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INVESTIGATION OF THE RADIOACTIVE PROMETHIUM LINES IN STELLAR SPECTRA

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ABSTRACT. Eleven lines of promethium Pm II in the spectra of the magnetic peculiar A0 V star HD 25354 were analysed thoroughly in order to obtain information about how the short-lived element lines behave in spectra acquired on different observation dates. It has turned out that the intensity variations in time are typical for these lines with some of them being observed as emissive or absent at certain time intervals. The obtained list of Pm II lines in the spectra of the magnetic peculiar star HD 25354 has been employed to investigate promethium abundances in atmospheres of other stars, such as HR 465 (T_{eff} = 111,840 K), HIP 13962 (T_{eff} = 6,250 K) and BL 138 (T_{eff} = 3,939 K). The investigation interval has been limited to the spectral range of 4000–5800 Å and oscillator strengths within –0.76 < log gf < 0.4.

Keywords: stars: abundances – promethium: atmospheres – stars: individual (HD25354, HR465, HIP13962, BL138).

АНОТАЦІЯ. Досліджується вміст радіоактивного прометію в атмосферах зір в діапазоні ефективних температур від 12800 до 4000 К, а саме: в атмосферах магнітно-пекулярних зір HD 25354 і HR 465, цефеїди HIP 13962, червоного гіганту BL 138, що належить кулястій карликовій галактиці Форнакс. Період піврозпаду найтривалішого ізотопу 17.7 років серед 24 нестабільних ізотопів прометію – цей факт привів до упередженого дослідження цього елементу в спектрах зір. З появою сил осциляторів для прометію, розрахованих Фіветом та ін. в 2007 році, з'явилась можливість дослідити кількісно цей елемент по відношенню до атомів водню в атмосферах зір. Першими оцінили Нієльсен та ін. (2020) вміст прометію в атмосфері магнітно-пекулярної зорі HR465, який виявився досить високим – трохи менше 5 dex. Дана робота є першою роботою, яка детальним чином досліджує лінії прометію в спектрах зір з використанням синтетичного спектру зір після детального дослідження параметрів їх атмосфер та хімічного складу стабільних елементів. Лінії прометію розглядались лиш ті, які не є блендованими іншими лініями. Для спостереження ліній прометію PmII в спектрах більш гарячих зір вміст прометію повинен бути більшим, ніж в спектрах холодних зір. Діапазон вмісту прометію від 6 dex до –0,5 dex при температурах атмосфер 12800 і 4000 К. Еквівалентні ширини не перевищують 20 міліангстрем в спектрах зір. Дана робота стимулює дослідження сил осциляторів в більш широкому діапазоні спектрів та більш низьких значень.

Ключові слова: зорі: кількість – прометій: атмосфера – зорі: індивідуальні (HD25354, HR465, HIP13962, BL138).

1. Introduction

Promethium is the only unstable element among lanthanides. The isotope ^{145}Pm is the longest-lived one with a half-live of only 17.7 years. Like other radioactive elements with short half-lives, promethium is not an element necessarily observed in stellar atmospheres. An active mechanism of replenishment of this element is a precondition for its observing in a spectrum, and it is most likely that such a production mechanism should not be the only one. Scenarios according to which promethium is likely to be produced in amounts sufficient for its spectral observability were considered in the study (Tjin et al., 1973), including scenarios of production of this element in the atmosphere of a binary star with a pulsar companion that emits high-energy particle fluxes to the target star. This scenario is corroborated by the case of the Cepheid HIP 13962, a former binary companion of a pulsar in the system that decayed just 3 million years ago, which is a too short period of time on the scale of the star's lifespan. Weak lines of the radioactive actinium with a short half-life can be observed in the star's spectra (Gopka et al., 2022). Identification of promethium lines in the spectra of HIP 13962 is an important substantiation of such a scenario.

According to the review of literature made in the study (Yushchenko et al., 2024), HD 25354 is an X-ray triple system made of three objects, including an additional 0.7 solar mass tertiary component separated by 2.246 AU with a period of orbit of 1.5–2 years about the centre of mass of the system that consists of the main component – HD 25354 – and a 1–2 solar mass invisible secondary component separated by 0.3 AU with an orbital period of 26 days. In this system of the main and secondary components a scenario of the radioactive enrichment of the HD 25354 atmosphere through the activity of the neutron star is not ruled out either. It bears reminding that the neutron star (pulsar) has a mass of about 1.4 solar masses and a diameter not greater than 30 km, which is in agreement with the observed characteristics of the invisible component.

This paper vividly demonstrates manifestation of the short-lived promethium lines in the spectra of HD 25354 obtained on two straight nights in 2006 as compared to the lines in the spectrum dated 1996 from the ELODIE archive (http://atlas.obs-hp.fr/elodie/). Each line with the maximum Pm contribution has been analysed, and the respective results are illustrated below. It allows us to avoid misunderstanding when using spectra obtained on other observation dates, for which the spectral pattern is different. Let us recall that the spectral lines intensity variations are typical for HD 25354, which was first reported by Babcock (1958). In order to compare promethium abundances in the atmospheres of cooler stars, we have considered the late-type red giant BL 138 with an effective temperature T_{eff} = 3,939 K that is located in the centre of the Fornax dwarf spheroidal galaxy, which is the most massive satellite galaxy of the Milky Way at twice the distance to the Magellanic Clouds.

2. Investigation of the radioactive promethium lines in the spectra of the atmospheres of HD 25354, HR 465 and BL 138

Promethium lines in the stellar spectra were identified based on the comparison of the synthetic spectrum with the observed one, having thoroughly examined parameters and chemical composition of the respective stellar atmospheres. Having employed the oscillator strengths for promethium lines determined in the study (Fivet et al., 2007), we identified promethium lines with the maximum contribution. The synthetic spectrum was calculated using the parameters found in our earlier study from the HD 25354 spectra covering the wavelength range of 4000–5800 Å: the effective temperature T_{eff} = 12,800 K; the surface gravity log g = 4.0; microturbulent velocity v_{mi} = 0.5 km s^{-1}, and chemical abundances as reported (Yushchenko et al., 2008) in the first approximation. We used the spectra obtained by Faik Adil oglu Musayev on two straight nights in 2006 – namely, on the nights of November 28 to November 29 and that one of November 29 to November 30 – with a 2-meter telescope at the Terskol Peak Observatory, as well as the ELODIE archive spectra acquired in 1996 at the Haute-Provence Observatory (OHP). Some lines in the spectra available exhibit profile and intensity variations even over two straight observation nights. However, the greatest variations can be observed in the spectrum obtained at OHP in 1996 that has narrow and sharp lines. Spectra acquired at the Terskol Peak Observatory in 2006 can be distinguished by their broad lines in which narrow emission lines of various intensities, sometimes strong ones, appear. The description of the spectral lines, given earlier in the study (Jaschek&Brandi, 1972) upon the analysis of two spectrogram plates obtained one month apart in 1957, has been completely borne out. We identified 11 absorption lines of promethium in the spectra of HD 25354 and determined the atmospheric promethium abundance. The magnetic peculiar star HR 465 (T_{eff} = 11,840 K; log g = 4.3; v_{mi} = 1.66 km s^{-1} as per (Fivet et al., 2007) and the red giant BL 138 (T_{eff} = 3,939 K; log g = 0.71; v_{mi} = 2.3 km s^{-1}, and the metallicity [Fe/H] = –1.01) were used to make a comparison of the respective promethium abundances with that one in the atmosphere of HD 25354 with T_{eff} = 12,800 K. We used the spectrum of BL 138 obtained by Letarte et al. (2010) with FLAMES multi-object instrument connected to GIRAFFE spectrograph with the high-resolution setups at the European Southern Observatory's (ESO) Very Large Telescope (VLT). The observation was performed with a spectral resolving power R = 30,000 in the wavelength ranges 5339–5608, 6119–6397 and 6308–6689 Å with a signal-to-noise ratio from 30 to 100 at different wavelengths.

Now let us consider fragments of the spectra of HD 25354 and BL 138 in the region of promethium lines. In this study, we used in-process fragments of spectra from the URAN software system (Yushchenko, 1998). The methods and techniques of investigation of promethium lines in the spectra of HIP 13962 are similar to those employed in the study of actinium lines (Gopka et al., 2022).

