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Article

Defying chemical tagging: inhomogeneities in the wide binary system HIP 34407/HIP 34426

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SUMMARY

In this work we assessed the hypothesis that stars in wide binary systems are chemically homogeneous because of their shared origin. We obtained the abundances of the HIP 34407/HIP 34426 binary by analyzing high-resolution spectra of the system. Our results indicated a mean metallicity discrepancy of Δ[M/H] ~0.22 decimal exponent (dex) between the two components, with HIP 34426 being the poorer in [X/Fe]. We observed an overall abundance difference of Δ[X/H] ~0.18 dex. We found that HIP 34426 showed an oddly high volatile vs. refractory element ratio of ~1.72 dex when compared to its companion's ratio of ~0.68 dex. We detected a Pearson correlation coefficient of -0.77 between the elemental condensation temperature and the differences in abundances. Lastly, we noted the presence of irregularities in the radial velocity data of HIP 34426. We speculated that this phenomenon, along with the system's discrepancy in elemental abundances, might be an indicator of the presence of rocky planets around this star. We concluded that the differences found in chemical composition might demonstrate limitations in the assumptions of chemical tagging.

INTRODUCTION

For many decades astronomers have performed detailed observations of stars and other interstellar structures to unravel the chemical and dynamic evolution of the Milky Way. Amongst the most ambitious objectives inherent in this field of study is the determination of star development through chemical tagging, a technique implemented in modern Galactic archaeology (1–3). As opposed to kinematic analysis, which can reconstruct the development of the galaxy through the position and the velocity of its stars, chemical tagging can allegedly accomplish the same objective by analyzing their elemental abundances (4, 5). It works by examining the chemical composition of stars' atmospheres through their spectra and identifying their homogeneities (1). Its purpose is to remodel long dissolved stellar clusters (5).

For this approach to function accurately, we must presuppose that (i) chemically identical stars have a shared origin and (ii) each association contains a unique composition which differentiates it from other stellar entities. The verification of these conditions would imply that even stars distant from their birth companions would maintain a distinctive chemical signature. This would enable us to identify them and trace them back to their initial point. However, the first assumption remains highly speculative, as studies found that stars not born together can also be homogeneous (6). The second assumption has also been difficult to corroborate through automated software when attempting to differentiate open clusters with similar ages or identify stars formed together (7-9). Additionally, studies find that a significant amount of stellar clusters display overlapping chemical signatures (10, 11).

Wide binaries are systems of stars separated by a distance equal to or larger than 100 Astronomical Units (AU) (i.e., 100 times the distance between the Earth and the Sun) (12). Since stars orbiting around a common center of mass are known to be born together, wide binaries are among the most promising candidates for assessing the feasibility of chemical tagging (13, 14). This is because analyzing their chemical composition can enable us to trace the stars back to their origin, which is the objective of this technique.

There exist several hypotheses for the formation of these systems, depending on the separation of their components. For stars a few thousand AU apart, the most plausible theory is the fragmentation of turbulent cores in star formation events (15, 16). For distances up to 1 parsec (pc), the predominant explanations offered are the presence of an unseen third star, the random pairing of cores from stars that have not been fully formed, and the dispersal of large groups of stars (17–19).

Stars in wide binaries are supposed to be chemically homogeneous due to their common origin (20). Differences in chemical composition are measured in decimal exponent (dex), which refers to the exponent of a number in scientific notation. Previous research indicates that most of the dissimilarities found between stars in wide binaries range from *Δ*[Fe/H] ~ 0.02 to 0.07 dex (21–24). These differences are mainly attributed to the uncertainty in the measurements, which is typically around 0.05 dex. However, there have been reports for elemental discrepancies up to 0.27 dex (25, 26).

Those unexpected results could be attributed to the accretion of rocky material because of planet formation processes (27–33). This scenario was invoked in a detailed elemental abundance analysis of the twin-star wide binary HIP 34407/HIP 34426 (34). Each element has a unique

Table 1. Atmospheric parameters of HIP 34407 and HIP 34426 relative to the Sun, estimated with iSpec.

Star	T_{eff} (K)	$log\ g$ (dex)	[M/H] (dex)	v_t (km/s)
HIP 34426	5868.07 ± 78.30	3.89 ± 0.10	-0.54 ± 0.14	1.47 ± 0.03
HIP 34407	5885.55 ± 69.38	4.10 ± 0.09	-0.32 ± 0.12	1.42 ± 0.03

Table 2. Abundances of HIP 34426 and HIP 34407 (dex) with respect to the Sun [X/H], along with the composition differences Δ[X/H] and the condensation temperature T_c of each element .

