ABUNDANCE PATTERN OF THE CHEMICALLY PECULIAR STAR FEH-DUF

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We present the results of a study of the very high velocity ($v_{\rm rad} = 448.0 \pm 1.0$ km·s^{-1}) low-metallicity ([Fe/H]$= -1.93$) star Feh-Duf (Fehrenbach & Duflot, 1981) showing peculiar chemical abundance. Using a high-resolution spectrum obtained at ESO 2.2-m telescope with the FEROS echelle spectrograph we determined atmospheric parameters of this star and performed the detailed analysis of its abundance pattern. We showed that this star has enhanced carbon and heavy *s*-process element abundance ([C/Fe]$= +0.58$, [hs/Fe]$= +0.88$ dex). The carbon isotopic ratio is low (^{12}C/^{13}C$= 8$). We found that the α-element abundance is reduced as compared to Galactic field stars of a similar metallicity. The evolution state of this star and its possible extragalactic origin are discussed.

INTRODUCTION

The star Feh-Duf was discovered in 1981 by Fehrenbach & Duflot [6] during their measurements of the radial velocities of the stars in the region of the Large Magellanic Cloud. They found that this star has a very high radial velocity (+440 km·s^{-1}) and also that exceedingly strong CH absorption bands are observed in the spectrum of this star. This spectral characteristic is typical for CH stars, a group of peculiar late-type population II giants whose overabundance of carbon, as well as of the *s*-process elements, is explained by mass-transfer in a binary system from a former asymptotic giant branch (AGB) star, now a white dwarf.

In this work we present the results of the high-resolution spectroscopic study of Feh-Duf, determine its abundance pattern and discuss the evolutionary state as well as a possible extragalactic origin of this star.

OBSERVATIONS

The high-resolution spectrum of Feh-Duf analyzed in this work was obtained with the FEROS echelle spectrograph at the 2.2-m telescope of ESO at la Silla, Chile, on November 20, 2008. The spectral resolution is $R = \lambda/\Delta\lambda = 48\,000$, corresponding to 2.2 pixels of 15 μm, and the spectral range coverage is from 3800 Å to 9200 Å. Two expositions, each of 3600 s, were obtained. The S/N ratio was evaluated by measuring the rms flux fluctuation in selected continuum windows, and the typical value was $S/N = 100$. The spectra were reduced with the MIDAS pipeline reduction package consisting of the following standard steps: CCD bias correction, flat-fielding, spectrum extraction, wavelength calibration, correction of barycentric velocity, and spectrum rectification. Figure 1 shows a section of the Feh-Duf spectrum in the 6120–6150 Å region.

ATMOSPHERIC PARAMETERS

The determination of atmospheric parameters, effective temperature ($T_{\rm eff}$), surface gravity ($\log g$), microturbulent velocity ($\xi_{\rm m}$), and metallicity ([Fe/H][1]) was carried out using the local thermodynamic equilibrium (LTE) atmosphere models of Kurucz [11] and the current version of the LTE spectral synthesis software MOOG [18]. The unblended Fe I and Fe II lines were used in the analysis. The $\log gf$ values of iron lines were taken from Lambert et al. [13]. Following the usual iterative procedure, we derived the effective temperature and microturbulence by requiring the iron abundances to be independent of the excitation potential and of the equivalent width (see Fig. 2). The surface gravity was determined through an ionization balance by forcing Fe II to yield the same total iron abundance as Fe I. We derived the following atmospheric parameters for Feh-Duf: $T_{\rm eff} = 4500 \pm 120$ K, $\log g = 0.9 \pm 0.1$, $\xi_{\rm m} = 1.9 \pm 0.2$, and [Fe/H]$\,=-1.93 \pm 0.10$.

[1]In this work, we use the standard spectroscopic abundance notation $\log\varepsilon({\rm X}) = \log(N_{\rm X}/N_{\rm H}) + 12$ and $[{\rm X/H}] = \log(N_{\rm X}/N_{\rm H})_* - \log(N_{\rm X}/N_{\rm H})_\odot$. The solar abundances are from Anders & Grevesse [2].

