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The Radioactive Elements in the Atmosphere of HD25354—Are They the Result of the Symmetric Decay of the Chemical Elements of the Island of Stability?

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Abstract: In this research, we investigated the observed spectra of the hot peculiar star HD25354 with an effective temperature $T_{\rm eff}$ = 12,800 K, identified the lines of radioactive chemical elements, including the elements with short decay time, and estimated the abundances of these elements. We tried to confirm or reject the existence of promethium lines and lines of other radioactive elements which were detected in previous investigations of this star and explain the physical mechanisms which are responsible for the synthesis of these elements in the stellar atmosphere. We used two high-dispersion spectra of HD25354 observed with the 2 m telescope of Terskol observatory with resolving power near R = 60,000, and a signal to noise ratio near 200. The spectrum of the star from the archive of the 1.93 m telescope of Haute-Provence observatory was also used. The observations were compared with synthetic spectra and the abundance of promethium was found using the best four lines of this element in the observed spectra: log N(Pm) = 5.84 $\pm$ 0.16 in the scale logN(H) = 12. It is comparable to the abundances of stable lanthanides in the atmosphere of this star. The abundance of thorium derived from two lines of double-ionized thorium is log N(Th) = 3.59 $\pm$ 0.15. The upper limits for technetium, radium, actinium, uranium, and americium abundances are found to be equal to 4.0, 3.0, 1.25, 3.5, and 4.0, respectively. Maybe the existence of promethium lines and lines of other unstable chemical elements in the spectra of HD25354, as well as the other stars of our Galaxy, Magellanic Clouds, and Fornax dwarf galaxy, can be explained by contamination of its atmosphere by the products of kilonova outburst and by symmetric decay of chemical elements with long decay times located at the island of stability (atomic numbers Z = 110–128) of transfermium elements. Maybe the decay of superheavy elements of the island of stability can be one of the reasons for the enhanced abundances of rare earth lanthanides in different types of stars.

Keywords: stars—abundances; stars—individual (HD25354); nuclear reactions; nucleosynthesis stellar evolution; cosmic rays; accretion

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1. Introduction

Nuclear reactions were discussed as a possible source of stellar energy more than a century ago. Let us point to the publications [1,2] as examples. Merrill [3] was the first to identify the lines of a radioactive element with a short half-life in stellar atmospheres: the lines of technetium were discovered in the spectra of red giants. This research represents direct confirmation of the existence of nuclear processes in stellar interiors.

Modern stellar evolution theory was finalized by the authors of [4,5]. A significant part of helium was believed to have a cosmological origin, with only a small part of helium atoms having been produced in stars. For heavy elements with atomic numbers $Z \geq 29$ the *r*-, *s*-, and *p*-processes were identified as the physical mechanisms responsible for the production of these elements.

Later, Fowler [6] found that the energy density of microwave background radiation, first detected by Shmaonov [7] and later by Penzias and Wilson [8], is equal to the density of energy released in stellar interiors as a result of the synthesis of all helium atoms from hydrogen. Initially, this was accepted as a coincidence, but it later spurred attempts to construct a new theory with typical stellar lifetimes at least 10 times longer than previously accepted. The origin of helium and the lightest elements in this theory was discussed in [9].

It is worth noting that the latest James Webb Space Telescope observations detected many observational facts that are unpredictable in standard cosmology, prompting the possible consideration of alternative ideas in cosmology [10,11].

The synthesis of the heaviest elements, including those without stable isotopes, in the *r*-process is still accepted as one of the main sources of these elements [12–14], but the astrophysical sites of this process are still under discussion. The important role of the *r*-process in kilonovas is discussed in many papers—ref. [15] can be cited as an example.

The detection of promethium and other radioactive elements with short decay times in stellar spectra remains unexplained. This suggests the continuous production of these elements within stellar atmospheres or possibly within stellar interiors or chromospheres, followed by their transport to the layers where spectral lines form. The lines of short-lived isotopes were not only detected in the spectrum of HD25354.

Among the recent investigations of our Galaxy's stars, we can point to Przybylsky's star (HD101065), HD965, HR465 [16–23], and HIP13962 [24]. Faint lines of actinium were also detected in the spectra of the red supergiants of the Magellanic Clouds [25] and the Fornax galaxy [26].

This paper attempts to confirm or reject the previous identification of lines of radioactive elements in the spectrum of HD25354, and to estimate the possible abundances of these elements. In the following sections, we will review the previous investigations of HD25354, describe the observed spectra and archived spectral observations used, explain the methods of line identifications and abundance determinations, and present the detected absorption lines of radioactive elements. Section 7 provides an overview of the possible physical scenarios that could explain the presence of chemical elements with short half-lives in stellar atmospheres.

2. Earlier Investigations of HD25354

The first high-dispersion spectral observations of HD25354 were published by [27]. Spectra were obtained with a dispersion of 10 Å/mm. The high spectral resolving power revealed that this A0-type peculiar star shows unpredictable variations in the profiles of Eu, Cr, Mn, and other spectral lines, changes in total intensities, and variations in the weak magnetic field from 0 to −380 gauss. The strength of the magnetic field and the amplitude of its variations were confirmed by recent measurements [28].

The star is known as the variable V380 Per of α^2 CVn type, with a rotational period of 3.9 days and an amplitude of light variations in different filters near 0.03^m [29–31]. Ref. [32] pointed out that the effective temperature of HD25354 ranges from 11,000 to 12,500 K, which is higher than the usually accepted effective temperature for an A0-type star.

Jaschek and Brandi [33] used two spectra observed on 10 November and 10 December 1957, with a dispersion of 10 Å/mm, and identified nine lines of singly ionized americium (atomic number Z = 95), eleven lines of neutral curium (Z = 96), five lines of neutral thorium (Z = 90), twenty lines of singly ionized uranium (Z = 92), lines of several chemical elements with atomic numbers from Z = 41 to Z = 48, and lines of iodine and xenon (Z = 53 and 54, respectively) in the spectrum of HD25354. They also noted the significant differences between the two spectra used.