The results of the investigation of promethium lines in the respective spectra of HD 25354, HR 465, HIP 13962 and BL 138 are given in the Table. The first column presents the identified wavelengths of the Pm II lines. The second column shows the degree of ionization (61.01) of the lines that have been investigated. The third and fourth columns give oscillator strengths and energies of lower levels for each line. Equivalent widths for the observations from the ELODIE archive and those obtained at the Terskol Peak Observatory are listed in the fifth and sixth columns, respectively; likewise, promethium abundances determined from those observations are given in the seventh and eight columns, respectively. The ninth and tenth columns present the promethium abundance in the atmosphere of HD 25354 determined through the synthetic spectrum technique from the mean of either four or two observed spectra obtained at the Terskol Peak Observatory and the percentage of promethium at the corresponding line wavelength, respectively.

We obtained the following mean promethium abundances: log N(Pm) = 5.80 ± 0.15 and log N(Pm) = 5.91 ± 0.12 for the observations at OHP and Terskol Peak Observatory; and log N(Pm) = 5.84 ± 0.16 for the observations at the Terskol Peak Observatory using the synthetic spectrum technique. Further, the Table shows the results of our investigations of the promethium abundance in the Cepheid HIP 13962 log N(Pm) = –0.37 ± 0.15, and the mean Pm abundance in BL 138 log N(Pm) = –0.54 ± 0.12.

The results of our investigations of promethium in the atmosphere of HR 465 with the parameters from the observations at Bohyunsan Optical Astronomy Observatory

(BOAO) reported in (Fivet et al., 2007): T_{eff} = 11,840 K, log g = 4.3 and v_{mi} = 1.66 km s^{-1}, are presented lower in the Table. The mean promethium abundance is log N(Pm) = 5.05 ± 0.01.

Further, the Table shows the results of our investigations of the promethium abundance in the Cepheid HIP 13962 log N(Pm) = –0.37 ± 0.15, and the mean Pm abundance in BL 138 log N(Pm) = –0.54 ± 0.12.

3. Conclusions

This paper presents an analysis of the lines of the radioactive short-lived promethium Pm II whose longest-lived isotope ^{145}Pm has a half-life of only 17.7 years. We consider spectra of magnetic peculiar stars HD 25354 and HR 465, the Cepheid HIP 13962, a former binary companion of a pulsar in the system that decayed just 3 million years ago, and the late-type red giant BL 138 that along with BL 148 are located in the centre of the Fornax dwarf spheroidal galaxy, which is the most massive satellite galaxy of the Milky Way at twice the distance to the Magellanic Clouds.

As expected, promethium lines can be distinguished by the intensity variations in time. Promethium lines at a wavelength of 5561.73 Å are observed in the spectra within a broad spectral range with T_{eff} from 12,800 K to 4.000 K. Promethium abundances in hotter stars are higher than those in the atmospheres of late-type stars. If the promethium line identification is only performed based on the coincidence of the line wavelengths in the stellar spectra with the laboratory ones, then the number of such lines beyond the wavelength of 5800 Å would be considerably greater. When determining stellar abundances of promethium, Pm lines beyond the wavelength of 5800 Å are not observed in synthetic spectra, but they can be identified in actual spectra, which may indicate the necessity to correct the oscillator strengths used.

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Analysis of the HD 25354 spectral lines at the Pm wavelength of 4137.95 Å

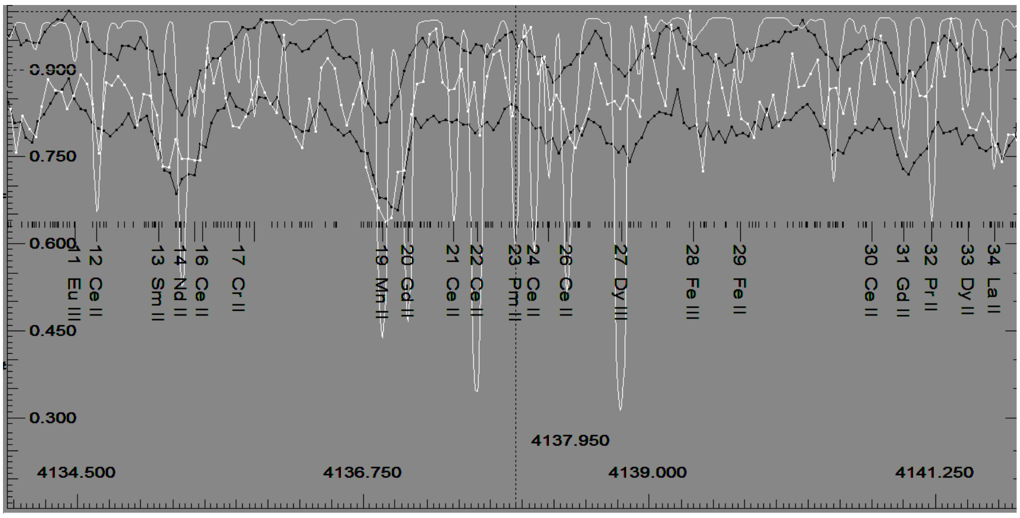

Figure 1: A fragment of the HD 25354 spectra obtained at the Terskol Peak Observatory, which are depicted in black colour. The upper spectrum was obtained on the second observation night – from November 29 to November 30, 2006 – while the lower one was acquired on the first night – from November 28 to November 29, 2006. The spectrum obtained at OHP is shown in white colour; in this spectrum, the promethium line is identified at a wavelength of 4137.95 Å, and the lines are sharp. The equivalent width is 16.2 mÅ, which corresponds to log N(Pm) = 5.69. In the spectra obtained at the Terskol Peak Observatory there is no Pm line at a wavelength of 4137.95 Å. As is seen, compared to the spectra obtained at the Terskol Peak Observatory, the spectrum from the ELODIE archive has stronger lines of other lanthanides, which are represented in the spectra by sharp lines (Ce II, Gd II, Dy II and La II).

For comparison, the promethium abundance in the atmosphere of HR 465 log N(Pm) = 5.0 at a wavelength of 4137.95 Å was determined from the spectra at the phase of stronger lanthanide lines with an equivalent width W = 12 mÅ and the following atmospheric parameters: T_{eff} = 11,840 K; log g = 4.3, and v_{mic} = 1.66 km s^{-1} (Fivet, 2007).

The line 4137.95 Å was used in the study by (Nielsen et al., 2020) to determine the promethium abundance, which yielded log N(Pm) < 4.2 and log N(Pm) < 4.9 at ϕ = 0.68 and 0.85 of the spectroscopic period, respectively, over the 21.5-year period.

Analysis of the HD 25354 spectral lines at the Pm wavelength of 4157.86 Å

Figure 2 represents the general appearance of the spectra in the region of the promethium line at 4157.86 Å. There are no absorption lines of promethium in the middle spectrum (obtained at OHP), the lines are sharp. Two lower spectra of HD 25354 were acquired on the first observation night – from November 28 to November 29, 2006 – at the Terskol Peak Observatory; they were recorded in the observation log as HD 25354-2181 and HD 25354-2182. Two upper spectra were obtained on the second observation night – from November 29 to November 30, 2006 – at the Terskol Peak Observatory; they were recorded in the observation log as HD 25253-2191 and HD 25354-2192.

The appearance of the spectra changed within the space of two straight nights: there is a strong emission line in the first observation at the Terskol Peak Observatory (HD 25354-2181), and then there is an emission line in the second observation on the first night as well, but it is weaker.