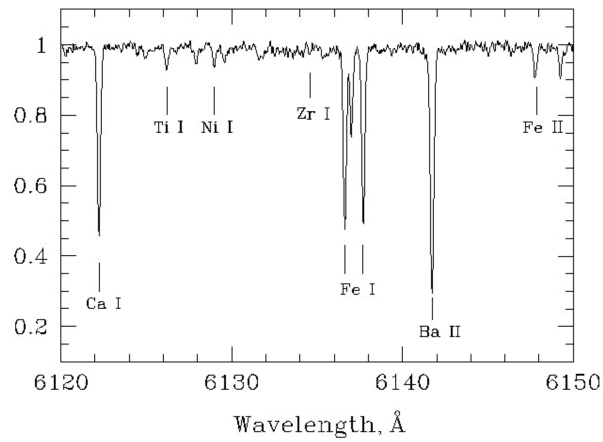

Figure 1. Spectrum of Feh-Duf in the 6120–6150 Å spectral region containing the line of Ba II 6141.73 Å

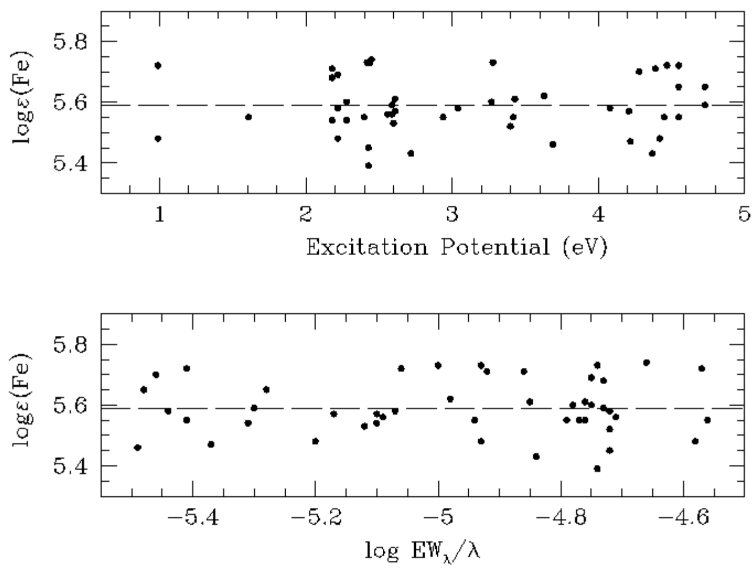

Figure 2. Star Feh-Duf. *Top:* Iron abundances from Fe I lines vs. equivalent width. *Bottom:* Iron abundances from Fe I lines vs. excitation potential. 45 Fe I and 9 Fe II lines were used for the atmospheric parameters determination

Since the parallax of Feh-Duf has not been measured, we estimated its luminosity and distance using theoretical evolutionary tracks. The value of the bolometric correction was estimated using the formula from Alonso et al. [1] $BC(V) = -0.495$. Assuming stellar mass of $0.8\,M_\odot$ and using the evolution tracks from Fagotto et al. [5] and Girardi et al. [7], we estimated the luminosity of the star $M_V = -2.3$ and $\log L/L_\odot = 3.01$ which results in a distance of about 5.9 kpc. We adopted the reddening to be $E_{B-V} = 0.06$ (Grieve & Madore [9], Pompeia et al. [16]). This value of the colour excess agrees well with the intensity of the interstellar Na I D_1 and D_2 lines of 126.9 mÅ and 176.1 mÅ, respectively.

The radial velocity of Feh-Duf was determined to be $v_{\rm rad} = +448.3 \pm 1.0$ km $\cdot$ s^{-1}. This value is in good agreement with the value of $v_{\rm rad} = +440$ km $\cdot$ s^{-1} obtained by Fehrenbach & Duflot [6].

CHEMICAL ABUNDANCE ANALYSIS

The abundance analysis was performed using the local thermodynamic equilibrium (LTE) model-atmosphere techniques and the current version of the MOOG program. The abundances of the elements which have unblended lines and are not affected by the hyperfine splitting were determined using the equivalent widths measured by