Element	HIP 34426	HIP 34407	T_C	Δ[X/H] (dex)
Al I	-0.18 ± 0.13	-0.01 ± 0.08	1653	-0.17 ± 0.21
*Ba II	-0.28 ± 0.06	-0.15 ± 0.03	1455	-0.13 ± 0.09
C I	0.03 ± 0.07	-0.01 ± 0.10	40	0.04 ± 0.17
Ca I	0.40 ± 0.08	-0.12 ± 0.44	1517	0.52 ± 0.52
Ca II	0.01 ± 0.22	0.22 ± 0.25	1517	-0.21 ± 0.47
Co I	0.21 ± 0.37	0.47 ± 0.84	1352	-0.26 ± 1.21
Cr I	-0.48 ± 0.14	-0.30 ± 0.12	1296	-0.18 ± 0.26
Cr II	-0.37 ± 0.16	-0.18 ± 0.24	1296	-0.19 ± 0.40
*Cu I	-0.07 ± 0.22	0.12 ± 0.38	1037	-0.19 ± 0.60
Fe I	-0.35 ± 0.49	-0.15 ± 0.63	1334	-0.20 ± 1.12
Fe II	-0.41 ± 0.07	-0.24 ± 0.16	1334	-0.17 ± 0.23
*K I	0.65 ± 0.04	0.53 ± 0.32	1006	0.12 ± 0.36
*Li I	1.81 ± 0.00	1.88 ± 0.00	1142	-0.07 ± 0.00
Mg I	0.06 ± 0.52	-0.10 ± 0.69	1336	0.16 ± 1.21
*Mn I	0.11 ± 0.33	-0.10 ± 0.30	1158	0.21 ± 0.63
Mo I	0.87 ± 0.00	1.03 ± 0.00	1590	-0.16 ± 0.00
*Na I	-0.33 ± 0.17	-0.25 ± 0.19	958	-0.08 ± 0.36
Nd II	0.07 ± 0.39	0.38 ± 0.14	1602	-0.31 ± 0.53
Ni I	-0.44 ± 0.18	-0.24 ± 0.63	1353	-0.20 ± 0.81
O I	0.37 ± 0.21	0.47 ± 0.27	180	-0.10 ± 0.48
*Pr II	1.18 ± 0.82	1.15 ± 0.58	1582	-0.03 ± 1.40
Sc II	-0.13 ± 0.44	0.05 ± 0.29	1659	-0.18 ± 0.48
Si I	-0.40 ± 0.05	-0.23 ± 0.04	1310	-0.17 ± 0.22
Sm II	1.93 ± 0.83	2.22 ± 1.09	1590	-0.29 ± 1.92
Ti I	-0.27 ± 0.24	-0.11 ± 0.15	1582	-0.16 ± 0.39
Ti II	-0.19 ± 0.27	0.07 ± 0.30	1582	-0.26 ± 0.57
V I	0.11 ± 0.46	0.22 ± 0.38	1429	-0.11 ± 0.84
V II	0.22 ± 0.43	0.37 ± 0.38	1429	-0.15 ± 0.81
Y II	-0.47 ± 0.00	-0.23 ± 0.00	1659	-0.24 ± 0.62

NOTE: * corresponds to volatile elements and no * to refractory elements.

equilibrium condensation temperature. According to the classification by Taylor, they generally fall into one of the two following categories (35). Volatile elements (e.g., K, Na, Sn) display relatively low equilibrium condensation temperatures; refractories (e.g., Al, Sc, Ca) are the opposite, meaning they form solids at high temperatures. Some elements hold a moderate degree of these characteristics and are classified as moderately volatile (e.g., Li, Sr, Mn, Cu, Ba) and moderately refractory elements (e.g., Mg, Si, Cr, Fe, Co, Ni, Nb).

The lack of refractory elements in the second component of this system relative to its companion could allow the authors to verify its planet-hosting condition. This is because rocky bodies developed in the early stages of a planetary system's evolution appear to accrete more high-condensation-temperature elements than low-condensation-temperature elements from their host star.