Adelman [34] examined [33] identifications, and found that most of them can be explained by the lines of other chemical elements, namely the lines of stable elements observed in the spectrum of solar chromosphere and in the spectra of similar Ap stars. The identification of neutral species in the spectrum of the relatively hot A0-type star HD25354 was pointed out to be highly suspect.

Later, Pyper and Hartoog [35] investigated the atmosphere of HD25354 using two spectra with a dispersion of 4.5 Å/mm and three spectra with a dispersion of 10 Å/mm. Four of these spectra covered one rotational period—from 25 August to 29 August 1969, and the last one was observed two months later on 1 November 1969.

The wavelength coincidence statistic was used to confirm or reject the existence of absorption lines of chemical elements in the spectrum of HD25354. The results of line identifications were published only for two best spectra observed with a dispersion of 4.5 Å/mm. For radioactive elements Pm, Ac, Th, Pa, U, Pu, Am, and Cm, the authors of [35] used the list of 31, 16, 29, 11, 34, 98, 29, and 18 lines with known wavelengths for the first ions of these elements, respectively.

The wavelength coincidences of these lines with absorption lines in observed spectra were found for 8, 4, 4, 0, 7, 15, 2, and 3 lines, respectively, for the first spectrum. For the second spectrum, the coincidences were found for 5, 5, 4, 3, 5, 12, 4, and 3 lines, respectively.

As a result, Pyper and Hartoog's [35] analysis of HD25354 did not confirmed Jaschek and Brandi's [33] identifications of rare earth actinide lines with short half-lives, but proposed a new extended list of possible detections of other lines of non-stable chemical elements in the observed spectra of this star.

Ref. [35] noted that the absorption lines of the third spectra of several stable chemical elements are present in the observed spectrum of HD25354; these are the lines of Ce III, Pr III, and Yb III.

The detectability of the absorption lines of third spectra confirms the high effective temperature of HD25354. The absorption lines of the first ions of elements with high ionization potentials, like Hg, Pt, Ta, and Au, were also detected. Ref. [35] pointed out that the effective temperature of the star can be close to $T_{\rm eff}$ = 11,000 K.

A year later, Pyper [36], on the basis of the same five spectral observations of HD25354 which were used before by [35], refined the list of line identifications. It was pointed that no strong spectrum variations were seen on any of the five spectrograms used in both studies. The identified species were distributed into four groups: present, probably present, possibly present, and not identified. The lines of U II were listed in the third group—possibly present. The lines of Pm II, Th II, Pu II, Am II, and Cm II were listed in the fourth group—not identified.

Refs. [37–39] confirmed the peculiarity of HD25354 and the variability of Sr, Cr, Eu, Ti, Fe, and Mn absorption lines. A total of 22 spectra with dispersions of 12.3 and 9.7 Å/mm were used. The star was found to be an SB1-type spectral binary system with a possible orbital period near 26 days. In this case, the eccentricity of the orbit was estimated to be near e = 0.26. The amplitude of radial velocity curve is near 5 km s^{-1}. The possibility of spots on the surface of the star was discussed.

The lines of the secondary component were not detected in the spectra. It was found that the spectral variations are not due to tidal motion but are bound to the rotation of the main component. The effective temperature and the surface gravity of the star were found to be equal to $T_{\rm eff}$ = 9050 K, and $\log g$ = 3.5.

Ref. [40] found the effective temperature $T_{\rm eff}$ = 9840 K using the observations of HD25354 in the Geneva photometrical system.

As mentioned earlier, the determinations of effective temperature of HD25354 show two extreme cases: the first with temperatures near 9000 K, and the second near to or higher than 11,000 K. This is very common for stars with peculiar chemical composition when temperature calibrations developed for stars with solar chemical compositions are used for peculiar stars.

As an example, ref. [41] published two values of effective temperature and surface gravity for HD25354, determined in the APOGEE survey using different methods. The first set of values is $T_{\rm eff}$ = 11,000 K and $\log g = 4.0$; the second set is $T_{\rm eff} = 8196.964 \pm 312.890$ K and $\log g = 4.7559 \pm 0.1155$.

Ref. [42], using 22 months of Gaia DR2 proper motion observations, estimated that the orbital radius of the HD25354 system is 2.246 astronomical units and the mass of the binary companion is equal to $464.69^{+130.63}_{-51.78}$ Jupiter masses (equivalent to 0.44 solar masses) if the orbital radius is reduced to one astronomical unit.

The results from [39,42] allow us to accept HD25354 as a multiple system. It seems reliable that HD25354 can be a triple system with an Ap (Bp) star as the main component, an invisible secondary component with a mass of at least 1–2 solar masses, an orbital period of 26 days, and a separation near 0.3 a.u. Additionally, there may be an invisible tertiary component with a mass near to or greater than 0.7 solar masses, a separation of about 2.246 a.u., and an orbital period of 1.5–2 years. More observations are necessary to confirm the structure of this system.

Note that the binarity or multiplicity of Ap stars can be one of the key properties of these objects. For more details, see the investigation by [43] and the recent review published by [44] for more details.

It should be noted that all above-listed investigations were based on spectral line identifications and radial velocity measurements. No determinations of the abundances of chemical elements in the atmosphere of HD25354 were published in the previous century.

Ref. [45], using spectra of HD25354 with a resolving power R = 60,000 identified 83 lines of ionized iron and 8 lines of double-ionized iron and found the effective temperature $T_{\rm eff}$ = 12,900 K and the surface gravity $\log g = 4.5$. The absorption lines of 18 stable chemical elements, from oxygen to erbium, were used to determine the abundances of these elements. The iron group elements show overabundances of approximately 1–2 dex, relative to solar values.

The lanthanides in the atmosphere of HD25354 are overabundant by 4.0 to 6.2 dex, relative to the Sun. The maximum overabundance relative to solar values was found for europium, with 6.0 dex for ionized europium and 6.2 dex for double-ionized europium. For lanthanides lighter and heavier than europium, the overabundances are lower.

