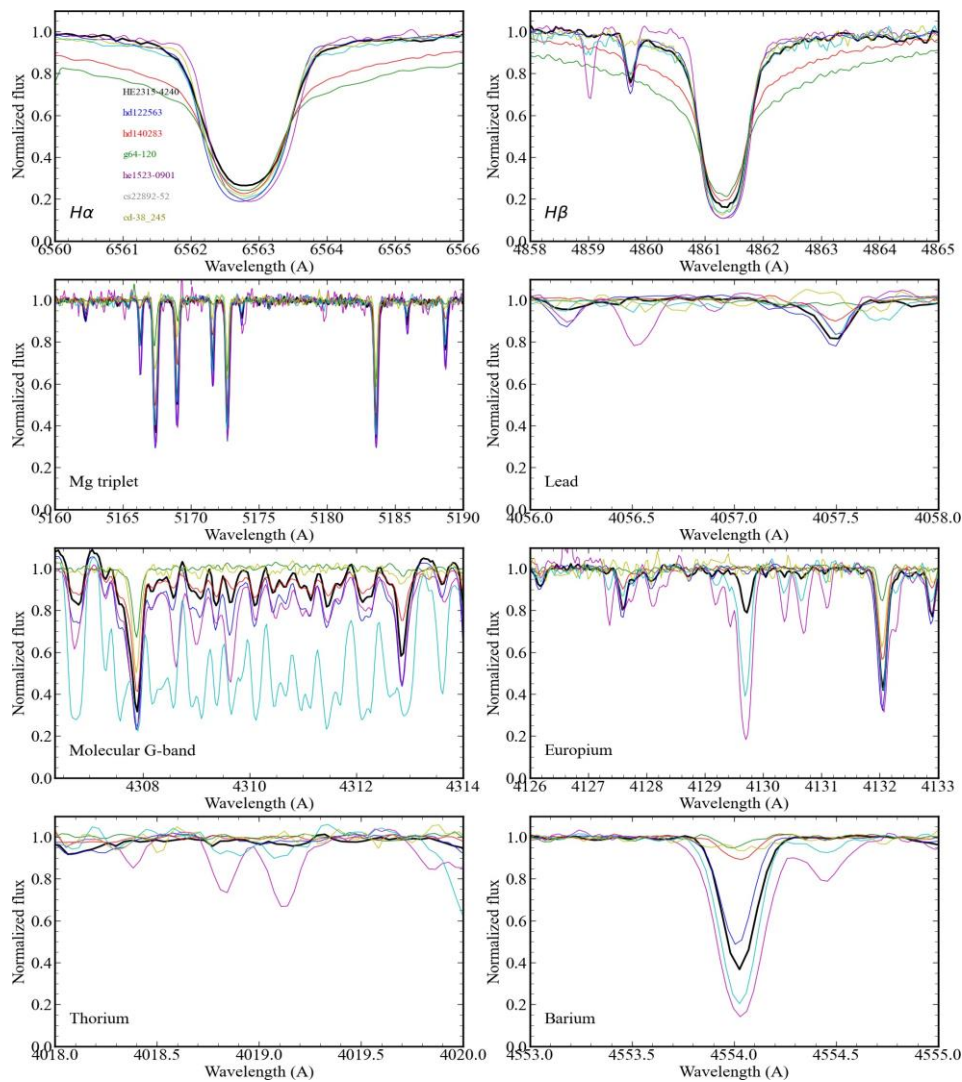


Fig. 1. Portions of the Magellan spectrum of HE 2315–4240 in comparison with other iron-poor stars near the H α line (first panel), H β line (second panel), around the Mg b lines around 5180 Å (third panel), around the lead line around 4057.5 Å (forth panel), the G-band near 4313 Å (fifth panel), around the europium line around 3132 Å (sixth panel), around the thorium line around 4019 Å (seventh panel), and around the barium line around 4554 Å (eighth panel).

The spectrum of the star is also the basis for deriving stellar parameters and then the detailed chemical abundances. In Fig. 1, we show several representative portions of the spectrum of HE 2315–4240 compared with several other metal-poor stars.

2.1. Telescope Observations

Prof. Frebel observed HE 2315–4240 (at a right ascension of R.A. = 23:17:59.86399, and a declination of Dec. = –42:24:30.7096) with the Magellan-Clay telescope at the Las Campanas Observatory in Chile by using a 0.7 slit. This yields a high resolution of $R = 30,000$ to $35,000$ across the wavelength range of 3500 \AA to 9500 \AA . All data was taken on June 23, 2014.

Data reductions were carried out with Prof. Frebel’s calculation programs. The resulting signal-to-noise (S/N) per pixel of the final processed and normalized spectrum is 114 at $\sim 4500 \text{ \AA}$, 139 at $\sim 4800 \text{ \AA}$, 109 at $\sim 5200 \text{ \AA}$, 145 at $\sim 6000 \text{ \AA}$, and 166 at $\sim 6500 \text{ \AA}$. This is an extremely high-quality spectrum. Radial velocity measurements yield $+63.1 \text{ km s}^{-1}$.

Table 1. Observation Details

Star	α	δ	B_{mag}	V_{mag}	G_{mag}	G_{error}	J_{error}	K_{error}	H_{error}
HE 2315–4240	349.499433	–42.40853	13.7	12.57	12.37	0.0028	0.021	0.025	0.024
Observing date	E(B–V)	J_{mag}	H_{mag}	K_{mag}	BC0	v_{radial}	Slit width	Parallax	Parallax _{err}
2014-06-23	0.013	11.035	10.605	10.54	0	63.1 km s^{-1}	0.7	0.35	0.0165
S/N	S/N	S/N	S/N	S/N	S/N	Verr	P.M. RA	P.M. DEC	AV
4000 $^{\circ}$ A	4500 $^{\circ}$ A	4800 $^{\circ}$ A	5200 $^{\circ}$ A	6000 $^{\circ}$ A	6500 $^{\circ}$ A		mas	mas	
39	114.2	138.8	109.4	144.7	165.5	0.05	4.658	–13.314	0.0343

Additional observation information is detailed in Table 1 as collected from “SIMBAD,” an astronomical database that provides basic data and measurements for astronomical objects.