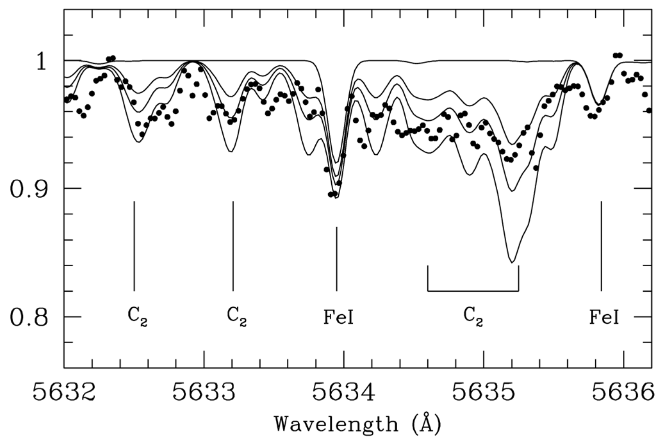

Figure 3. Observed (dots) and synthetic (lines) spectra of Feh-Duf in the region around the C_2 5635 Å band head. The synthetic spectra are shown for the carbon abundances of $\log\varepsilon(\mathrm{C}) =$ none, 7.16, 7.21, 7.26

means of the SPLOT task of the IRAF package. For other elements we used the synthetic spectrum method. Carbon and nitrogen abundances as well as the $^{12}\mathrm{C}/^{13}\mathrm{C}$ isotopic ratio were determined with spectrum synthesis technique by means of successive iterations using the following molecular spectral features: C_2 $(0, 1)$ band head of the Swan system $A^3\Pi_g - X^3\Pi_u$ at 5635 Å, C_2 feature at 5086 Å, CH lines of the $A^2\Delta - X^2\Pi$ system, ^{12}CN and ^{13}CN lines of the (2, 0) red system $A^2\Pi - X^2\Sigma$ in the 7994–8020 Å wave range. The oxygen abundance was determined by synthesis of the [O I] 6300.304 Å line. The detailed description of the CNO and $^{12}\mathrm{C}/^{13}\mathrm{C}$ determinations may be found in Drake & Pereira [4] and Pereira & Drake [15]. The lead abundance was obtained from the Pb I line at λ4057.81 Å. The line data which include isotopic shifts and hyperfine splitting have been taken from van Eck et al. [21]. Figures 3 and 4 show the observed and synthetic spectra in the regions around the C_2 molecule lines at 5635 Å and the Pb I 4057.81 Å line, respectively. The obtained elemental abundances are presented in Fig. 5.

Our analysis shows the large overabundance of carbon and nitrogen in Feh-Duf ([C/Fe] = +0.58, [N/Fe] = +0.66). The carbon isotope ratio is low, $^{12}\mathrm{C}/^{13}\mathrm{C} = 8$, above, however, the equilibrium isotope ratio reached in the CN cycle ($^{12}\mathrm{C}/^{13}\mathrm{C} = 3.6$). The enhancement of the $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio may be caused by the mass transfer from the AGB donor – a carbon star which may have had a high value of the carbon isotope ratio (Lambert et al. [12]). The oxygen abundance is [O/Fe] = +0.10. Comparison of the oxygen-to-iron ratio in Feh-Duf and Galactic halo stars indicate that the [O/Fe] ratio in the Feh-Duf is about 0.3 dex below the corresponding value for the stars of the same metallicity in the Galaxy (Carretta et al. [3], Ryan, Norris & Bessel [17]). Other α-elements, such as Ca and Ti, also have lower abundances ([Mg/Fe] = 0.42, [Ca/Fe] = 0.29, [Ti/Fe] = –0.02, [Mg+Ca+Ti/3Fe] = 0.23).

The abundances of the heavy s-process elements are enhanced ([Ba/Fe] = 0.95, [La/Fe] = 0.75, [Ce/Fe] = 0.88, [Nd/Fe] = 0.92, and [Pb/Fe] = 1.58) whereas the abundance of the light s-process element Y is low ([Y/Fe] = –0.07). According to the theories, the neutron-capture nucleosynthesis in AGB stars is metallicity-dependent. The first-peak elements (such as Y) are bypassed in favor of second-peak elements and those from the third peak. The high [Ba/Y] and [Pb/Ce] ratios are consistent with the expectations from metal-poor AGB s-process yields (Travaglio et al. [20], Venn et al. [22]).

KINEMATICS

Assuming the distance to the star to be $d = 5.9$ kpc, we calculated Galactic space-velocity components (U, V, W) for Feh-Duf using the algorithm proposed by Johnson & Soderblom [10]. Proper motions were taken from NOMAD catalog (Zacharias [23]). The obtained heliocentric space velocities are (U, V, W) = (–116, –491, –106) $\mathrm{km\cdot s^{-1}}$. We transformed the V component of the space velocity of Feh-Duf to the Galactic Reference Frame using the $(U, V, W)_\odot$ = (9, 232, 7) (Venn et al. [22]) which results in $V_{\mathrm{GRF}} = -259\ \mathrm{km\cdot s^{-1}}$. This value of V_{GRF} shows that Feh-Duf has extreme retrograde motion. As pointed out by Marsakov & Borkova [14], a star born in a monotonically collapsing single protogalactic cloud could not be in a retrograde orbit. The extreme retrograde motion of Feh-Duf may be a sign that this star was accreted by the Milky Way from a dwarf satellite galaxy.