The abundance pattern of HD25354 in the region of lanthanides can be described as an overlap of the left and right panels of Figure 7 published by Cowley [46]. There are the signs of odd–even abundance variations in the left panel and the strong maximum of abundances of europium with decreased values for the other lanthanides in the right panel. HD25354 is a typical Ap star and all the detected properties of the investigated object can be found in other stars of this type.

3. Observations

In this paper, we used two spectra of HD25354 observed at the 2-m telescope of the Ukrainian Peak Terskol observatory located in the Northern Caucasus. The spectral resolving power is approximately R = 60,000, the wavelength region spans from 3700 to 9400 angstroms, and the signal to noise ratio in coadded spectrum is over S/N = 200 in the centers of echelle orders. The spectra were observed on 28 and 29 August 2006.

We also used the spectrum of HD25354 from the ELODIE archive of the Haute-Provence observatory's 1.93-m telescope [47]. The wavelength region of this spectrum is from 4000 to 6800 angstroms, the spectral resolving power is R = 42,000, and the signal to noise ratio S/N is approximately 100. The spectrum was observed on 8 February 1996.

The described Peak Terskol observatory spectra were previously used by [45]. The initial reduction in these two spectra was conducted in 2006 with DECH20 software [48]. The URAN code [49] was used for the final processing of Peak Terskol and Haute-Provence observatory spectra.

It should be noted that no significant differences in line profiles between two Peak Terskol observatory spectra were found, allowing the coadding of these spectra to increase the signal to noise ratio.

All the results described in the next sections are based on the coadded spectra from the Peak Terskol observatory. There were clear differences detected between the Peak Terskol and Haute-Provence telescopes spectra; however, the main results obtained from the Peak Terskol observatory spectra are confirmed by the Haute-Provence observatory spectrum.

4. Methods

In this paper, we started with the atmosphere model of HD25354 selected by [45]. The use of new oscillator strength for lines of neutral, ionized, and double-ionized iron allows us to refine the values of the effective temperature to $T_{\rm eff}$ = 12,800 K, surface gravity to $\log g$ = 4.15, microturbulent velocity to $v_{\rm micro}$ = 0.23 km s^{-1}, and iron abundance to $\log N$(Fe) = 8.41 in the scale $\log N$(H) = 12.

We used the method described by [50,51]. The model with the parameters mentioned above was interpolated from the [52] grid of atmosphere models.

Low microturbulent velocity values have been observed in many late B-type stars. For example, ξ Oct with $T_{\rm eff}$ near 14,000 K, $v_{\rm micro}$ = 0.2 km s^{-1} [53], 66 Eri A with $T_{\rm eff}$ near 11,100 $\pm$ 100 K, $v_{\rm micro}$ = 0.9 $\pm$ 0.2 km s^{-1}, 66 Eri B with $T_{\rm eff}$ near 10,900 $\pm$ 100 K, $v_{\rm micro}$ = 0.7 $\pm$ 0.2 km s^{-1} [50], and ν Cap with $T_{\rm eff}$ = 10,200 $\pm$ 220 K, $v_{\rm micro}$ = 0.96 $\pm$ 0.55 km s^{-1} [54].

The synthetic spectrum of HD25354 with the described parameters and the chemical elements abundances from [45] was calculated for the whole wavelength region. This spectrum was compared with the observed spectra to make the reliable identification of spectral lines.

As mentioned earlier, the first investigations of the lines of radioactive elements in stellar atmospheres were conducted with wavelength coincidence statistics. Abundance calculations for these elements were not possible because the oscillator strengths and partition functions were not known for those elements. It was only possible to use wavelengths for investigations of most of the elements without stable isotopes.

An improved methodology was used by [17,22]. A line in the observed spectrum was identified as belonging to an unstable element in the absence of stable elements' lines in the synthetic spectrum. The synthetic spectrum should be calculated with reliable abundances of stable chemical elements. Refs. [19–21] calculated the oscillator strengths and partition functions for Tc, Pm, Ra, and Ac and identified several lines of these elements in the observed spectra of Przybylski's star, HR465, and HD125248, but the possible abundances or upper limits of these values were not published.

In this research, we focus exclusively on unstable elements with known oscillator strengths and partition functions. A spectral line was attributed to technetium or promethium if the abundance of the unstable element calculated from that line was similar to or lower than the abundances of stable elements with comparable atomic numbers.

This is considered a reliable criterion for technetium and promethium because stable elements with similar atomic numbers are present in the investigated stellar atmosphere.

Since all elements with atomic numbers $Z > 83$ are unstable, we first looked for those with the longest decay times, such as thorium and uranium. Lines corresponding to other elements with $Z > 83$ were identified if their abundances were comparable to or lower than those of thorium and uranium.

This approach enabled us to not only identify the spectral lines but also estimate possible abundances or upper limits for the unstable elements under investigation.

The identified lines were analyzed using the spectrum synthesis method. This method requires information about the broadening of spectral line profiles. In this study we used a Gaussian instrumental profile for a spectral resolving power of R = 60,000 and a rotational profile with $v \sin i = 15$ km s^{-1}. The projected rotational velocity of HD25354 was estimated using the profiles of iron lines with precise oscillator strengths. This value accounts for all possible mechanisms of spectral line broadening, including potential macroturbulent velocities. Therefore, the actual projected rotational velocity of the star may be lower. The derived value is in good agreement with the APOGEE survey [41] which found $v \sin i = 12.6$ km s^{-1}.

More details about the methodology used for stable chemical elements can be found in [55,56].

5. Lines of Radioactive Elements in the Spectrum of HD25354

Here, we will show the results of identification of absorption lines of unstable chemical elements in the spectrum of HD25354. We only analyzed unstable elements with known atomic data, namely ionization potentials, wavelengths, oscillator strengths, and partition functions. For all identified lines, the possible abundances or the upper limits of abundances were calculated using spectrum synthesis.