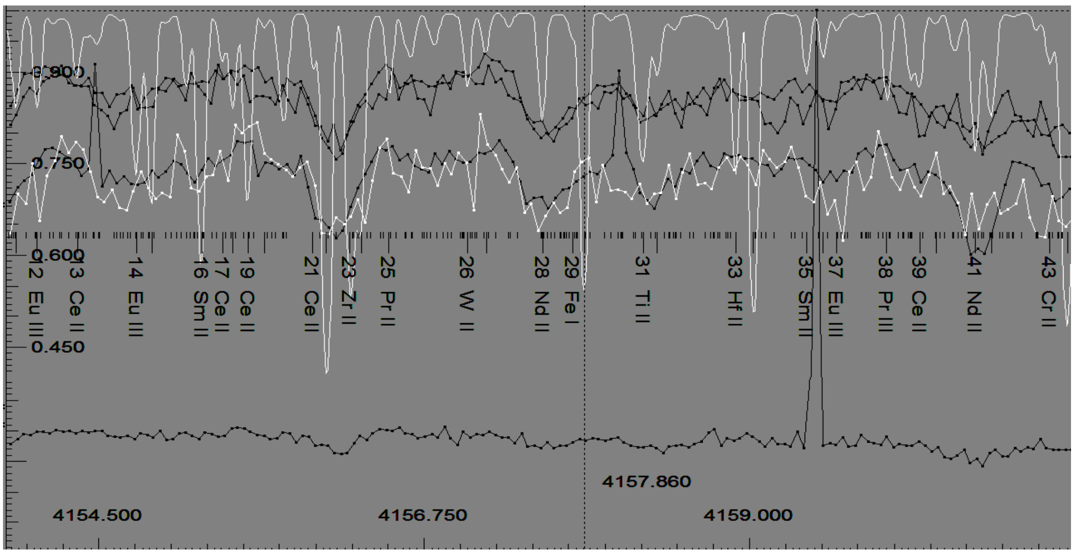

Figure 2a: An in-process fragment of spectra (from the URAN soft system (Yushchenko, 1998) taken when investigating the Pm line at 4157.86 Å in the spectra of HD 25354; it confirms the spectral line description given by (Jaschek & Brandi, 1972). In the spectrum obtained at OHP, plotted in white colour, the promethium line has not been identified. Th mean of the spectra obtained at the Terskol Peak Observatory was employed to determine the promethium abundance using a synthetic-spectrum technique.

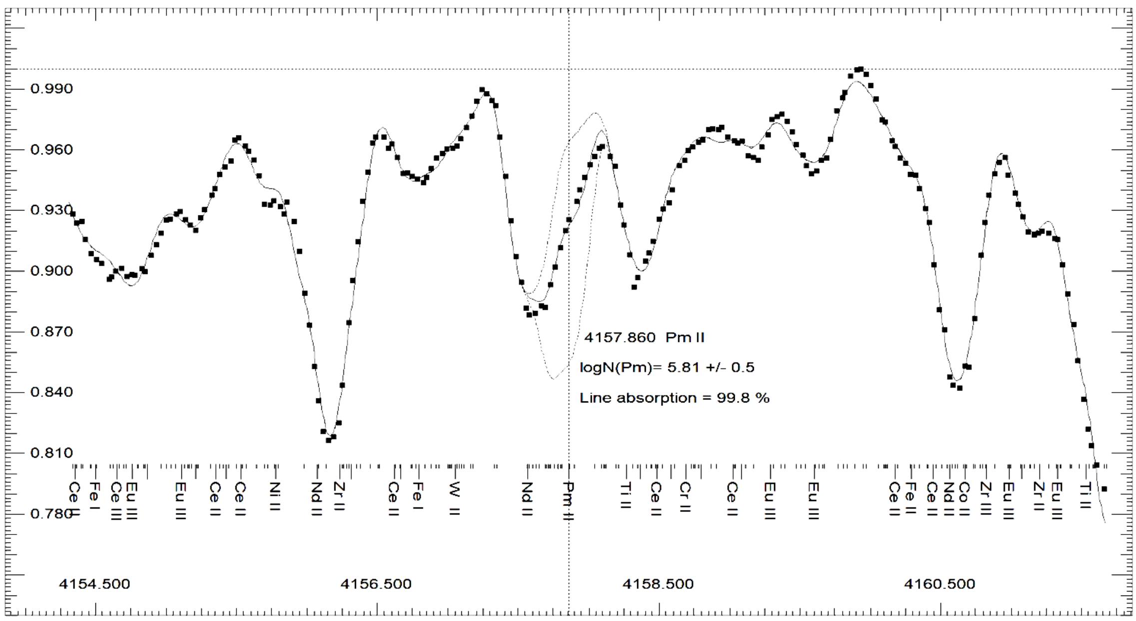

Figure 2b: The promethium abundance in the atmosphere of HD 25354 from the spectrum representing the mean of four observations at the Terskol Peak Observatory was determined through a synthetic-spectrum technique and equal to log N(Pm) = 5.81 ± 0.5. The percentage of promethium at a wavelength of 4157.86 Å is 99.8%, with the emission lines being excluded. The figure shows chemical elements for which the percentage is greater than 50%.

Analysis of the HD 25354 spectral lines at the Pm wavelength of 4186.03 Å

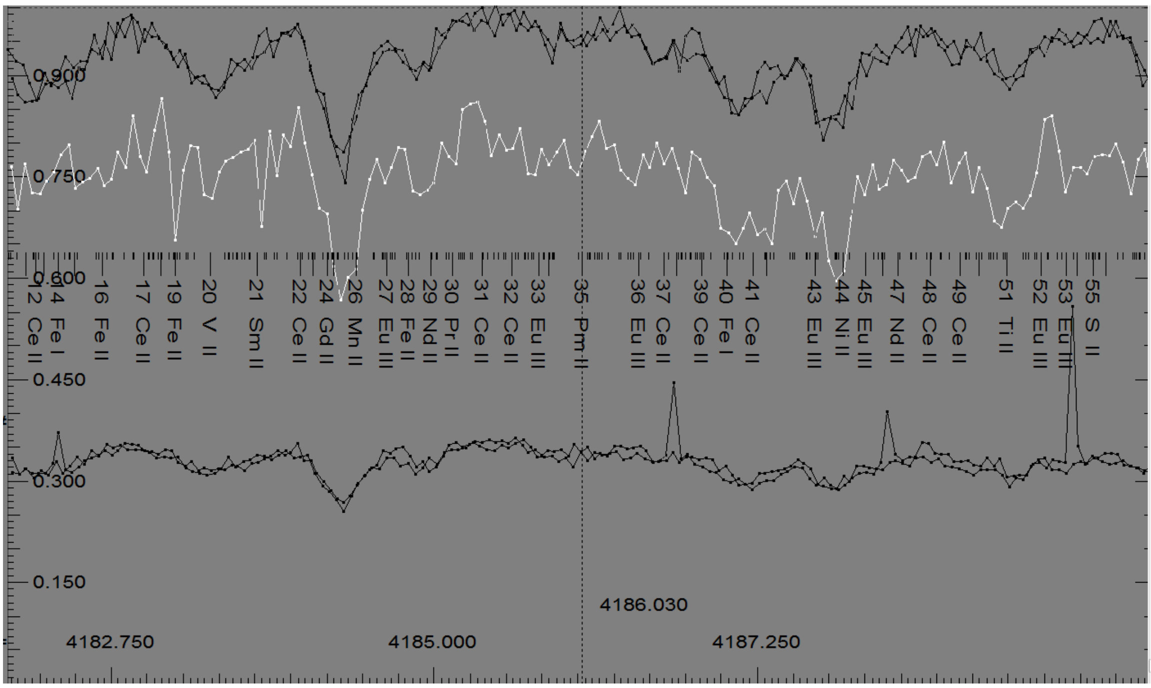

Figure 3a: The observed spectra in the region of the Pm II line at 4186.03 Å. The spectra are shifted relative to each other along the Y axis similar to Fig. 1. Narrow emission lines can be observed within the broad lines of the spectra obtained on the first observation night at the Terskol Peak Observatory. The Pm II line at 4186.03 Å in the spectrum dated 2005 has an equivalent width W = 17 mÅ, which corresponds to the Pm abundance log N(Pm) = 5.94 on the hydrogen scale log N(H) = 12. In the spectrum obtained on the second observation night at the Terskol Peak Observatory, recorded in the observation log as HD 25354-2192, which is best approximated by the Gaussian distribution, the promethium line has an equivalent width W = 16.4 mÅ, which corresponds to the Pm abundance log N(Pm) = 5.91.