HIP 34407/HIP 34426 are known to have similar stellar parameters (**Table 1**). However, this system has some discrepancies in its elemental abundance homogeneity patterns which might defy the underlying assumptions intrinsic to chemical tagging. To test the hypothesis that wide binaries can be traced back to their origins based solely on their chemical composition, we conducted a study on this wide binary system. Firstly, we performed a thorough spectral analysis on the components of both stars of the system and inferred their dominant elemental abundances. We found that HIP 34407/HIP 34426 has an abundance inhomogeneity Δ[X/H] ~ 0.18 dex and a metallicity difference of Δ[M/H] ~ 0.22 dex. These values are significantly higher than those found among other wide binaries. Finally, we concluded that the differences in elemental composition found may pose limitations to the assumptions inherent to chemical tagging.

RESULTS

To obtain the stellar parameters and determine the elemental abundances, we obtained the system's chemical composition by analyzing high-resolution spectra. The spectra were obtained by the MIKE spectrograph at Las Campanas Observatory (F. Espinoza-Rojas priv. comm.). We analyzed the spectra via iSpec. The results are expressed in [X/H] notation, which represents the abundance ratio of X element to hydrogen with respect to the solar value. The depth of the absorption lines as normalized flux represents the abundance of the corresponding elements in [X/H]. We found a value for overall metallicity difference of Δ[M/H] ~ 0.22 dex (**Table 1**). The results we obtained in chemical composition show a mean abundance difference of *Δ[*X/H] ~ 0.18 dex between the two stars (**Table 2**).

Oxygen abundances

We analyzed the O I absorption lines around the oxygen triplet region at 777 nm **(Figure 1).** We can see no significant differences in the equivalent widths of the O I absorption lines between the two stars. We found the difference in oxygen abundances to be relatively low at Δ[O/H] ≈ -0.10 dex.

Iron abundances

The Fe I line displays a notable contrast between the two spectra **(Figure 2)**. The analysis revealed the inhomogeneity in iron to be *Δ*[Fe/H] ≈ -0.19 dex. This difference is unexpectedly high when compared to other wide binaries.

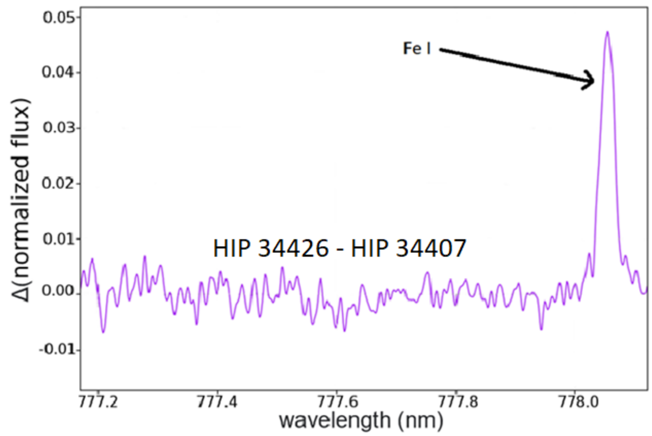

Figure 2. Fe I has the most different absorption line from the two spectra. Normalized flux difference of HIP 34407 and HIP 34426 around the 777 nm region obtained via iSpec. HIP 34407 was subtracted from HIP 34426. The purple line represents HIP 34407 subtracted from HIP 34426. The arrow is pointing at the peak in flux difference corresponding to Fe I.

Lithium abundances

We found a difference of *Δ*[Li/H] = -0.07 dex **(Figure 3)**. This element is known to get exhausted over time in solar-type stars, given that it burns at temperatures which are almost identical to those found in the bottom of the upper convective zone. Research determined that stars with lower effective temperatures and higher metallicity indexes experience a more profound lithium depletion (36). We found that HIP 34426 has a smaller [Li/H] ratio than its twin. This contradicts the scenario proposed above because HIP 34426 has a higher effective temperature and a lower metallicity than HIP 34407 (**Table 1**).