2.2. Radial Velocity Measurements

The radial velocity of a star is the velocity of an object that moves along the line of sight of an observer. To calculate the radial velocity, one first needs a comparison spectrum that is in the rest frame, i.e., a spectrum of an object that is not moving. The stellar spectrum will show absorption lines at wavelengths different from the rest-frame template spectrum. The difference between the wavelengths corresponds to the radial velocity, which can be measured in the spectrum. The cross-correlation method is used to derive the relative velocity between the stellar spectrum and a template spectrum at rest. The geocentric velocity of HE 2315–4240 is found to be $+41.9 \text{ km s}^{-1}$.

Since the Earth is orbiting the Sun, radial velocities measured at a given time will be orbit-position-dependent. That prevents meaningful, time-independent absolute measurements. By shifting the reference point from the Earth to the Sun, this problem is alleviated. The final heliocentric velocity of the star can then be found by taking the geocentric radial velocity and adding the heliocentric correction to it. The correction can be determined by knowing the UT date and time of the observation, the right ascension, the declination of the star, and the coordinates of the observatory on Earth. The heliocentric correction of HE 2315–4240 is $+21.2 \text{ km s}^{-1}$, and the final heliocentric velocity of HE 2315–4240 is $+63.1 \text{ km s}^{-1}$. The correction is determined using Prof. Frebel’s calculation programs. Since the final heliocentric velocity is positive, the star is moving away from the Earth.

2.3. Equivalent Width Measurements

Equivalent width is the strength of the absorption lines present in the star spectrum. Mathematically, it represents the area under the curve that the absorption line makes up. Each line arises from electron transitions within the various atoms present in the star’s atmosphere. Some atoms have very new absorption lines across the spectrum (e.g., Si, Al, Zn, Sr), and others have many (Fe, Ca, Ti). All of the

equivalent widths of HE2315–4240 are listed in Table 2. Under “Species,” values numerically depict the atomic number and ionization state. For example, 22.0 refers to neutral Ti (Ti I), and 22.1 refers to singly ionized Ti (Ti II). λ refers to the wavelength of the absorption line; χ refers to the excitation potential of the line; $\log gf$ refers to the oscillator strength (occurrence probability) of the line; EW refers to equivalent width; and $\log \epsilon(X)$ refers to the raw number density abundance of element X as determined with the model atmosphere analysis.

Table 2. Equivalent Widths Measurements

Species	λ [Å]	χ [eV]	$\log gf$ [dex]	EW [mÅ]	$\log \epsilon(X)$ [dex]
11.0	5889.950	0.000	0.110	140.84	3.595
11.0	5895.920	0.000	-0.190	127.38	3.635
12.0	4057.510	4.350	-0.900	33.72	5.165
12.0	4167.270	4.350	-0.740	45.60	5.241
12.0	4702.990	4.330	-0.440	59.90	5.136
12.0	5172.680	2.710	-0.360	170.36	5.176
12.0	5183.600	2.720	-0.170	189.50	5.197
13.0	3944.000	0.000	-0.640	110.75	3.336
13.0	3961.520	0.010	-0.330	91.98	2.543
14.0	3905.520	1.910	-1.040	172.24	5.045
14.0	4102.940	1.910	-3.340	49.45	4.977
20.0	4283.010	1.890	-0.200	46.44	3.747
20.0	4318.650	1.900	-0.210	44.54	3.722
20.0	4425.440	1.880	-0.410	42.77	3.851
20.0	4454.780	1.900	0.260	71.02	3.883
20.0	4455.890	1.900	-0.550	31.95	3.771
20.0	5588.760	2.520	0.300	40.59	3.766
20.0	5601.290	2.530	-0.570	9.74	3.790
20.0	5857.450	2.930	0.170	19.77	3.877
20.0	6102.720	1.880	-0.810	27.13	3.801
20.0	6122.220	1.890	-0.330	48.90	3.782
20.0	6162.170	1.900	-0.110	62.44	3.846
20.0	6439.070	2.520	0.330	47.31	3.829
21.1	4246.820	0.320	0.240	88.26	-0.046
21.1	4324.980	0.590	-0.440	63.54	0.224
21.1	4374.450	0.620	-0.420	49.32	-0.115
21.1	4400.390	0.600	-0.540	48.82	-0.034
21.1	4415.540	0.590	-0.670	45.77	0.017
21.1	4670.410	1.360	-0.580	14.80	0.071
21.1	5031.010	1.360	-0.400	24.23	0.141
22.0	3989.760	0.020	-0.130	49.17	2.093
22.0	3998.640	0.050	0.020	51.88	2.046
22.0	4533.240	0.850	0.540	36.04	2.053
22.0	4534.780	0.840	0.350	28.55	2.062
22.0	4981.730	0.840	0.570	38.69	2.018
22.0	4991.070	0.840	0.450	37.49	2.112
22.0	4999.500	0.830	0.320	28.37	2.032
22.1	4028.340	1.890	-0.920	37.67	2.078
22.1	4337.910	1.080	-0.960	76.43	2.116
22.1	4394.060	1.220	-1.770	37.91	2.098
22.1	4395.030	1.080	-0.540	94.54	2.239
22.1	4395.840	1.240	-1.930	28.35	2.067
22.1	4399.770	1.240	-1.200	60.18	2.067
22.1	4417.710	1.170	-1.190	70.61	2.258
22.1	4418.330	1.240	-1.990	25.63	2.057
22.1	4443.800	1.080	-0.710	89.65	2.226
22.1	4450.480	1.080	-1.520	59.59	2.175
22.1	4464.450	1.160	-1.810	39.63	2.096
22.1	4533.960	1.240	-0.530	89.23	2.195
22.1	4571.970	1.570	-0.310	83.48	2.206
22.1	5188.690	1.580	-1.050	59.63	2.200
24.0	4274.800	0.000	-0.220	88.41	2.450