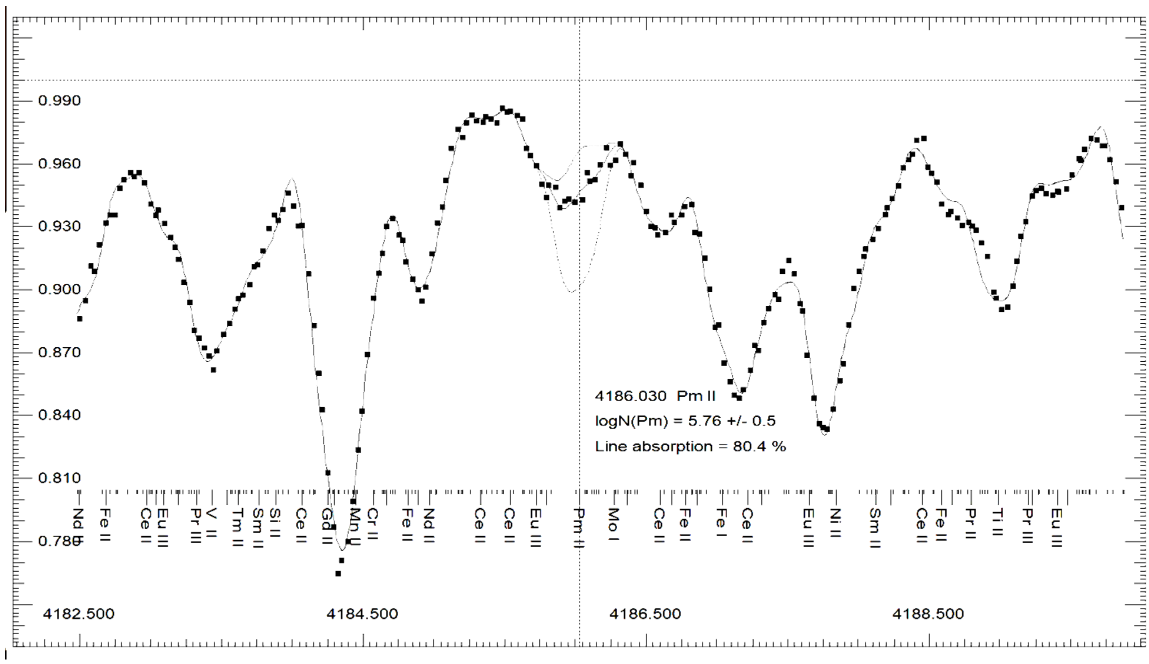

Figure 3b: Using the mean of four HD 25354 spectra obtained at the Terskol Peak Observatory, we determined the promethium abundance log *N*(Pm) = 5.76 from the Pm II line at 4186.03 Å with the promethium percentage of 80.4%.

Analysis of the HD 25354 spectral lines at the Pm wavelength of 4216.31 Å

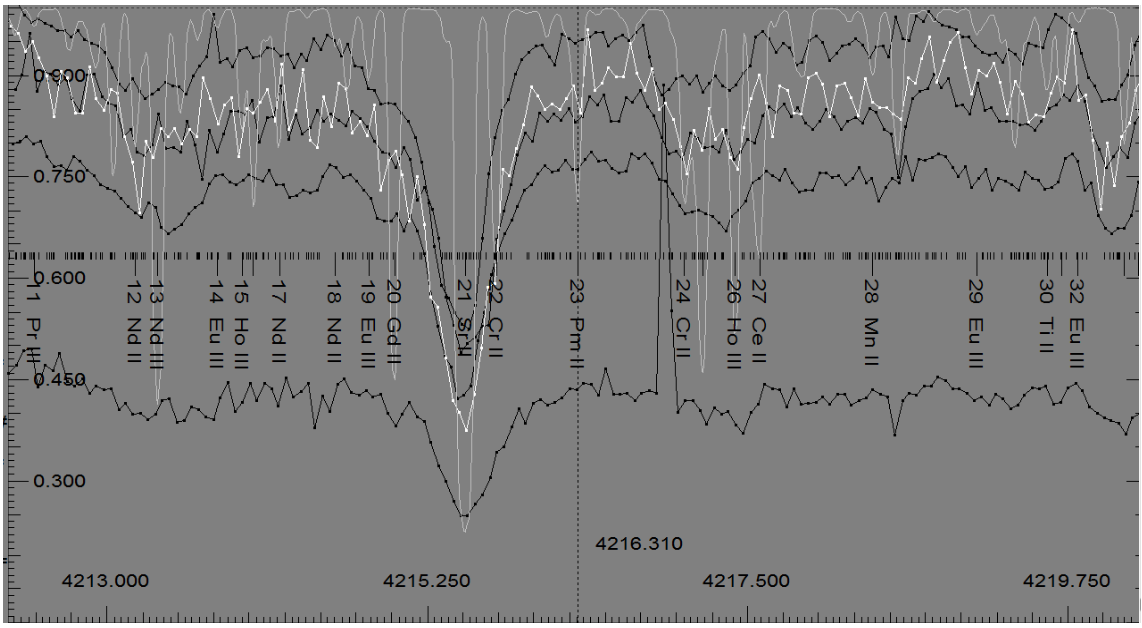

Figure 4: The spectrum obtained at OHP is depicted in white colour; it exhibits sharp and narrow lines. The equivalent width of the promethium line (λ 4216.31 Å) is 9.8 mÅ, which corresponds to the Pm abundance log N(Pm) = 5.60. From the spectrum obtained during the last observation at the Terskol Peak Observatory, recorded in the observation log as HD 25354-2192, the equivalent width W = 11.2 mÅ, which corresponds to log *N*(Pm) = 5.67.

For comparison, the promethium abundance in the atmosphere of HR 465 log N(Pm) = 5.08 at a wavelength of 4216.31 Å (W = 4 mÅ) was determined from the spectra at the phase of stronger lanthanide lines with an equivalent width W = 9 mÅ and the following atmospheric parameters: T_{eff} = 11,840 K; log *g* = 4.3, and v_{mic} = 1.66 km s^{-1} (Fivet, 2007).

Analysis of the HD 25354 spectral lines at the Pm wavelength of 4297.78 Å

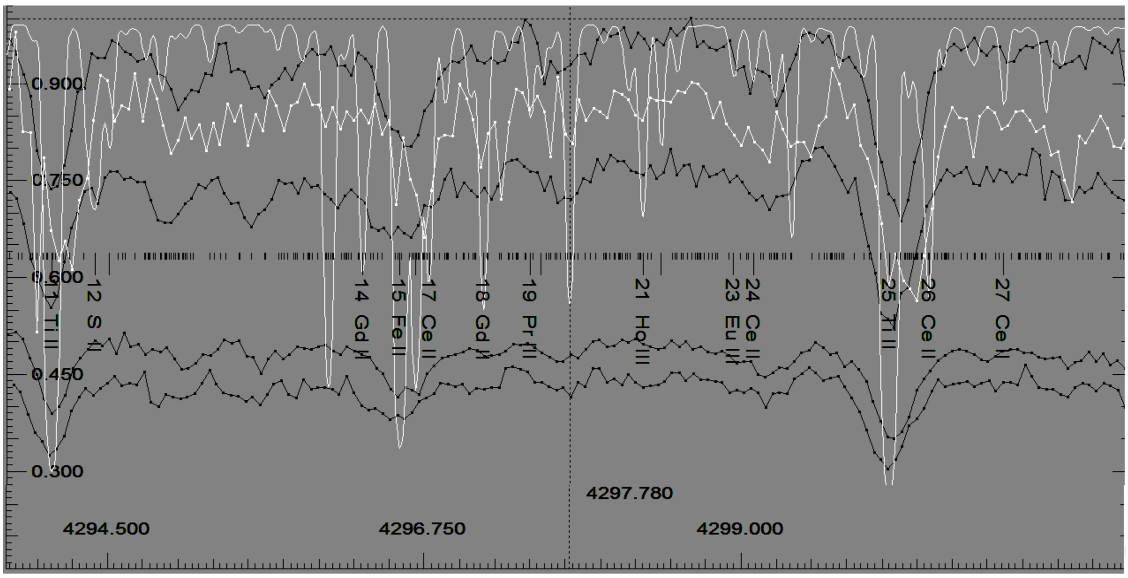

Figure 5a: Using the Pm II line at 4297.78 Å with an equivalent width of 11.7 mÅ, we determined the promethium abundance log *N*(Pm) = 5.523 on the scale of log N(H) = 12 (from the ELODIE archive spectrum). Stronger lanthanide lines (Pr III at 4297.50 Å; Ce II at 4297.575 Å, and Eu II at 4297.647 Å) can be observed in the blue wing of the Pm line in the spectra obtained at the Terskol Peak Observatory over two observation nights. The first observation at the Terskol Peak Observatory (recorded as HD 25354-2181, the middle spectrum) with the least blended line in the spectrum yields W = 20.5 mÅ, which corresponds to log *N*(Pm) = 5.91.