The identifications of the absorption lines for neutral atoms in the atmosphere of HD25354 are difficult because of the high effective temperature of the star. Decay times of the most stable isotopes are taken from [57,58]. The ionization potentials for all investigated species were updated in accordance with [59]. The estimates of partition functions for Ac III, U II, and Am I were taken from [60].

5.1. Technetium, Z = 43

We did not find the lines of neutral and singly ionized technetium in the observed spectrum of HD25354. To estimate the upper limit of technetium abundance in the atmosphere of HD25354, we selected the line of ionized technetium at λ 3975.017 Å. This line is located in the wing of a hydrogen line and is strongly blended with a line of ionized iron at λ 3975.016 Å. No signs of technetium absorption were detected at this wavelength. Synthetic spectra were calculated in the vicinity of this line with different abundances of technetium. This allowed us to find the upper limit $\log N(\mathrm{Tc}) \leq 4$.

The most stable technetium isotopes are ^{97}Tc and ^{98}Tc with decay times of $4.21 \cdot 10^6$ and $4.20 \cdot 10^6$ years, respectively. The oscillator strengths and partition functions were taken mainly from [21].

5.2. Promethium, Z = 61

We found many signs of singly ionized promethium lines in the observed spectrum of HD25354. The abundance calculations for all these lines show the abundances of promethium from $\log N(\mathrm{Tc}) = 5.5$ to $\log N(\mathrm{Tc}) = 6.1$. The strongest four lines are shown in Figure 1. The mean promethium abundance derived using these lines is $\log N(\mathrm{Pm}) = 5.84 \pm 0.16$. This value is similar to the abundances of other lanthanides in the atmosphere of HD25354 [45].

The most stable promethium isotopes ^{145}Pm and ^{146}Pm have decay times of 17.7 and 5.53 years, respectively. The oscillator strengths and partition functions are mainly taken from [19].

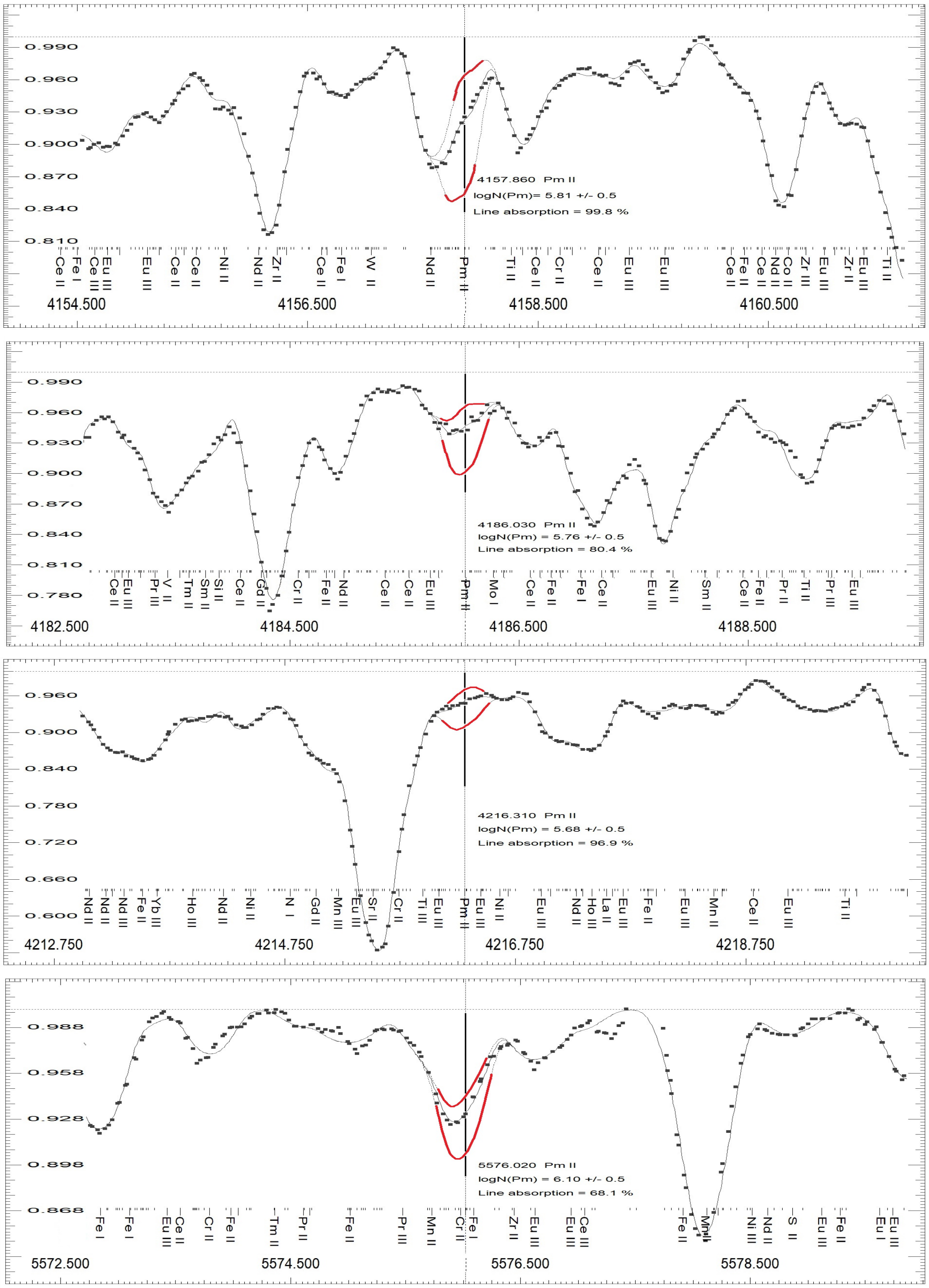

Figure 1. The observed spectra of HD25354 (points) and its approximation by synthetic spectra (solid lines) in the vicinities of four lines of ionized promethium. The axes show the wavelength in angstroms and the relative fluxes. The positions of the spectral lines taken into account in the calculations are marked in the bottom parts of the figures. Identifications are given for some of the strongest lines. The position of ionized promethium lines are marked by a vertical dotted/bold lines. Note that three synthetic spectra are shown in the vicinities of the promethium lines. These synthetic spectra are calculated for the best promethium abundance for this line, and the abundances which are lower and higher by 0.5 dex. The last two spectra are shown by bold red lines in the vicinities of the investigated line. The wavelengths of the Pm II line, the best promethium abundances, and the percentage of the promethium line in the total line absorption coefficient in the synthetic spectrum are pointed out in the central part of all panels.