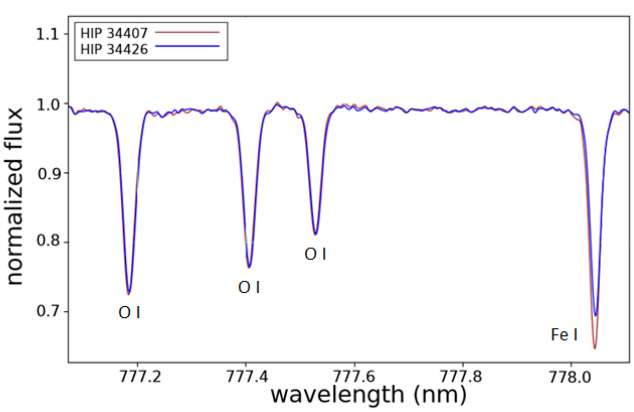

Figure 1. Normalized flux is the same for O I, but not for Fe I. Spectra of HIP 34426/HIP 34407 around the 777 nm oxygen triplet region. HIP 34426 is represented in royal blue and HIP 34407 is represented in sienna brown. Spectra was obtained from the MIKE spectrograph at Las Campanas Observatory and normalized via iSpec software.

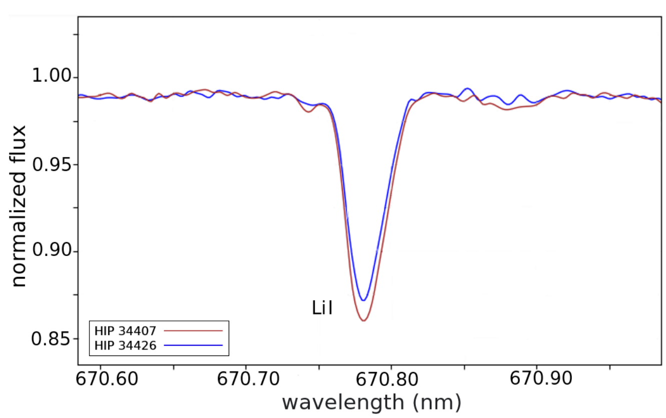

Figure 3. Lithium absorption line in the 670 nm region. Bar graphs represent the wavelength (nm) against the flux of the normalized spectra. Spectra was obtained from the MIKE spectrograph at Las Campanas Observatory and normalized via iSpec software.

Despite these findings, we must highlight that there is only one lithium line in the spectra and it is not very prominent, which overall implies that the values we obtained for lithium abundances may be particularly inaccurate.

Alpha-element abundances

Given that HIP 34407 and HIP 34426 display a relatively low metallicity, we expected to detect a slight enhancement of α -elements (e.g., C, O, Mg, Si, Ca) in their [X/Fe] ratios (37, 38). Overall, we found that the mean value of the alpha elements' abundances is [α /Fe] ~ 0.08 dex for HIP 34426 and [α /Fe] ~ 0.04 dex for HIP 34407 (data not shown). This lack of alpha elements is compatible with the expected alpha enhancements of stars found in the thin disk, a relatively flat structural component of the Milky Way (39).

Elemental condensation temperatures

Numerous studies discovered that discrepancy in abundance of an element among wide binaries is strongly negatively correlated with that element's condensation temperatures (33, 40–42). HIP 34407/HIP 34426 also seems to follow this trend, as we found a Pearson correlation coefficient of -0.77 **(Figure 4)**.

We calculated the volatile vs. refractory element ratio of the two stars contemplating two separate scenarios. In the first, we only consider volatile and refractory elements, while in the second scenario we also consider moderately volatile and moderately refractory elements (**Table 3**). We found that the overall abundance difference was 0.97 dex higher when we included the moderately volatile and moderately refractory elements.

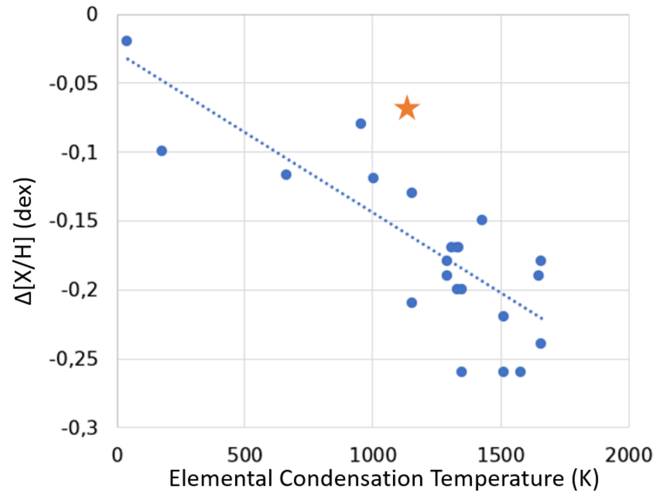

Figure 4. Lithium is the element that deflects the most from the overall correlation. Relationship between the system's abundance differences ([X/H]) and the elemental condensation temperature T_C of the binary star system HIP 34407/HIP 34426. We found a Pearson correlation coefficient of -0.77. The orange star corresponds to the value exhibited by lithium.