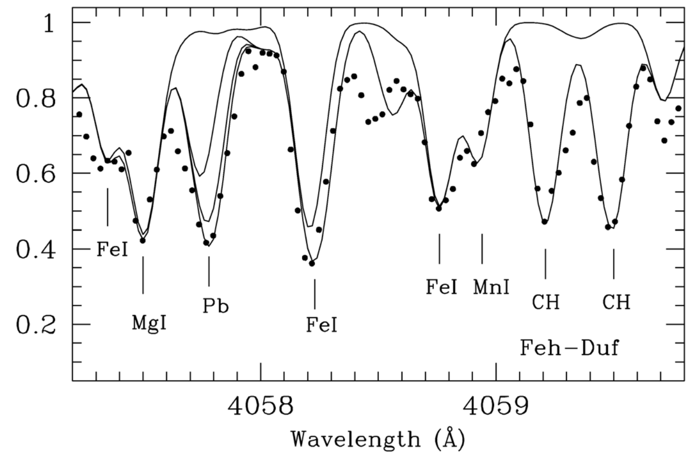

Figure 4. Observed (dots) and synthetic (lines) spectra of Feh-Duf in the region around the Pb I line at 4057.8 Å. The synthetic spectra are shown for the lead abundances of $\log\varepsilon(\mathrm{Pb})$ = 0.10, 1.40, and 1.75. The upper line shows a synthesis without contribution from the CH molecule lines

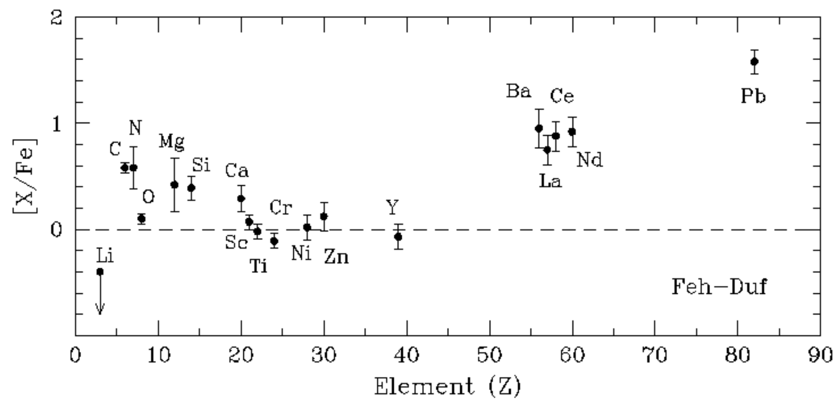

Figure 5. Abundance pattern of Feh-Duf. Error bars represent the estimated uncertainties

CONCLUSIONS

We assumed that Feh-Duf has a mass of $0.8\,M_\odot$ to be compatible with the low metallicity determined for this star of [Fe/H] = −1.93. Even though the luminosity of the Feh-Duf is compatible with the star at the early AGB phase, the binary nature of the carbon and s-element enrichment to be preferred, since the envelope mass of a $0.8\,M_\odot$ star is too small for the third dredge up phenomenon to occur (Staniero et al. [19]). That is, Feh-Duf is a CH star. Feh-Duf is also a "lead star" since its lead-to-cerium ratio is high, [Pb/Ce] = +0.70.

Recently, Venn et al. [22] carried out an analysis of the chemical abundances of the stars in the Galaxy and in the Milky Way dwarf spheroidal (dSph) satellite galaxies. They confirmed that the [α/Fe] ratios of most stars in the dSph galaxies are lower than Galactic stars of similar metallicity. Figure 2 from Venn et al. [22] shows that dSph stars are well separated from the majority of Galactic disk and halo stars. They also found that there is overlap in the low [α/Fe] ratios between dSphs stars and Galactic halo stars on extreme retrograde orbits ($V < -420$ km·s^{-1}).