24.0	4289.720	0.000	-0.370	86.00	2.518
24.0	5206.040	0.940	0.020	65.23	2.459
25.0	4030.750	0.000	-0.500	97.54	2.416
25.0	4034.480	0.000	-0.840	85.38	2.337
26.0	4005.240	1.560	-0.580	98.96	4.588
26.0	4045.810	1.490	0.280	168.89	4.767
26.0	4063.590	1.560	0.060	137.44	4.712
26.0	4071.740	1.610	-0.010	129.01	4.711
26.0	4132.060	1.610	-0.680	102.53	4.780
26.0	4134.680	2.830	-0.650	44.02	4.487
26.0	4143.870	1.560	-0.510	106.87	4.649
26.0	4147.670	1.490	-2.070	53.78	4.545
26.0	4154.500	2.830	-0.690	42.29	4.482
26.0	4174.910	0.910	-2.940	50.50	4.618
26.0	4175.640	2.850	-0.830	37.81	4.534
26.0	4181.760	2.830	-0.370	57.22	4.548
26.0	4187.040	2.450	-0.560	64.21	4.476
26.0	4187.800	2.420	-0.510	73.54	4.674
26.0	4191.430	2.470	-0.670	63.02	4.574
26.0	4199.100	3.050	0.160	60.82	4.385
26.0	4202.030	1.490	-0.690	101.44	4.598
26.0	4216.180	0.000	-3.360	76.26	4.631
26.0	4227.430	3.330	0.270	58.84	4.548
26.0	4233.600	2.480	-0.600	65.11	4.566
26.0	4238.810	3.400	-0.230	37.32	4.562
26.0	4250.120	2.470	-0.380	73.68	4.589
26.0	4250.790	1.560	-0.710	98.54	4.602
26.0	4260.470	2.400	0.080	96.13	4.695
26.0	4271.150	2.450	-0.340	81.32	4.749
26.0	4271.760	1.490	-0.170	127.35	4.631
26.0	4282.400	2.180	-0.780	69.60	4.533
26.0	4325.760	1.610	0.010	132.89	4.692
26.0	4352.730	2.220	-1.290	54.46	4.624
26.0	4375.930	0.000	-3.000	87.93	4.565
26.0	4404.750	1.560	-0.150	130.94	4.693
26.0	4415.120	1.610	-0.620	110.06	4.783
26.0	4427.310	0.050	-2.920	93.93	4.716
26.0	4442.340	2.200	-1.230	57.71	4.592
26.0	4447.720	2.220	-1.360	51.19	4.584
26.0	4461.650	0.090	-3.190	80.81	4.617
26.0	4466.550	2.830	-0.600	55.58	4.685
26.0	4489.740	0.120	-3.900	49.28	4.510
26.0	4494.560	2.200	-1.140	61.88	4.600
26.0	4531.150	1.480	-2.100	60.67	4.659
26.0	4602.940	1.490	-2.210	49.48	4.494
26.0	4871.320	2.870	-0.340	63.18	4.595
26.0	4872.140	2.880	-0.570	53.78	4.599
26.0	4890.760	2.880	-0.380	61.35	4.597
26.0	4891.490	2.850	-0.110	70.30	4.526
26.0	4918.990	2.860	-0.340	61.76	4.535
26.0	4920.500	2.830	0.070	85.66	4.732
26.0	4994.130	0.920	-2.970	49.42	4.499
26.0	5049.820	2.280	-1.360	53.41	4.634
26.0	5051.630	0.920	-2.760	64.58	4.635
26.0	5171.600	1.490	-1.720	73.06	4.503
26.0	5191.450	3.040	-0.550	44.15	4.521
26.0	5192.340	3.000	-0.420	51.17	4.498
26.0	5194.940	1.560	-2.020	60.91	4.572
26.0	5216.270	1.610	-2.080	49.06	4.422
26.0	5232.940	2.940	-0.060	74.69	4.641
26.0	5266.560	3.000	-0.380	55.38	4.546
26.0	5324.180	3.210	-0.110	59.30	4.618
26.0	5341.020	1.610	-1.950	69.53	4.761
26.0	5371.490	0.960	-1.640	113.14	4.763
26.0	5397.130	0.920	-1.980	100.52	4.716
26.0	5405.770	0.990	-1.850	99.63	4.652

26.0	5429.700	0.960	-1.880	105.37	4.781
26.0	5434.520	1.010	-2.130	93.57	4.788
26.0	5497.520	1.010	-2.820	54.33	4.501
26.0	5506.780	0.990	-2.790	63.64	4.652
26.0	6494.980	2.400	-1.240	64.49	4.762
26.1	4173.450	2.580	-2.380	54.17	4.682
26.1	4178.860	2.580	-2.510	41.83	4.489
26.1	4233.160	2.580	-2.020	69.34	4.728
26.1	4508.280	2.860	-2.420	38.94	4.625
26.1	4555.890	2.830	-2.400	39.80	4.588
26.1	4583.830	2.810	-1.940	60.83	4.615
27.0	3842.050	0.920	-0.740	39.72	2.076
27.0	3845.470	0.920	0.060	67.63	2.087
27.0	3995.310	0.920	-0.180	57.42	1.957
27.0	4121.320	0.920	-0.330	57.96	2.091
28.0	3807.140	0.420	-1.230	89.17	3.435
28.0	4714.420	3.380	0.250	24.85	3.422
28.0	5476.900	1.830	-0.780	60.62	3.345
30.0	4810.540	4.080	-0.150	12.26	1.766
38.1	4077.710	0.000	0.150	123.43	-0.177
56.1	4554.030	0.000	0.140	123.65	-0.083
56.1	4934.080	0.000	-0.160	129.19	0.209
56.1	5853.680	0.600	-0.910	25.70	-1.009
56.1	6141.710	0.700	-0.030	68.57	-0.779
56.1	6496.900	0.600	-0.410	66.66	-0.618
63.1	4129.720	0.000	0.220	34.03	-1.883
63.1	4205.040	0.000	0.210	35.82	-1.836
63.1	4435.580	0.210	-0.110	44.91	-1.047

The equivalent width of each line is calculated using Spectroscopy Made Harder software that allows Gaussian fits to the absorption lines in a semi-automated fashion. The user then has to check the measurement and make adjustments to the fit as necessary. The goal is to convert equivalent width line strength measurements into chemical abundances. This works with a so-called model atmosphere, which is a program that simulates the physics conditions of the outer stellar atmosphere, where the absorption processes take place in the star. This is also where the observed light from the star originates.

3. Chemical Abundance Analysis

To understand the chemical evolution of the early universe, the chemical composition—the chemical abundance of each element—of the star has to be measured. The star’s chemical composition preserves that of the gas cloud that made it in the early universe. The abundances are calculated with a radiative transfer model atmosphere code that approximates the physics of the stellar atmosphere. The equivalent widths and their data are used to calculate the abundance $\log \epsilon(X)$ of elements. The final $[X/H]$ and $[X/Fe]$ values for each element are calculated using fundamental equations that use solar abundances: $[X/H] = \log \epsilon(X)_{\text{star}} - \log \epsilon(X)_{\text{sun}}$ and $[X/Fe] = \log \epsilon(X)_{\text{star}} - \log \epsilon(X)_{\text{sun}} - [Fe/H]$ [10].