5.3. Radium, Z = 88

No lines of radium were detected. We were only able to find the upper limit of radium abundances log N(Ra) ≤ 3. The line of singly ionized radium at λ 4682.28 Å was used to find this limit. The most stable radium isotopes ^{226}Ra and ^{228}Ra have decay times of 1600 and 5.75 years, respectively. The oscillator strengths and partition functions are taken from [20].

5.4. Actinium, Z = 89

This unstable chemical element also shows no detectable lines of its neutral atom and first ion in the observed spectrum of HD25354. The lines of the second ion allow us to find the upper limit of its abundance, which is log N(Ac) ≤ 1.25. Two of these lines are shown in Figure 2. The most stable radium isotopes, ^{225}Ac and ^{227}Ac, have decay times of 9.919 days and 21.773 years respectively. The oscillator strengths are mainly taken from [20], and the atomic data for Ac III from [61]. The partition functions for Ac I and Ac II are from [20].

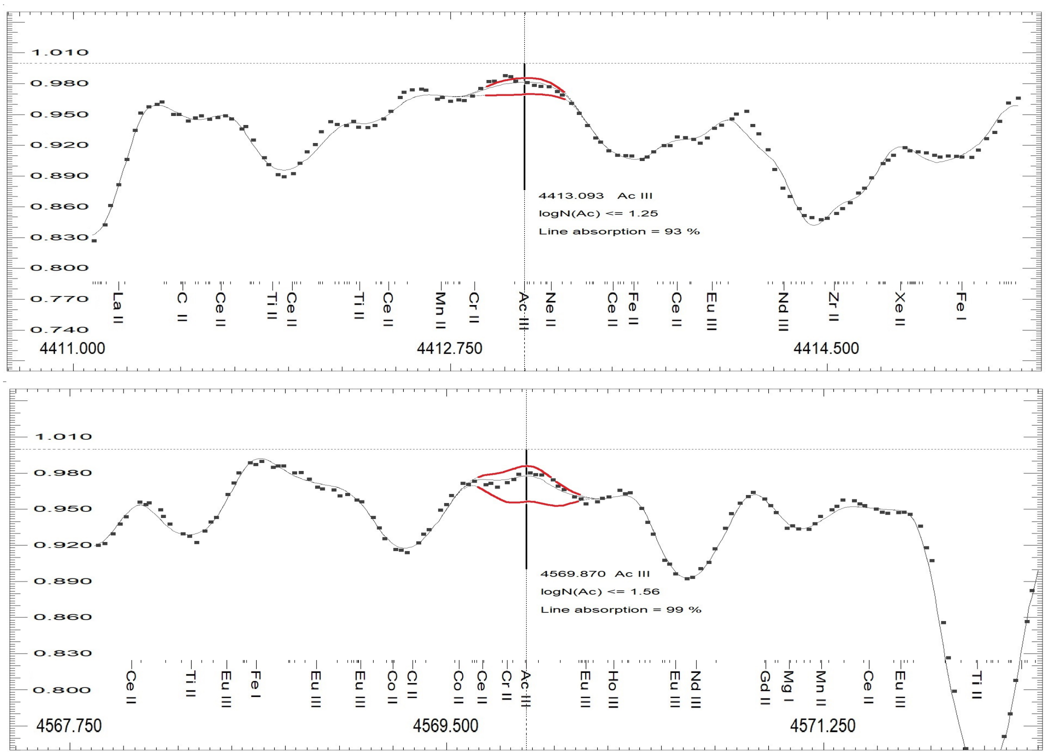

Figure 2. Similar to the previous figure, but for lines of double-ionized actinium.

5.5. Thorium, Z = 90

No lines of neutral or first ionized species were found in the observed spectrum. We found several lines of double-ionized thorium and determined the thorium abundance to be log N(Th) = 3.59 $\pm$ 0.15. The best two lines are shown in Figure 3. The most stable thorium isotopes, ^{230}Th and ^{232}Th, have decay times of $7.54 \cdot 10^4$ and $14.05 \cdot 10^9$ years, respectively. The oscillator strengths for ionized thorium were taken from [62], and for doubly ionized thorium, from [63].