DISCUSSION

The discrepancies in iron abundances we found are significantly larger than those determined by previous research. For example, a study examined the abundances of 25 wide binaries, and uncovered that 20 of those pairs had iron homogeneity levels of Δ[Fe/H] ≤ 0.02 dex (34). Another study analyzed the chemical composition of 23 wide binaries. The authors discovered that a majority of pairs had abundance differences smaller than 0.02 dex, with some extreme cases showing discrepancies up to 0.07 dex (23). The follow-up article to this research studied 33 wide binaries and obtained differences usually no larger than 0.09 dex (25). Nevertheless, they encountered a case (HD 113984) where the difference was as high as 0.27 dex. This large value was mainly attributed to the peculiar stellar evolution of the primary star in the system. Still, they argued that this number might be explained by the effective temperature differences between the two stars, high levels of magnetic activity, or the accretion of refractory materials.

In summary, it seems that wide binaries are mostly homogeneous, and those cases which show differences above uncertainties, are tentatively explained by some exceptional circumstances (27, 32). These circumstances would be responsible for depleting or enhancing the [Fe/H] abundance ratios in one of the stars.

We also found that HIP 34407 and HIP 34426 display a significant difference in the ratio of volatile element abundance to refractory element abundance (Vol/Ref). These inhomogeneities in the distribution of refractory elements (e.g., Al, Ti, Fe) as opposed to volatile elements (e.g., C, N, O) are rather uncommon among twin-star binary systems (43). Nevertheless, a number of exceptions appear when we consider planet-hosting stars. For example, Melendez *et al*. conducted a high-precision (~ 0.01 dex) study of solar abundances with the aim of contrasting them to those of 11 solar twins (28). Their results indicated that the Sun has an

Table 3. Volatile vs. refractory element abundances of HIP 34407 and HIP 34426, along with the difference between the two stars.

Elements	HIP 34426 (dex)	HIP 34407 (dex)	Δ(Vol/Ref) (dex)
$(Vol/Ref)_1$	0.72	0.65	0.07
$(Vol/Ref)_2$	1.72	0.68	1.04

NOTE: $(Vol/Ref)_1$ is the quotient between volatile and refractory elements, while $(Vol/Ref)_2$ includes volatile, refractory, moderately volatile and moderately refractory elements. In the calculation of $(Vol/Ref)_1$ we obtained the quotient by dividing the mean value of the volatile elements by the mean value of the refractory elements. Similarly, we calculated $(Vol/Ref)_2$ by dividing the mean value of the volatile and moderately volatile elements by the mean value of the refractory and moderately refractory elements.

oddly elevated depletion of refractory elements ($a \simeq 20\%$) when compared to the rest of stars analyzed, which may be explained by the presence of planets in our Solar System. Another study found a notable difference (~ 0.20 dex) when contrasting the abundances of specific moderately volatile elements in the HD 240430/HD 240429 system (27). In this case, the enhancement of refractory elements (mostly lithium) in the first star's atmosphere relative to its companion was attributed to the accretion of rocky material by a planet forming after the star's birth. Researchers also detected an enhancement of refractory elements of ~ 0.1 dex and a depletion of volatiles of ~ 0.02 dex when studying the WASP-94Aa/WASP-94Ab system (44). Thus, if we consider these findings, HIP 34426 would seem to be the best candidate for holding a planet-hosting status. This is because this star displays much lower abundances (~ 0.32 dex) of refractory elements when compared to HIP 34407.

In the case of HIP 34407/HIP 34426, we found a Pearson correlation coefficient of -0.77. When we examined how each element is placed with respect to the correlation line, we found that lithium did not follow the trend. Indeed, we observed in our results that the [Li/H] abundances in HIP 34407 are higher than expected, and thus do not match well with the condensation temperature trend. Still, we must note that any conclusions regarding the lithium abundances may be compromised by the uncertainty in our calculations.