Stellar parameters (effective temperature, surface gravity, microturbulence, and metallicity) also need to be derived as they determine the physics occurring in the stellar atmosphere where the absorption processes are taking place. All of these parameters are physical properties of the star that help further understand it.

3.1. Stellar Parameter and Abundance Determination

Stellar parameters fully describe the physical properties of a star’s outer atmosphere. They form the basis for carrying out a chemical abundance analysis. These include the effective temperature, which is the temperature of a black body with the same luminosity per surface area as the star; surface gravity, which is the log of the gravitational acceleration at the surface of the star; microturbulence, which is the velocity that

caused the broadening of the absorption lines; and metallicity, which is typically taken as the iron abundance and handled as a proxy for the total metal content of the star.

3.2. Effective Temperature

The effective temperature, T_{eff} , is determined by using J , K , and V magnitudes, $[\text{Fe}/\text{H}]$, AV , $E(B-V)$, and their uncertainties. Then the calculation is carried out using Prof. Frebel's calculation programs for dereddened colors and color- T_{eff} -relations that have been established, and an effective temperature of 5181 K is derived. This makes HE 2315-4240 a warm giant near the bottom of the Red Giant Branch in the Hertzsprung-Russell-Diagram. Typical uncertainties are around 100 K. For comparison, the Sun's effective temperature is 5777 K.

3.3. Surface Gravity

The log of the surface gravity, $\log g$, is determined by using parallax, V magnitude, $[\text{Fe}/\text{H}]$, AV , the effective temperature, and their uncertainties. Then the calculation is carried out using Prof. Frebel's calculation programs based on isochrone, temperature, fundamental equations, and parallax. The log of the surface gravity ($\log g$) obtained is 2.24 ± 0.04 dex. This agrees with the evolutionary phase of a warm red giant. For comparison, the Sun's surface gravity is 4.43 dex as it is a main-sequence star.

3.4. Microturbulence

The microturbulence is obtained from established relations of v_{mic} vs. $\log g$, which is based on spectroscopic measurements. The relationship is $v_{\text{mic}} = 0.06 \times \log^2 g - 0.569 \times \log g + 2.585$. Using the relationship, $v_{\text{mic}} = 1.61 \pm 0.3 \text{ km s}^{-1}$. A higher microturbulence leads to a higher metallicity of the star.

3.5. Metallicity $[\text{Fe}/\text{H}]$

The metallicity, $[\text{Fe}/\text{H}]$, is calculated from $[\text{Fe}/\text{H}] = \log \epsilon(\text{Fe})$ of my star $- \log \epsilon(\text{Fe})$ of the Sun which are the number densities of Fe atoms in the star and the Sun. Using 67 Fe I lines, the metallicity of HE 2315-4240 is -2.89 ± 0.09 . Since the metallicity of HE 2315-4240 is between -2 and -3, it is classified as a very metal-poor star, although it is nearly an extremely metal-poor star.

3.6. Chemical Abundance Results

Measuring chemical abundances can be used to determine the abundance pattern of the star and how metal-poor it is. Most importantly, it can be used to determine the abundance trends compared with other stars, which helps with the overall interpretation of the origin of the observed abundance pattern. This holds information about the nature of the first stars, first enrichment events, and early star formation environments.

To determine the abundances, a so-called stellar model atmosphere is used to calculate the absorption processes occurring on the outer layers of the star. This allows for deriving abundances from the observed spectrum, which shows various absorption lines as a result of the presence of different elements in the stellar surface layers.

The chemical abundance signature is then determined from 19 elements by using the custom Spectroscopy Made Harder software from Prof. Frebel. The final abundance ratios $[\text{X}/\text{Fe}]$, $[\text{X}/\text{H}]$, their uncertainties, and the number of element lines used are all listed in Table 3. Chemical abundances of carbon, aluminum, silicon, scandium, manganese, cobalt, strontium, barium, and europium are derived from spectrum synthesis for blended features of absorption lines.

Table 3. Chemical Abundances of HE 2315–4240

Element	$\log \epsilon(X)$	$[X/H]$	$[X/Fe]$	stdev	N
CH (Syn.)	5.26	-3.17	-0.28	0.01	2
Na I	3.62	-2.62	0.26	0.02	2
Mg I	5.18	-2.42	0.47	0.04	5
Al I (Syn.)	3.45	-3.00	-0.11	0.20	2
Si I (Syn.)	5.02	-2.49	0.40	0.05	2
Ca I	3.81	-2.53	0.35	0.05	12
Sc II (Syn.)	0.16	-2.99	-0.10	0.02	7
Ti I	2.06	-2.89	0.00	0.03	7
Ti II	2.15	-2.80	0.09	0.07	14
Cr I	2.48	-3.16	-0.28	0.03	3
Mn I (Syn.)	2.40	-3.03	-0.14	0.04	4
Fe I	4.61	-2.89	0.00	0.09	67
Fe II	4.62	-2.88	0.01	0.07	6
Co I (Syn.)	2.09	-2.90	-0.01	0.03	5
Ni I	3.40	-2.82	0.07	0.04	3
Zn I	1.77	-2.79	0.09	0.10	1
Sr II (Syn.)	0.09	-2.78	0.11	0.07	2
Ba II (Syn.)	-0.74	-2.92	-0.03	0.09	5
Eu II (Syn.)	-2.32	-2.84	0.04	0.04	4

Lithium was not detected because its surface abundance is gone from being at the base of the red giant branch. The CH abundance is determined from spectrum synthesis from the CH G-band at 4313 Å and another feature at 4323 Å. Both vanadium, copper, and chromium II lines are distorted and were excluded from the measurement.