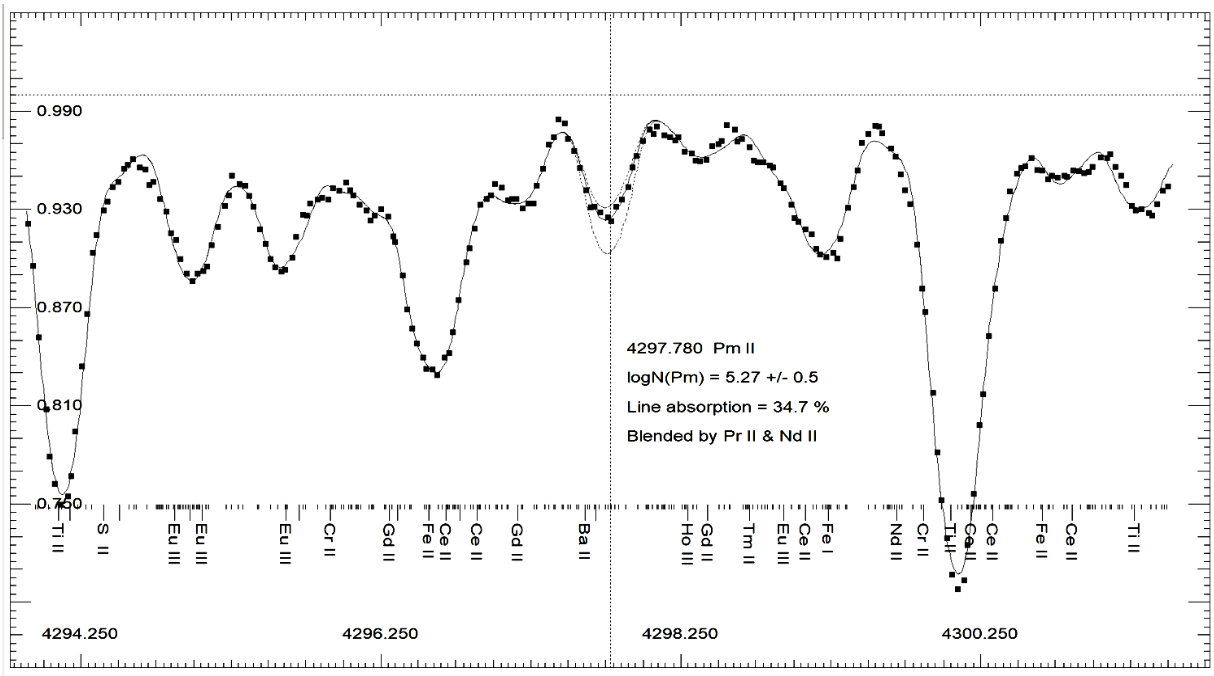

Figure 5b: Factoring in the blended lines of promethium results in an underestimated Pm abundance from the total spectrum.

Analysis of the HD 25354 spectral lines at the Pm wavelength of 4651.93 Å

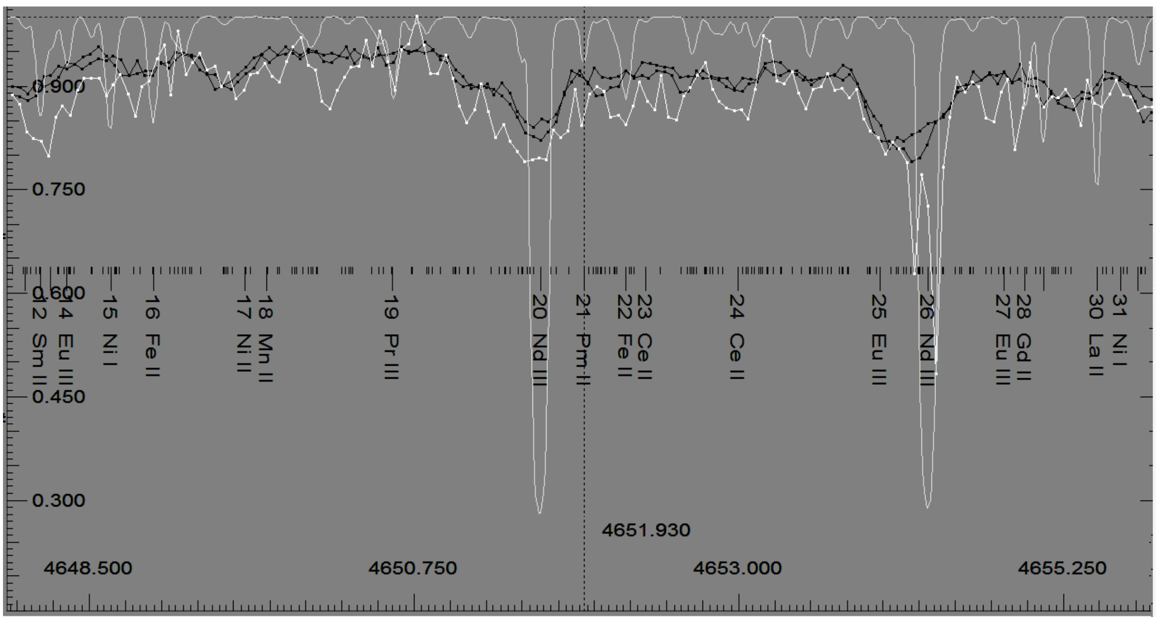

Figure 6: The Pm line at a wavelength λ 4297.78 Å in the spectrum obtained at OHP has an equivalent width of 5 mÅ (the spectrum is depicted as a white line). In the synthetic spectrum, shown in light grey colour, the profile of the Pm line is almost identical to the observed line profile in the spectrum acquired at OHP. The promethium abundance is log *N*(Pm) = 6.01.

Analysis of the HD 25354 and BL 138 spectral lines at the Pm wavelength of 5546.08 Å

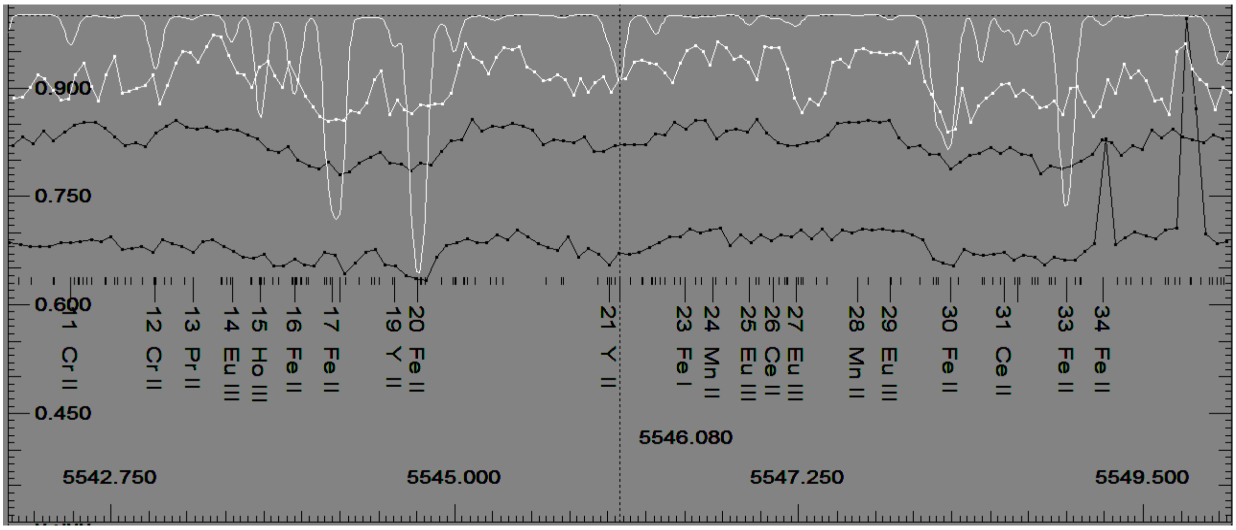

Figure 7a: The Pm abundance log *N*(Pm) = 5.80 was determined from the ELODIE archive spectrum using the Pm line at a wavelength λ 5546.08 Å with W = 4 mÅ. When using the spectrum obtained at the Terskol Peak Observatory without emission lines, the Pm abundance is log *N*(Pm) = 6.00 with W = 7.3 mÅ.