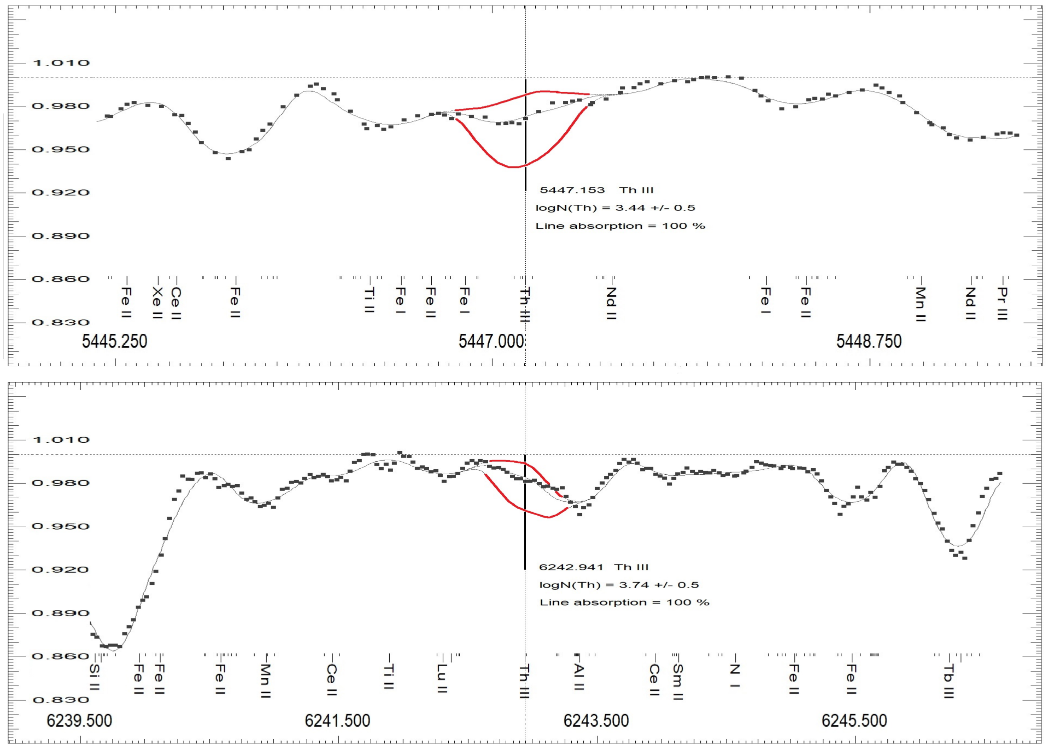

Figure 3. Similar to the previous figure, but for lines of double-ionized thorium.

5.6. *Uranium, Z = 92*

We were not able to identify uranium lines in the spectrum of HD25354. The most stable uranium isotopes, ^{235}U and ^{238}U, have decay times of $0.704 \cdot 10^9$ and $4.468 \cdot 10^9$ years, respectively. The oscillator strengths for singly ionized uranium were taken from [64,65]. The atomic data for lines of double-ionized uranium were taken from [66], but all these lines are outside the wavelength range of our observations. The upper limit of uranium abundance was estimated to be log N(U) ≤ 3.5.

5.7. *Americium, Z = 95*

Unfortunately, only information about the lines of neutral americium was published by [67]. Our attempts to find these lines in the observed spectrum were not successful. We estimate the upper limit of americium in the atmosphere of HD25354 to be log N(Am) ≤ 4. The most stable americium isotopes, ^{241}Am and ^{243}Am, have decay times of 432.6 and 7370 years, respectively.

5.8. *Summary of Lanthanide Abundances*

The high effective temperature of HD25354 weakens all lines of neutrals atoms. To find the abundance pattern in the atmosphere of HD25354 [45,68] used model atmospheres method and measured the equivalent widths of 18 stable chemical elements from oxygen to erbium. The equivalent widths of lanthanides were measured for all elements between La and Er with the exception of Pm and Gd. To obtain the full abundance pattern from La to Er, we found the gadolinium abundance using the spectrum synthesis method.

Table 1 summarizes the results of the abundance determinations for Pm, Ac, Th, and Gd.

The mean abundance of gadolinium in the atmosphere of HD25354 is found to be log N(Gd) = 5.87 ± 0.20. Figure 4 shows the abundance pattern of HD25354 for elements from lanthanum to erbium. The axes are atomic numbers and absolute abundances (the scale is log N(H) = 12). The values for promethium and gadolinium are derived in this paper, while the abundances of other lanthanides are taken from [68].

Table 1. The abundances of Pm, Ac, Th, and Gd in the atmosphere of HD25354.

Ion	λ (Å)	E_{low} (eV)	loggf	log N	%	Y	Ref.
Pm II	4157.860	0.246	0.360	5.81	100	0.92	[19]
Pm II	4186.030	0.182	0.000	5.76	80	0.95	[19]
Pm II	4216.310	0.055	−0.060	5.68	97	0.95	[19]
Pm II	5576.020	0.661	−0.170	6.10	68	0.93	[19]
Ac III	4413.093	0.099	−0.489	≤1.25	93	0.98	[61]
Ac III	4569.870	0.521	−0.277	≤1.56	99	0.98	[61]
Th III	5447.153	0.063	−0.790	3.44	100	0.97	[63]
Th III	6242.941	0.598	−0.980	3.74	100	0.98	[63]
Gd II	5092.249	1.727	−0.230	6.01	99	0.94	[69]
Gd II	4732.609	1.102	−0.540	5.66	96	0.97	[69]
Gd II	4438.254	0.662	−0.820	5.90	100	0.92	[69]
Gd II	4408.250	0.556	−0.750	6.08	100	0.91	[69]
Gd II	4059.359	1.727	−0.149	5.87	98	0.93	[70]
Gd II	4037.323	0.662	−0.110	5.51	99	0.90	[69]
Gd II	3861.147	1.616	−0.006	6.07	99	0.82	[70]

The columns of the table are as follows: the identification of the used line (Ion), the wavelength (λ (Å)), the energy of the low level (E_{low}(eV)), the used oscillator strength (loggf), the calculated abundance (log N) in the scale log N(H) = 12, and the part of line absorption produced by this line at its central wavelength in percent (%). The last value is taken from the synthetic spectrum calculation before the convolution of the synthetic spectrum with rotational and instrumental profiles. The next column is the relative intensity in the observed and calculated spectra in the core of the line (Y), where the continuum level corresponds to the value Y = 1.0. The last column is the reference to the used oscillator strength (Ref.).

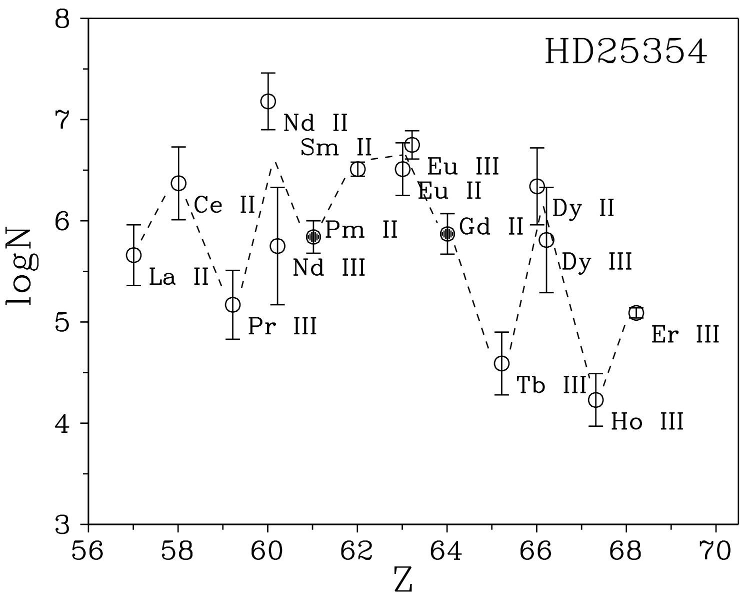

Figure 4. The abundance pattern of HD25354 for elements from La to Er. The values for Pm and Gd are found in this paper, the abundance of other elements are taken from [68].