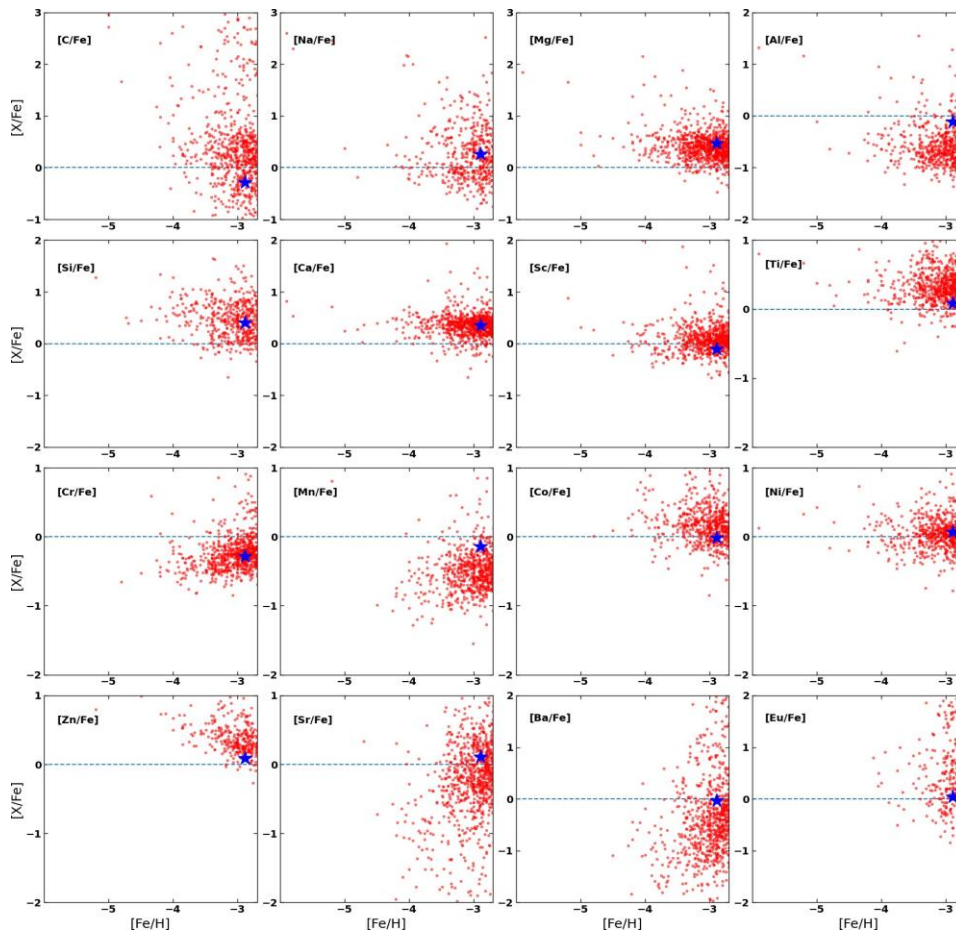


Fig. 2. Abundance ratio ($[X/Fe]$) over metallicity ($[Fe/H]$) for various elements of HE 2315–4240 (blue star symbol) along with other metal-poor stars. HE 2315–4240 show similarities in its abundances compared with many other metal-poor stars from JINAbase (shown in red). Element ratios are labeled in each panel.

3.6.1. Lighter element abundance trends

Fig. 2 shows all elemental abundance ratios in comparison with those of other metal-poor stars from the literature. Noteworthy features are as follows: The α -element abundance (Mg, Si, Ca, Ti) of HE 2315–4240 is enhanced, as is expected for stars formed from early gas clouds that have been enriched by massive core-collapse supernovae. Iron-peak elements also agree very well with the abundance trends set by the other metal-poor stars. This further confirms that at least one supernova contributed these elements to the gas cloud from which HE 2315–4240 formed.

3.6.2. Heavy element abundance trends

Fig. 3 shows Sr and Ba abundance ratios in comparison with those of other metal-poor stars from the literature. We show both $[\text{Sr}/\text{H}]$ and $[\text{Sr}/\text{Fe}]$ as well as the $[\text{Sr}/\text{Ba}]$ ratio for a more detailed analysis.

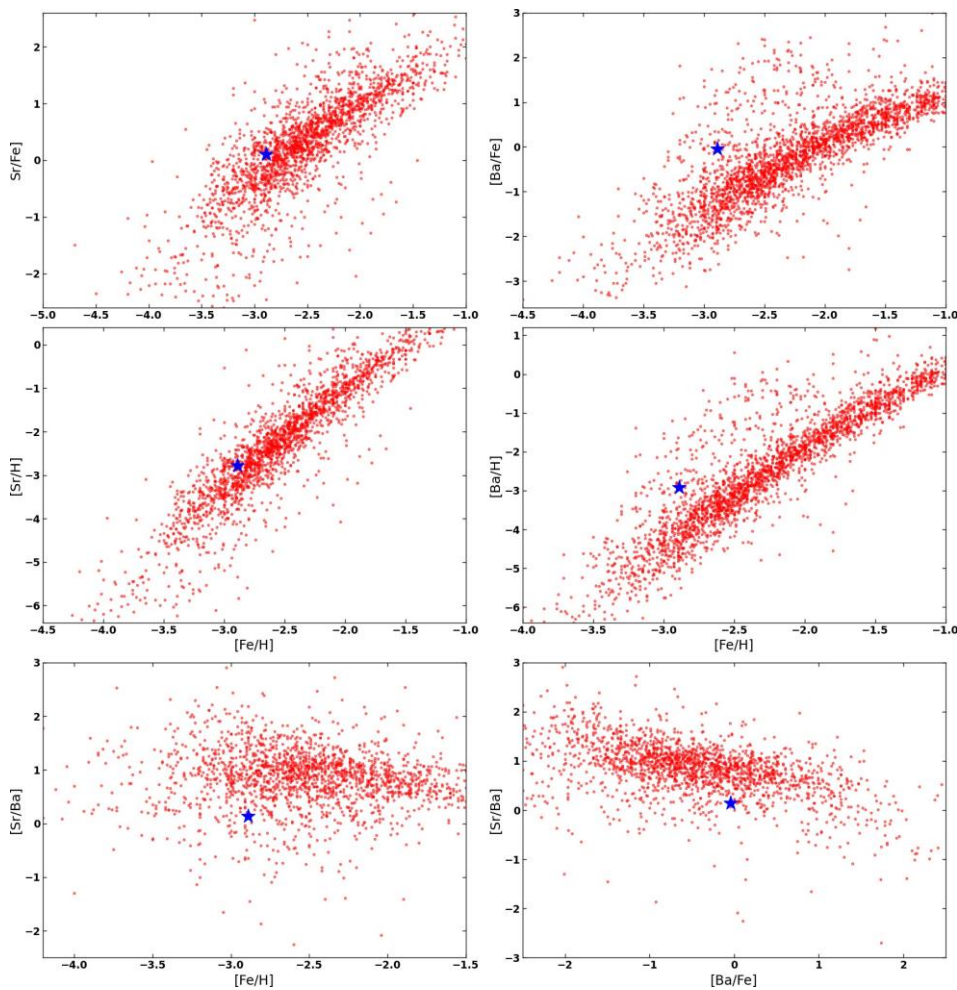


Fig. 3. Abundance ratio ($[\text{X}/\text{Fe}]$) over metallicity ($[\text{Fe}/\text{H}]$) for heavy elements Sr and Ba of HE 2315–4240 (blue star symbol) along with other metal-poor stars from JINAbase (shown in red).