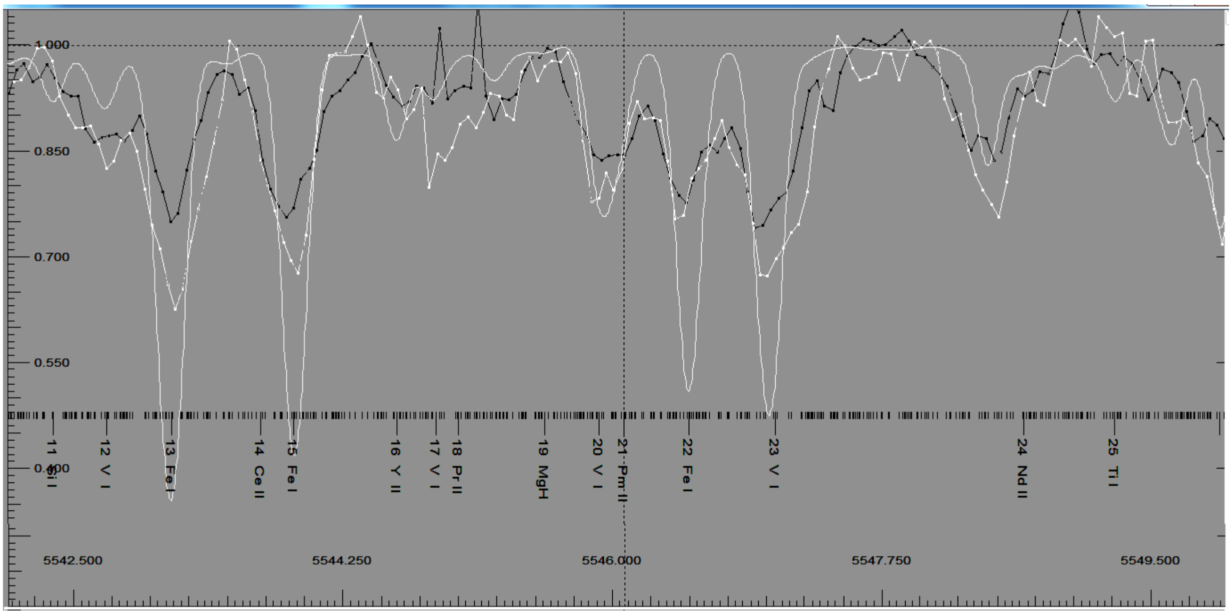

Figure 7b: In order to compare the Pm abundance in the atmospheres of late-type stars, we took the Pm line at a wavelength of 5546.08 Å from the spectrum of BL 138 located in the Fornax dwarf spheroidal galaxy; the selected line has an equivalent width W = 17.2 mÅ, which corresponds to the Pm abundance log *N*(Pm) = 0.76 (shown in black colour) on the hydrogen scale log *N*(H) = 12. The Pm line in the BL 18 spectrum is blended; this spectrum is depicted in white colour. We used the spectrum of BL 138 obtained by Letarte et al. (2010) with FLAMES multi-object instrument connected to GIRAFFE spectrograph with the high-resolution setups at the European Southern Observatory's (ESO) Very Large Telescope (VLT).

Analysis of the HD 25354 and BL 138 spectral lines at the Pm wavelength of 5561.73 Å

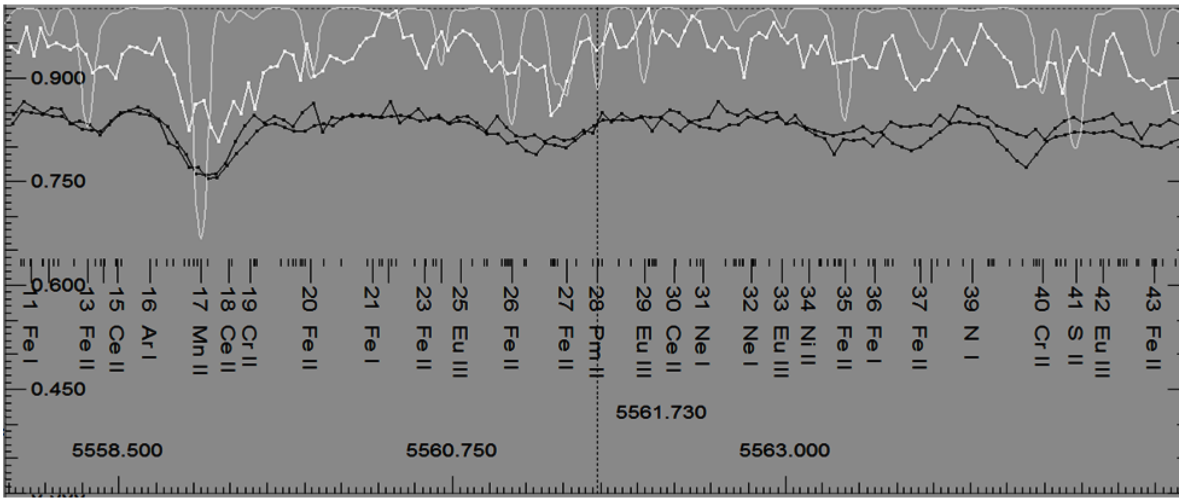

Figure 8a: A comparison between the spectra obtained at the Terskol Peak Observatory (the lower two spectra with broad lines) and at OHP (the upper spectrum with narrow and sharp lines). The Pm line at a wavelength of 5561.73 Å with an equivalent width W = 5 mÅ, which corresponds to the Pm abundance log N(Pm) = 5.65, has been identified in the spectrum obtained at OHP. The non-extended synthetic spectrum is plotted in light grey colour while the ELODIE archive spectrum is shown in white colour.

For comparison, according to a working hypothesis of Fivet et al. (2007) (Fivet, 2007), the promethium abundance in the atmosphere of HR 465 log N(Pm) = 5.08 at a wavelength of 5561.73 Å with an equivalent width W = 4 mÅ was determined from the spectra at the phase of stronger lanthanide lines with the following atmospheric parameters: T_{eff} = 11,840 K; log g = 4.3, and v_{mic} = 1.66 km s^{-1}. The effective temperature T_{eff} is lower than in HD 25354, so is the Pm abundance on the hydrogen scale log N(H) = 12.