Researchers brought attention to the fact that stars with different atmospheric parameters such as surface gravity (log *g*) and effective temperature (T_{eff}) can experience different alterations in their chemical composition throughout their lives (45). This scenario would be explained by atomic diffusion, and its signature would vary depending on the star's evolutionary stage (46, 47). Despite this, the effects of atomic diffusion in the case of HIP 34407/HIP 34426 are probably insignificant. This is because atomic diffusion models are highly dependent on surface gravity, and our stars have similar (log *g*) values (**Table 1**). If we also consider that the two stars are in the same evolutionary stage and have very similar masses, the chances of finding traces of atomic diffusion within this system are low. The reason is that the effects of diffusion would be nearly identical for both stars, and thus they would likely cancel each other when looking for any differences.

To confirm or discard the possible presence of planets around HIP 34426, we must also look for any substantial discrepancies in radial velocity trends. Researchers collected data for the radial velocity of this system (33). In the case of HIP 34407, the radial velocity of the star did not change with time. HIP 34426, in contrast, exhibited a noteworthy linear trend in its radial velocity shifts. This phenomenon may reinforce our previous speculation of a planet orbiting the star. These findings might also be compatible with alternative scenarios, such as the presence of a third unseen companion in this system. We must state, however, that the likelihood of finding planets solely through the elemental abundances of their host star is very limited, given our current knowledge. Therefore, we suggest that the confirmation of this hypothesis should be explored by means of exoplanet transit surveys.

The differences in chemical composition we encountered bring us back to the initial question that motivated this work. Our results regarding the homogeneity of the system are dissimilar to those found mostly among wide binaries. Because of this, we must question whether this is an exceptional case which displays several discrepancies (possibly due to an external factor). However, it is still possible that these exceptional cases may be more common than previously thought. This would exhibit the limitations in the assumptions intrinsic to chemical tagging. We must take into account that thorough research around the chemical homogeneity of wide binary systems remains very limited. To the best of our knowledge, only 12 studies have carried out extensive abundance analyses on specific twin-star pairs, which is why we do not yet have an answer to the dilemma raised above. Since we cannot assure with certainty whether the inhomogeneities found in this system make it an exceptional case, we strongly propose that further research around this topic should be carried out in the years to come.

To summarize, we have found a mean metallicity discrepancy of Δ[M/H] ~ 0.22 dex between HIP 34407 and HIP 34426, which is significantly higher than the typical value of Δ[M/H] ≤ 0.07 dex found in other wide binary systems. Subsequently, we have detected an overall abundance difference of Δ[X/H] ~ 0.18 dex. The chemical inhomogeneity in this system was particularly elevated when contrasting its volatile vs. refractory element proportion. HIP 34426 displayed a value of ~ 1.72 dex, which was much higher than that of HIP 34407 at ~ 0.68 dex. Thus, this work rejects the hypothesis that wide binary systems are chemically homogeneous. This prompts a reevaluation of our understanding of stellar formation and evolution in wide binaries.

MATERIALS AND METHODS

The system's chemical composition was computed from high-resolution spectra. They were obtained from the Magellan Inamori Kyocera Echelle (MIKE) spectrograph on the 6.5m Magellan Clay Telescope located at Las Campanas Observatory (F. Espinoza-Rojas priv. comm.). The resolution of the spectra is R ~ 83,000 for the blue and R ~ 65,000 for the red orders, with their respective wavelengths ranging from ~ 320 to ~ 480nm and ~ 490 to ~ 950nm. The estimated S/N ratio is above 400 in both cases.

Statistics

The spectra were analyzed via iSpec, an open-source framework capable of determining these values via the generation of synthetic spectra (9, 48).

Firstly, a continuum fit and a flux normalization were performed and the radial velocity of each of the stars was obtained. This is done automatically by iSpec by fitting the spectra and correcting the radial velocity with respect to a chosen template. The template "NARVAL_Sun_370_1048" was selected because the physical characteristics of the investigated stars are relatively similar to those of the Sun.

After the spectra was normalized and a continuum fit was performed, the stellar parameters were obtained via iSpec's equivalent width method. This requires a model atmosphere and model abundances. For this, the solar abundances proposed by Grevesse *et al*. were considered, as well as the MOOG code developed by Sneden (49, 50).

For the obtention of chemical abundances, the Global Astrometric Interferometer for Astrophysics European Southern Observatory recommended lines in the 480-680 nm region were selected. The abundances in both HIP 34407 and HIP 34426 were identified by iSpec as well as their error range by comparing their spectra to the set lines.

The Pearson correlation coefficient between the system's abundance differences and elemental condensation temperatures was found via a correlation analysis performed with Microsoft Excel.

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