For Sr, HE 2315–4240 displays similar abundances compared with many other metal-poor stars from JINAbase. But for Ba, HE 2315–4240 shows an enhanced relative to the bulk of stars. This is not a unique feature; the number of stars with enhanced Ba values is much smaller than the main branch. Interestingly, the overall Ba abundance is very low, despite this relative enhancement compared to other stars. As a result, the $[\text{Sr}/\text{Ba}]$ ratio is low—it is close to the region where dwarf galaxy stars typically reside and is below the main branch of halo stars. This suggests that HE 2315–4240 was possibly accreted and formed in an environment that is similar to that of the surviving dwarf galaxies [11].

3.7. Abundance Uncertainties

The random uncertainties of element abundance X are derived by using the standard deviation of $\log \epsilon(X)$. Using a sample of 67 Fe I lines, it is easier to more accurately map the abundance distribution about the mean compared to elements with only a few lines. By checking for measurement errors and inaccuracies and correcting for them, the scatter is reduced, leading to a standard deviation of only $\sigma = 0.09$.

When only one or two lines are available for an element, the standard deviation is typically less well defined. In those cases, the Fe standard deviation is used as a guide and adopted for the elements. Both aluminum and zinc originally did not allow for a standard deviation calculation. We then adopted standard deviations of 0.2 and 0.1 dex, respectively. This reflected the S/N ratio, which is higher for zinc than aluminum.

Systematic uncertainties come from analysis and physics choices that are related to the model atmosphere, data quality, and abundance calculations. They are more complex and are not further considered here.

4. Nucleosynthetic Interpretation of Stellar Abundances

By assembling the abundance pattern of HE 2315–4240 by plotting $[X/H]$ versus atomic number X , we can graphically display the star’s composition (See Fig. 4). Since the stellar abundances have not changed since the star was born, presumably these are the abundances of the star’s early birth gas cloud. The next step is to learn which objects and processes enriched that gas cloud in the early universe.

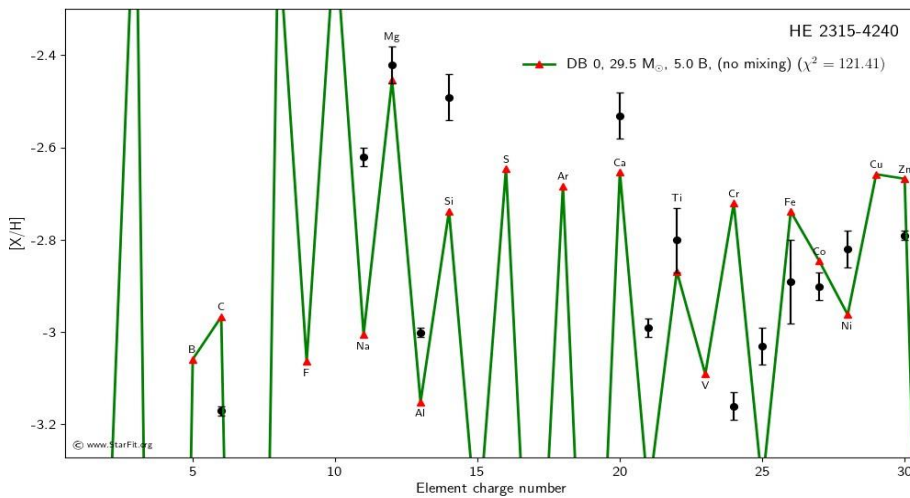


Fig. 4. Abundance ratios $[X/H]$ of HE 2315–4240 (black-filled circles) as a function of atomic number. Overplotted in green is the best-matched Population III nucleosynthesis model. The model’s mass and energy are shown in the upper right.

We matched the abundance pattern with predictions from theoretical models of the chemical yields of a Population III first star by using an online tool named Starfit, as shown in Fig. 4. The graph shows in green the yields of the elements that were produced and ejected during the previous Population III supernova explosion. Overall, the fit is moderate. The best-fit Population III star model has $M = 29.5 M_{\odot}$, $E = 5 \times 10^{51}$ erg, and $\chi^2 = 121.41$.

However, due to the low amount of $[C/Fe] = -0.28$ in HE 2315–4240, the first few elements are not well-fit because the Starfit models used are all so-called fallback explosion models, which are carbon-rich by design, and HE 2315–4240 is carbon-poor. This implies that the results may not be trusted as much, which is also reflected in the mismatch of many elements in the model. Nevertheless, it indicated a massive progenitor

first star. Regarding further clues about the origin of HE 2315–4240 and in which environment it formed billions of years ago, we also consider the α -element abundances. The amount of [Mg/Fe] and [Si/Fe] in HE 2315–4240 is enhanced compared to the Sun. This indicated a Type II supernova explosion that enriched the birth gas cloud, such as a massive Population III star. Those short-lived massive stars can blow new elements that came from stellar nucleosynthesis into the surrounding gas cloud that later gave rise to the observed low-mass star. The fact that the star is almost extremely metal-poor can mean that the explosion indeed came from one Population III star.

However, the observed low [C/Fe] ratio in the star likely meant that it is not a result of fallback supernovae and has low explosion energy, which likely meant that the Pop III star's mass is lower, perhaps around 10 solar masses.

Regarding neutron-capture element abundances, HE 2315–4240 has low values overall. Nevertheless, its [Ba/Fe] abundance is higher than most metal-poor stars at that [Fe/H] abundance. As a result, there is a low value for [Sr/Ba] = [Sr/Fe] – [Ba/Fe] = 0.14, suggesting a connection to early dwarf galaxy environments. This is supported by the low carbon abundance, as the vast majority of dwarf galaxy stars are not carbon-enhanced.