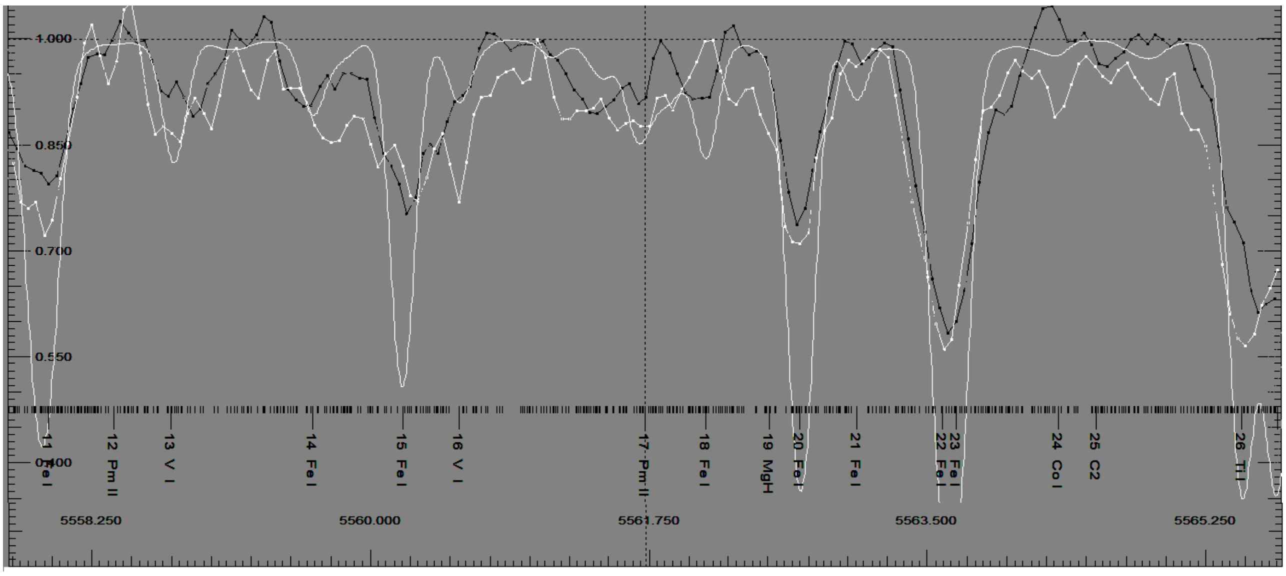

Figure 8b: The Pm line at a wavelength of 5561.73 Å with an equivalent width W = 11.9 Å, which corresponds to the Pm abundance log N(Pm) = –0.655 on the hydrogen scale log N(H) = 12, has been identified in the spectrum of BL 138 located in the centre of Fornax dwarf spheroidal galaxy (the line is shown in black colour). The blended Pm line in the BL 148 spectrum, depicted in white colour, is more intense as well. In the BL 148 spectrum, the Pm line at a wavelength of 5556.88 Å with an oscillator strength log gf = –0.036 and the energy of a lower level of 1.131 has an equivalent width W = 21.7 mÅ, which corresponds to the Pm abundance log N(Pm) = –0.16 on the hydrogen scale log N(H) = 12.

Analysis of the HD 25354 and BL 138 spectral lines at the Pm wavelength of 5576.02 Å

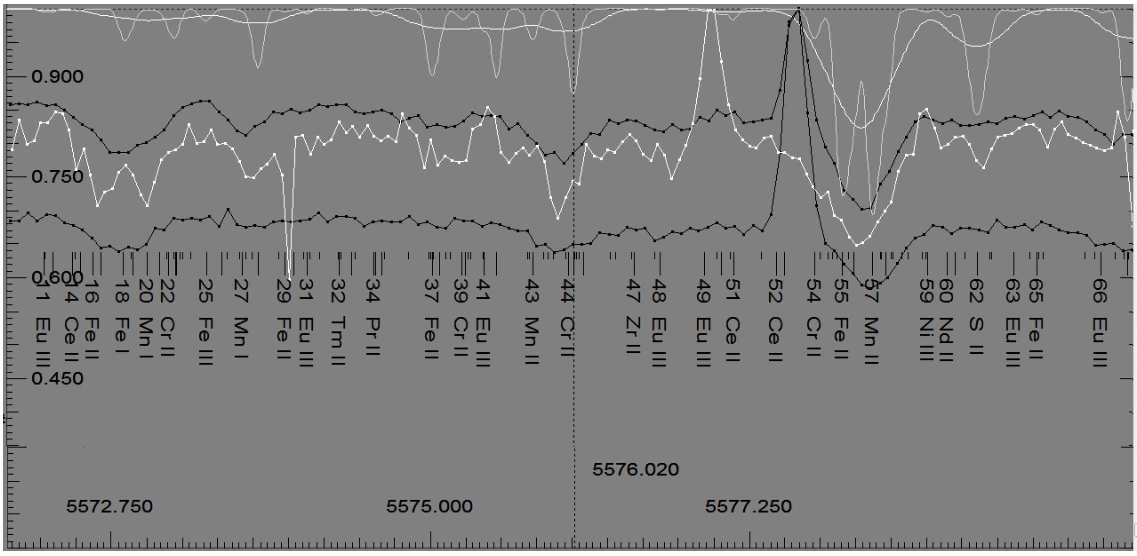

Figure 9a: The Pm line at a wavelength of 5576.02 Å with an equivalent width W = 10.5 Å, which corresponds to the Pm abundance log N(Pm) = 5.97 has been identified in the spectrum HD 25354-2181 (the lower spectrum depicted in black colour). In the ELODIE archive spectrum, shown in white colour, the Pm line at a wavelength of 5576.02 Å has an equivalent width W = 10.5 Å, which corresponds to the Pm abundance log N(Pm) = 6.05. All three spectra exhibit strong emission lines. The Pm line identified in the upper spectrum is blended with a relatively greater contribution of the chromium line.

Analysis of the BL 148 and BL 138 spectral lines at the Pm wavelength of 5576.02 Å

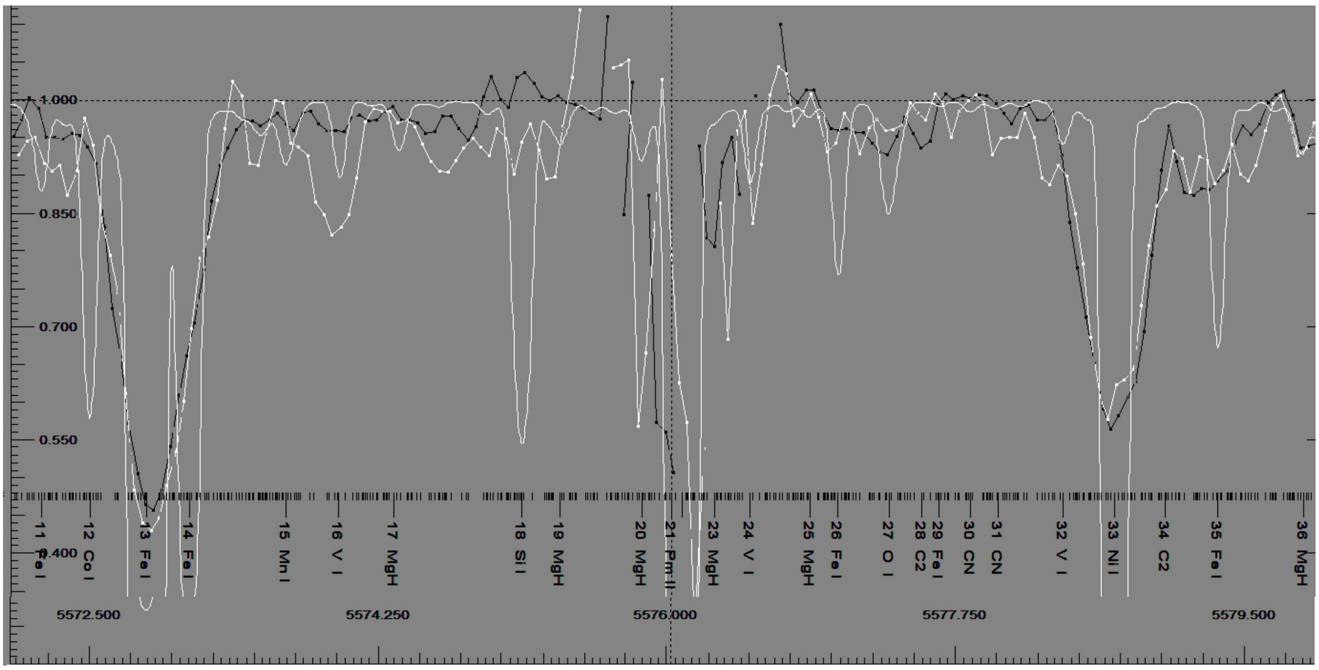

Figure 9b: The Pm line at a wavelength of 5576.02 Å in the spectra of BL 138 (shown in black colour) and BL 148 (depicted in white colour) exhibits a strong emission pattern.