6. Discussion

The explanation of the existence of radioactive elements with short decay times in stellar atmospheres requires a better understanding of stellar evolution history.

As mentioned earlier, modern stellar evolution theory was established by Burbidges, Fowler, and Hoyle in 1957 [4]. The foundation of this theory was laid by their pioneering work. An excellent review of the subsequent developments in this field can be found in [71]. However, the analysis of the chemical composition of different types of stars, especially hot main sequence stars, demonstrated that nuclear reactions in stellar interiors are not sufficient to explain the variety of abundance patterns in peculiar stars.

As a result, in 1965, the same authors [72] accepted that the explanation of observed stellar chemical compositions requires developments in several directions. These are the following:

- Refining the theory of nuclear reactions in stellar interiors;
- More detailed theory of physical processes in stellar atmospheres;
- Taking into account the influence of the outer environment, particularly the accretion on the surface of the stellar atmosphere.

Let us point out a few unsolved problems in the mentioned directions. One example of a non-standard nuclear reaction inside stars is the possible existence of degenerated neutron cores within stars: Thorne-Żytkow objects [73,74]. These are neutron stars surrounded by a nondegenerate massive diffuse envelope. The observed spectra can be very similar to those of red supergiants. Modern problems in the observational identification of these objects are discussed by [75].

Michaud, in 1970 [76], pointed out that radiative diffusion should be very important in stellar atmospheres dominated by radiative energy transport. This theory was developed in many papers, for example in [77]. This phenomenon is important for main sequence stars with effective temperatures higher than 6500 K or 7000 K, and also for red giant and supergiant stars [78]. The interplay of radiative diffusion and the accretion of nuclear-processed matter from the evolved binary companion was discussed by [79].

Another possibility of contamination of normal stellar atmospheres by heavy elements is the accretion of asteroids and planets discussed by [80,81]. Note that this was proposed several decades before the discovery of the first exoplanets. This scenario allows for an alternative explanation of different anomalies in the chemical composition of stellar atmospheres, first of all the spots on stellar surfaces and, maybe, the stratification of chemical elements' abundances with height in the atmosphere. It is now discussed as one of the possible explanations for anomalies in Am and Ap stars [82] and also in other types of stars [83].

An additional unsolved problem in the theory of stellar atmospheres is the dependence of relative (to the Sun) abundances of chemical elements in stellar atmospheres on the second ionization potentials of these elements. This effect was found for chemical elements with second ionization potentials close to the ionization potentials of hydrogen (13.6 eV). It was discovered in 1949 [84] for A-F main sequence peculiar stars. It was proposed that this effect can be explained by charge-exchange reactions between hydrogen atoms and the first ions of different chemical elements in stellar atmospheres.

Later, in 1971 [85], it was pointed out that hydrogen atoms can come from the interstellar environment and the above mentioned charge-exchange reactions can be the source of low-energy cosmic rays in the Galaxy, and the reason for braking the rotational velocities of A- and B-type magnetic peculiar stars. Bohm-Vitense [86] confirmed the existence of this effect also for chemical elements with second ionization potentials close to the first ionization potential of helium (24.6 eV).

This effect was found in several binary stars [87–89] and in several thousand main sequence, barium, and red giant stars with effective temperatures between 3500 K and 12,000 K [55,90,91]. Most of these stars do not have strong magnetic fields. A detailed theory of the described effect has not yet been constructed.

The aforementioned unsolved problems primarily concern stable chemical elements. But what could the possible explanation for the presence of non-stable elements be? The detection of spectral lines of chemical elements with short decay times necessitates a physical process responsible for the synthesis of these elements in stellar atmospheres.

Refs. [17,18,22] identified the lines of elements from Z = 84 to Z = 99, with the exception of At (Z = 84) and Fr (Z = 87) in the atmosphere of Przybylski's star (HD101065). The effective temperature of this star is near 6500 K. Refs. [17,22] attempted to explain these identifications by proposing the existence of shells with increased abundances of long-lived radioactive elements (such as Th and U) in the stellar atmosphere, and by the natural α-

and β-decay of these elements. The final step of most of these radioactive decay chains is the creation of lead (Z = 82) or bismuth (Z = 83).

It is worth noting that Przybylski's star exhibits overabundances of many heavy elements. Ref. [16] found overabundances of Ta, W, Re, Os, Ir, Pt, Au, Hg, Th, and U ranging from 4.4 to 2.7 dex relative to Solar system values, yet no signs of Pb and Bi lines were detected. Ref. [17] pointed out that the upper limits of Pb and Bi abundances in the atmosphere of Przybylski's star are 2.8 and 1.4, respectively (in the scale log N(H) = 12). These values correspond to upper limits of log N(Pb) $\leq$ 0.77 and log N(Bi) $\leq$ 0.75 with respect to the solar system values published by [92]. The low upper limits of Pb and Bi overabundances in the atmosphere of Przybylski's star suggest that the radioactive decays of heavier elements (Z $\geq$= 84) are still occurring in this star.

An additional mechanism that can contribute to the abundance anomalies in Przybylski's star and similar objects might be spallation reactions.