The question is which nucleosynthesis process produced these elements in the early universe. HE 2315–4240 has a relatively high value for [Ba/Eu] = [Ba/Fe] – [Eu/Fe] = –0.07, given its low [Fe/H]. This ratio provides information on neutron-capture nucleosynthesis processes. A ratio of [Ba/Eu] = –0.7 would indicate prior enrichment by an r-process, but the observed ratio is too high for that. Instead, [Ba/Eu] \sim –0.1 rather suggests the operation of a limited r-process that can occur during core-collapse supernova explosions above the proto-neutron star and produce a limited amount of heavy elements. However, whether this occurred in a Population III star or another star that contributed elements to the birth gas cloud of HE 2315–4240 remains unclear.

5. Kinematic Analysis

Gaia is a satellite in space that measures the positions of billions of stars in the Milky Way Galaxy. There is an associated database that provides the results of the micro-arcsec Gaia astrometry: information about 3D spatial information, velocity distributions, and stellar parameters of 2 billion stars.

Each star's information can be accessed by submitting the star's coordinates or its name. One of the goals of this section is to determine the distance of the star to Earth, which can be derived by finding the parallax of HE 2315–4240. Parallax is the displacement in the apparent position of an object viewed along two different lines of sight and is usually measured in arc seconds. Using Prof. Frebel's calculation programs, which use an adapted version of the parallax formula to correct imperfections in the instrument and data processing methods, the final distance to HE 2315–4240 obtained is 2.86 ± 0.14 kpc.

We derived HE 2315–4240's galactic coordinates ((l,b) in deg) to be (348.09127352, –65.61395908). Its galactic coordinates (X, Y, Z) in kpc are (1.16262417, –0.24518828, –2.62106309). Galactocentric coordinates (x, y, z) in kpc for a right-handed system are (–7.02201605, –0.24518552, –2.60321035). The velocities in the Cartesian Galactic coordinate frame are then (U, V, W) in km/s (23.78, –197.4, –44.23). U is the outward radial motion within the galaxy. V is the motion in the direction of the rotation about the galactic center. W is the motion out of the galactic plane.

This implies that HE 2315–4240 is currently moving radially away from the galactic center and out of the galactic disk to the south. Furthermore, it has a retrograde orbit, i.e., its motion is not aligned with the bulk motion of stars moving about the galactic center.

5.1. Orbital Motions

We used a program called "The ORIENT" [12] from Dr. Mohammad Mardini to calculate the orbital

history of the star for the last 8 billion years. The program approximates how the Milky Way has grown over time and how its mass has been distributed. This determines how an individual star moves within the galaxy under the influence of the gravity of the galaxy's mass [13].

The results clearly show that my star is located in the halo of the Milky Way. The maximum height above the galactic plane, Z , is around 3 kpc, which suggests inner halo membership. As can be seen in Fig. 5, the orbit is not confined to the disk but extensive and very elliptical.

This kinematics analysis suggests that the star formed not in the Milky Way's disk but was instead accreted at some point in the past. Accordingly, HE 2315–4240 likely formed in a small dwarf galaxy early on in the universe that was later absorbed by the growing Milky Way. The progenitor system was perhaps accreted before many other systems. This would place the star in the inner halo today.

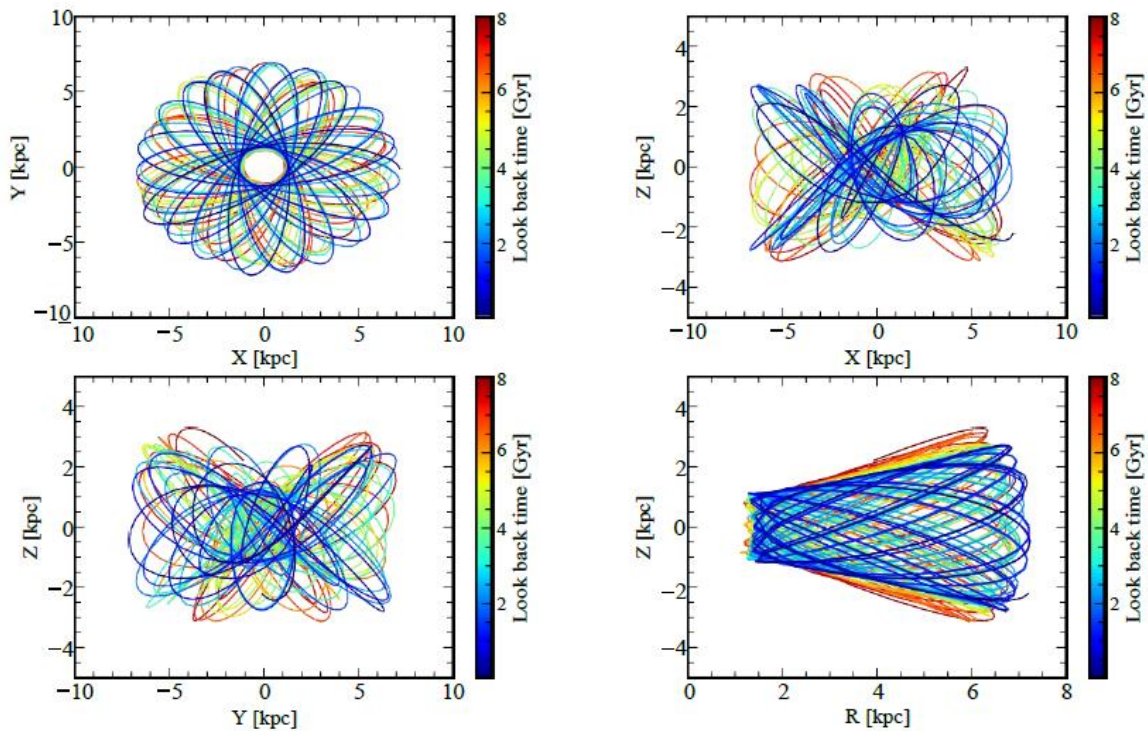


Fig. 5. Orbital history of HE 2315–4240 for the past eight billion years. Blue colors indicate more recent orbits. Shown are four different views of the galactic center.

Interestingly, the orbits of HE 2315–4240 never reach a solar radius of 8 kpc. We are observing it at a distance of ~ 2 kpc towards the galactic center, where it appears to be on its maximum orbital radius at present.