Promethium emission lines in the spectra of HD 25354

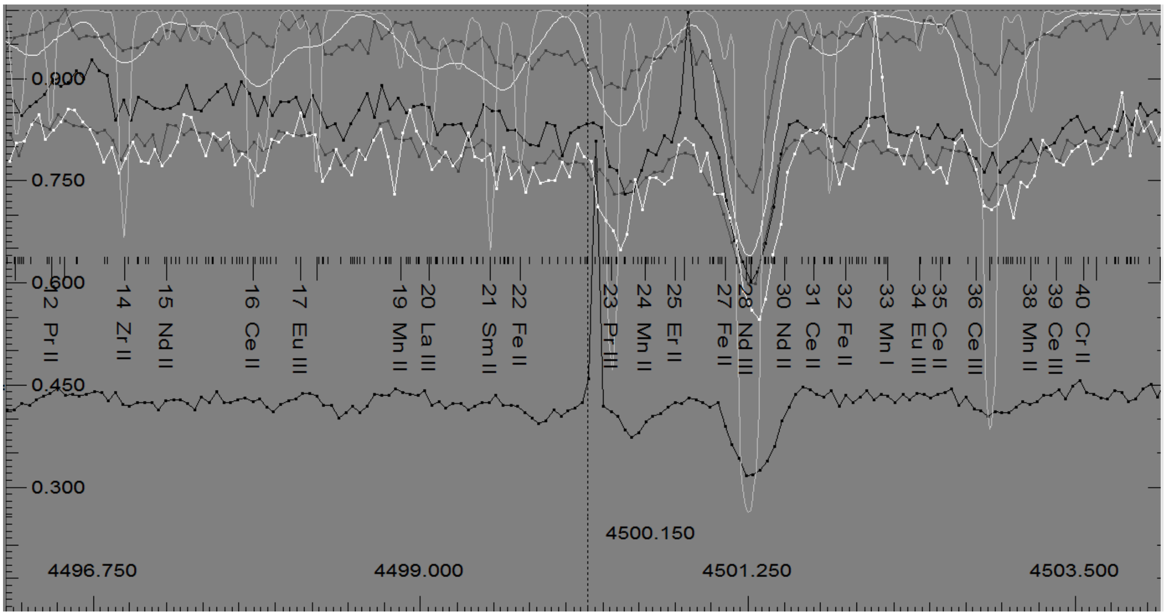

Figure 10: The line at a wavelength of λ 4500.15 Å has been identified as a blend of the Pm II at λ 4500.15 Å with the line Ni II at λ 4500.142 Å of a very weak intensity given the afore-specified stellar parameters. In the actual spectrum of HD 25354-2181, one can observe a strong emission line. The second spectrum HD 25354-2182 has a sharp emission line at λ 4500.85 Å as well. In the ELODIE archive spectrum (shown as a white line), an emission line can also be observed at λ 4502.22 Å. The synthetic spectrum lines are weak or practically absent at the wavelengths λ 4500.85 Å and λ 4502.2 Å. Observations performed on the second night at the Terskol Peak Observatory are depicted in dark grey colour; there are no emission lines in the respective spectra.

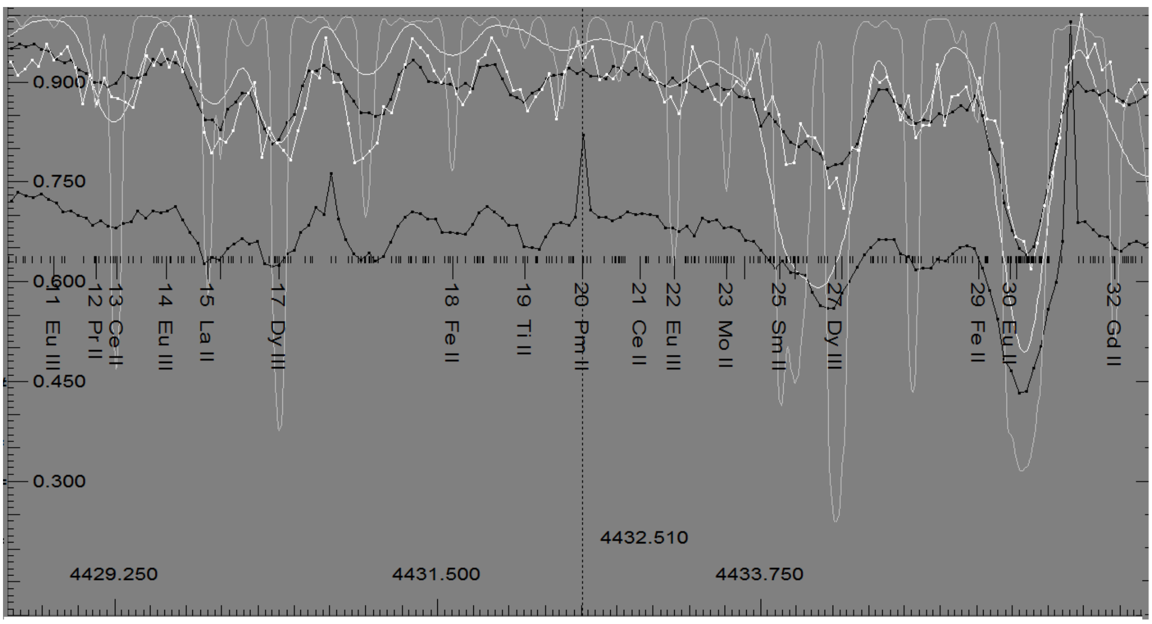

Figure 11: Either the absence of any line or wakening of the line intensity can be considered as a superposition of the absorption and emission lines.

Table: Investigation of the radioactive promethium lines in stellar spectra

HD 25354: T_{eff} = 12,800 K, log g = 4.15, v_{mic} = 0.23 km s^{-1}

Wave	Code	log *gf*	E_{low}	The ELODIE archive spectra		The Terskol Peak Observatory spectra		Synthetic spectra from the mean of the Terskol Peak Observatory ones	
				W(mÅ)	log *N*(Pm)	W(mÅ)	log *N*(Pm)	log *N*(Pm)	% log *N*(Pm)
4137.95	61.01	0.30	0.366	16.2	5.69	–	–	–	–
4157.86	61.01	0.36	0.246	–	–	–	–	5.81	99.8
4186.03	61.01	0.00	0.182	17.0	5.94	16.4	5.91	5.76	80.4
4216.31	61.01	–0.06	0.055	9.8	5.60	11.2	5.67	5.68	96.9
4297.78	61.01	0.08	0.000	11.7	5.52	20.0	5.91	5.27	34.0
4615.87	61.01	–0.76	0.199	3.4	5.87	4.0	5.94	–	–
4651.93	61.01	–0.67	0.331	5.0	6.01	–	–	–	–
5546.08	61.01	–0.26	0.760	4.0	5.80	7.3	6.00	–	–
5556.88	61.01	–0.03	1.131	0.48	5.83	–	–	–	–
5561.73	61.01	–0.04	0.873	5.0	5.74	–	–	–	–
5576.02	61.01	–0.17	0.661	9.0	5.97	10.5	6.05	6.10	68.1
					5.80 ± 0.15		5.91 ± 0.12		5.84 ± 0.16

HR 465: T_{eff} = 11,840 K, log g = 4.3, v_{mic} = 1.66 km s^{-1}

Wave	Code	log *gf*	E_{low}	The Bohyunsan Optical Astronomy Observatory spectra	
				W(mÅ)	log *N*(Pm)
4137.95	61.01	0.30	0.366	12.0	5.00
4216.31	61.01	–0.06	0.055	9.0	5.08
5561.73	61.01	–0.04	0.873	4.0	5.08
					5.80 ± 0.15

HIP 13962: T_{eff} = 6,250 K, log g = 1.2, v_{mic} = 12.0 km s^{-1}

Wave	Code	log *gf*	E_{low}	The Bohyunsan Optical Astronomy Observatory spectra	
				W(mÅ)	log *N*(Pm)
4137.95	61.01	0.30	0.366	12.4	–0.41
4157.86	61.01	0.36	0.246	14.5	–.045
4186.03	61.01	0.00	0.182	12.2	–0.30
4297.78	61.01	0.08	0.00	29.4	–0.16
4216.31	61.01	–0.06	0.055	6.9	–0.63
5561.73	61.01	–0.04	0.873	3.6	–0.25
					–0.37 ± 0.15

BL 138: T_{eff} = 3,939 K, log g = 0.71, v_{mic} = 2.3 km s^{-1}, [Fe/H] = –1.01

Wave	Code	log *gf*	E_{low}	The Bohyunsan Optical Astronomy Observatory spectra	
				W(mÅ)	log *N*(Pm)
5546.08	61.01	–0.26	0.760	17.2	–0.42
5561.73	61.01	–0.04	0.873	11.9	–0.65
5576.02	strong emission				
					–0.54 ± 0.12