Ref. [93] demonstrated that the reactions of flare-accelereted particles with neodymium offer a mechanism for the production of observable quantities of Pm. Later Ref. [94] proposed that similar reactions could be responsible for the anomalous ratio of lithium isotopes in the atmosphere of Przybylski's star. Ref. [16] suggested that spallation reactions might also produce Tc and Pm in Przybylski's star.

Goriely [95] calculated a numerical model of a star with an initial solar chemical composition and a powerful flux of accelerated particles from the external environment. All nuclei with 0 $\leq$ Z $\leq$ 102 and located between the proton drip line and the neutron-rich side of the valley of stability were included in the network. The study demonstrated that the observed anomalies in the abundance pattern of stable chemical elements in Przybylski's star could be the result of irradiation by this particle flux. The irradiation is time-limited. Therefore, for unstable elements with short lifetimes, such as promethium, the time elapsed between the nucleosynthesis event and the observation cannot be much longer than a few years.

Refs. [96–99] developed several simple models of a binary system with a main sequence primary component and a neutron star as the secondary component. These models allow for the continuous irradiation of the primary component by jets from pulsar. The possible binarity of Przybylski's star can not be excluded. As discussed earlier, HD25354 might be a triple system with an invisible secondary component. The mass of this component suggests that it could be a neutron star. To confirm or to reject this model it would be necessary to combine the models proposed by [96–99] with the nuclear network described by [95].

It is also possible to expect X-ray or other high-energy emissions from this triple system. In 1974, a strong X-ray flare was observed 5 degrees from the position of HD25354 [100], with the size of the error box exceeding this distance by a factor of two. The flare lasted approximately 12 min, with an intensity about half that of the Crab nebula at comparable energies.

It is important to mention another possibility for the production of promethium in stellar atmospheres: the fission of superheavy elements, including those in the island of stability. These elements may have atomic numbers between Z = 112 and Z = 128. According to theoretical predictions, the isotopes with the longest decay time should have a magic neutron number of 184 and proton numbers of Z = 114, Z = 120, and Z = 126. The predicted lifetime for Fl^{298}_{114} is 10^7 years [101,102]. Recent theoretical calculations by [103] indicate a longest decay time near 10^{10} seconds, which corresponds to approximately 300 years. It is worth noting that only unstable isotopes of elements with Z $>$ 110 have been discovered so far. The synthesis of stable isotopes requires higher energies, which cannot be achieved in current experiments.

The only hope is to find these elements in the Universe. Ref. [104] detected three tracks of elements with atomic numbers 113 $<$ Z $<$ 129 in cosmic rays. If these discoveries can be confirmed, it would suggest that the longest decay time of superheavy elements could be comparable to the time required for cosmic rays to propagate at least to the nearest stars.

Kuchowicz [105–107] proposed a scenario for the synthesis of promethium in stellar atmospheres as a result of the aforementioned fission of superheavy elements. The long lifetimes of some of these elements allow for the continuous production of promethium if the stellar atmosphere is contaminated by material from a binary companion. The symmetric fission of superheavy elements in meteorites was discussed by [108] to explain the anomalous isotopic composition of Xe and Kr.

The synthesis of superheavy elements is usually discussed as a result of the *r*-process, but other possibilities have also been considered. One possible site for the production of superheavy elements is in binary systems with a black hole as the primary component and a neutron star as the secondary component. Ref. [109] discussed the possible collisions of these components. While it is not possible to consider the black hole itself as the site of superheavy element synthesis, the neutron star in such a binary system was proposed by [110–112] as a source of superheavy nuclei with mass ranging, for example, from A = 200 to A = 400. The most interesting prediction from these papers is the possibility of a new nuclear process, where superheavy nuclei are produced only within the specified mass numbers. One possible site for this process could be kilonova explosions.

The symmetric fission of superheavy elements was suggested by [113] to explain the overabundance of rare earth elements observed in many types of stars. For example, the overabundance pattern shown in Figure 7 (right panel) published by [46] and Figure 4 of this paper could be the result of this process. We can also point to the overabundance of tellurium (Z = 52) in Procyon as a result of the symmetric fission of elements with atomic numbers $Z > 100$ [114,115]. If nucleosynthesis in the *r*-process can reach the region of superheavy long-lived nuclei with Z = 110–120, the decay of these nuclei could strongly influence the structure of the plot of stellar relative abundances in the region of mass numbers $A > 130$. Recent investigations into element abundance patterns in stars have suggested the reality of the fission of nuclei heavier than uranium [116].

It is worth noting that many of the scenarios discussed here have only tentative theoretical explanations. For example, consider using these scenarios to describe the evolution of binary stellar systems, as in [117]. Any uncertainties in the theory could result in very different predictions. Currently, the spectroscopy of superheavy elements is still in the early stages of theoretical development [118]. Even the masses of black holes in binary systems can be overestimated by as much as a factor of two [119,120].

7. Conclusions

We used the spectral observations of HD25354 to determine the abundances and upper limits of radioactive elements in the atmosphere of this star. The abundances for promethium and thorium are log N(Pm) = 5.84 ± 0.16 and log N(Th) = 3.59 ± 0.15, respectively. We only found the upper limit for the abundances of technetium, radium, actinium, uranium and americium: 4.0, 3.0, 1.25, 3.5, and 4.0, respectively.

We point to four plausible scenarios to explain the presence of radioactive elements with short decay times in stellar atmospheres. These are the following:

- The existence of long-lived radioactive elements, such as Th and U, in the stellar atmosphere, along with their natural α- and β-radioactive decay.
- Spallation reactions.
- Irradiation of stellar atmosphere by a pulsar in a binary system.
- Fission of superheavy elements with $Z > 110$ if the atmosphere is contaminated by these elements as a result of supernova or kilonova explosion of the binary component. Only the synthesis of superheavy elements is discussed.

All four scenarios could operate simultaneously. To construct a realistic explanation for the synthesis of superheavy elements in stellar atmospheres, it is necessary to take into account the radiative diffusion, the accretion of hydrogen and helium from the interstellar environment, the possible accretion of planets and asteroids, the influence of magnetic fields, and other physical effects. Creating detailed theories for most of these effects still requires significant research.

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