6. Summary

In this work, we analyzed the metal-poor star, HE 2315–4240, to deepen our understanding of the properties of the ancient star and to understand the chemical evolution of the early universe. Using the stellar spectrum obtained from the Las Campanas Observatory through the Magellan-Clay telescope on June 23, 2014, we used Prof. Frebel's calculation programs to cross-correlate the spectrum with another spectrum shifted to rest to find the radial velocity of the HE 2315–4240, which is $+41.9 \text{ km s}^{-1}$. The heliocentric velocity of the star is then obtained by adding the heliocentric correction, derived from the time and coordinates of the star and the observatory, to the radial velocity, to a value of $+61.3 \text{ km s}^{-1}$. The spectrum shifted to rest is then analyzed by using the software, "Spectroscopy Made Harder", to obtain the chemical

abundance of HE 2315–4240 and equivalent widths.

The metallicity, [Fe/H], derived is -2.89 ± 0.09 dex, which makes HE 2315–4240 a very metal-poor star. This abundance is then used to determine the other stellar parameters HE 2315–4240. The effective temperature we obtained from the calculation program that produces photometric stellar parameters is 5181 ± 100 K, making the star a warm giant. Using established relationships with isochrone, parallax, and effective temperature, the log of the surface gravity ($\log g$) obtained is 2.24 ± 0.04 dex. The microturbulence obtained from established relations of v_{mic} vs. $\log g$ is 1.61 ± 0.3 km s⁻¹.

All abundances, except aluminum and zinc, which have adopted a standard deviation that reflects the S/N ratio, have an uncertainty of less than 0.1 dex. The abundances of 19 elements are derived. The α -elements and iron-peak elements of HE 2315–4240 agree well with the abundance trend of other metal-poor stars, which confirms that at least one supernova contributed these elements to the gas cloud that formed HE 2315–4240. For Sr, the star shows similar abundance trends but shows an enhanced value for Ba, which led to a low [Sr/Ba] ratio and suggests that HE 2315–4240 is accreted and formed in a dwarf galaxy.

The stellar abundance data fits moderately with the Population III supernova explosion yields but doesn't fit well because of the star's low carbon ratio. It indicated a massive progenitor first star. Both the amount of [Mg/Fe] and [Si/Fe] in HE 2315–4240 and the fact that the star is almost extremely metal-poor indicated a Type II supernova explosion that enriched the birth gas cloud, such as a massive Population III star around 10 solar masses. The low value for [Sr/Ba] = 0.14 and the low carbon abundance suggest a connection to early dwarf galaxy environments. The value of [Ba/Eu] \sim -0.1 suggests the operation of a limited r-process, but it is unclear where it occurred.

Using an adapted version of the parallax formula, we obtained the final distance to HE 2315–4240, which is 2.86 ± 0.14 kpc. The velocities in the Cartesian galactic coordinate frame are (23.78, -197.4, -44.23), which implies that HE 2315–4240 is currently moving radially away from the galactic center and out of the galactic disk to the south and has a retrograde orbit. Using a program called "The ORIENT", the results show that HE 2315–4240 is located in the halo of the Milky Way. The maximum height above the galactic plane suggests inner halo membership. The orbit is not confined to the disk but is extensive and very elliptical. The kinematics analysis suggests that the star formed outside the Milky Way's disk, likely in a small dwarf galaxy, and was later absorbed by the growing Milky Way. The progenitor system was likely accreted before other systems, placing the star in the inner halo as we know it today.

Conflict of Interest

The author declares no conflict of interest.

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References

- [1] Urbarri, S. G., & Cervantes-Cota, J. L. (2022). Nucleosynthesis in the Cosmos: What we think we know and forthcoming questions. arXiv preprint, arXiv:2208.05518. doi: 10.48550/arXiv.2208.05518
- [2] Klessen, R. S., & Glover, S. C. O. (2023). The first stars: Formation, properties, and impact. *Annual Review of Astronomy and Astrophysics*, 61, 65–130. doi: 10.1146/annurev-astro-071221-053453
- [3] Frebel, A. (2010). Stellar archaeology: Exploring the universe with metal-poor stars. *Astronomical*

Notes, 331(5), 474–488. doi: 10.1002/asna.201011362

- [4] Frebel, A. (2008). Metal-poor stars. arXiv preprint, arXiv:0802.1924. doi: 10.48550/arXiv.0802.1924
- [5] Hansen, T., Hansen, C. J., Christlieb, N., *et al.* (2015). An elemental assay of very, extremely, and ultra-metal-poor stars. *The Astrophysical Journal*, 807(2), 173. doi: 10.1088/0004-637X/807/2/173
- [6] Skuladottir, A., Hansen, C. J., Salvadori, S., & Choplin, A. (2019). Neutron-capture elements in dwarf galaxies. I. Chemical clocks and the short timescale of the r-process. *Astronomy & Astrophysics*, 631, A171. doi: 10.1051/0004-6361/201936125
- [7] Hansen, C. J., Jofre, P., Koch, A., McWilliam, A., & Sneden, C. S. (2017). Something borrowed, something blue: The nature of blue metal-poor stars inferred from their colours and chemical abundances. *Astronomy & Astrophysics*, 598, A54. doi: 10.1051/0004-6361/201629628
- [8] Keller, S. C., Bessell, M. S., Frebel, A., *et al.* (2014). A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36–670839.3. *Nature*, 506, 463–466. doi: 10.1038/nature12990
- [9] Frebel, A., Simon, J. D., Geha, M., & Willman, B. (2010). high-Resolution spectroscopy of extremely metal-poor stars in the least evolved galaxies: ursa major ii and coma berenices. *The Astrophysical Journal*, 708, 560. doi: 10.1088/0004-637X/708/1/560
- [10] Frebel, A., & Norris, J. E. (2015). Near-field cosmology with extremely metal-poor stars. *Annual Review of Astronomy and Astrophysics*, 53, 631–688. doi: 10.1146/annurev-astro-082214-122423
- [11] Frebel, A. (2018). From nuclei to the cosmos: Tracing heavy-element production with the oldest stars. *Annual Review of Nuclear and Particle Science*, 68, 237–269. doi: 10.1146/annurev-nucl-101917-021141
- [12] Mardini, M. K., Frebel, A., Chiti, A., *et al.* (2022). The atari disk, a metal-poor stellar population in the disk system of the milky way. arXiv preprints, arXiv:2206.08459. doi: 10.48550/arXiv.2206.08459
- [13] Bland-Hawthorn, J., & Gerhard, O. (2016). The galaxy in context: Structural, kinematic, and integrated properties. *Annual Review of Astronomy and Astrophysics*, 54, 529–596. doi: 10.1146/annurev-astro-081915-023441

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