Almost all of the nuclei of α-elements are synthesized during shell burning in Type II supernovae (SNe II), while the iron-peak elements are ejected to the interstellar medium during the SN Ia explosions. Therefore, a lower [α/Fe] ratio means that a star has originated within a dSph galaxy having the SN Ia/SN II ratio enhanced as compared to the Galaxy.

The large retrograde velocity and chemical abundances distinct from Galactic halo stars of same metallicity may suggest that Feh-Duf has an extragalactic origin and was captured by the Milky Way.

[1] *Alonso A., Arribas S., Martinez-Roger C.* The effective temperature scale of giant stars (F0–K5). II. Empirical calibration of $T_{\rm eff}$ versus colours and [Fe/H] // Astron. and Astrophys. Suppl. Ser. – 1999. – **140**, N 3. – P. 261–277.

[2] *Anders E., Grevesse N.* Abundances of the elements – Meteoritic and solar // Geochim. et Cosmochim. Acta. – 1989. – **53**, N 1. – P. 197–214.

[3] *Carretta E., Gratton R., Cohen J. G., et al.* Stellar archaeology: A Keck pilot program on extremely metal-poor stars from the Hamburg/ESO survey. II. Abundance analysis // Astron. J. – 2002. – **124**, N 1. – P. 481–506.

[4] *Drake N. A., Pereira C. B.* Light Element Abundances in Two Chemically Peculiar Stars: HD 104340 and HD 206983 // Astron. J. – 2008. – **135**, N 3. – P. 1070–1082.

[5] *Fagotto F., Bressan A., Bertelli G., Chiosi C.* Evolutionary sequences of stellar models with new radiative opacities. III. $Z = 0.0004$ and $Z = 0.05$ // Astron. and Astrophys. Suppl. Ser. – 1994. – **104**. – P. 365–376.

[6] *Fehrenbach Ch, Duflot M.* Une etoile à CH très intense et à très grande vitesse radiale situee dans la direction du Grand Nuage de Magellan // Astron. and Astrophys. – 1981. – **101**. – P. 226–227.

[7] *Girardi L., Bressan A., Chiosi C., et al.* Evolutionary sequences of stellar models with new radiative opacities. VI. $Z = 0.0001$ // Astron. and Astrophys. Suppl. Ser. – 1996. – **117**. – P. 113–125.

[8] *González Hernández J. I., Bonifacio P.* A new implementation of the infrared flux method using the 2MASS catalogue // Astron. and Astrophys. – 2009. – **497**, N 2. – P. 497–509.

[9] *Grieve G. R., Madore B. F.* Photometric studies of Magellanic Cloud Supergiants. I. Mean magnitudes and reddenings // Astrophys. J. Suppl. Ser. – 1986. – **62**. – P. 427–449.

[10] *Johnson D. R. H., Soderblom D. R.* Calculating galactic space velocities and their uncertainties with an application to the Ursa Major group // Astron. J. – 1987. – **93**, N 4. – P. 864–867.

[11] *Kurucz R. L.* Atlas9 Stellar Atmosphere Programs and 2 km s^{-1} Grid. – CD-ROM 13. – Cambridge: Smithsonian Astrophys. Obs., 1993.

[12] *Lambert D. L., Gustafsson B., Eriksson K., Hinkle K. H.* The chemical composition of carbon stars. I. Carbon, nitrogen, and oxygen in 30 cool carbon stars in the Galactic disk // Astrophys. J. Suppl. Ser. – 1986. – **62**. – P. 373–425.

[13] *Lambert D. L., Heath J. E., Lemke M., Drake J.* The chemical composition of field RR Lyrae stars. I. Iron and calcium // Astrophys. J. Suppl. Ser – 1996. – **103**. – P. 183–210.

[14] *Marsakov V. A., Borkova T. V.* Formation of Galactic subsystems in light of the magnesium abundance in field stars: the halo // Astron. Lett. – 2006. – **32**, N 8. – P. 545–556.

[15] *Pereira C. B., Drake N. A.* High-resolution spectroscopic observations of two chemically peculiar metal-poor stars: HD 10613 and BD+04°2466 // Astron. and Astrophys. – 2009. – **496**, N 3. – P. 791–804.

[16] *Pompéia L., Hill V., Spite M., et al.* Chemical abundances in LMC stellar populations. I. The inner disk sample // Astron. and Astrophys. – 2008. – **480**, N 2. – P. 379–395.

[17] *Ryan S. G., Norris J. E., Bessell M. S.* Subdwarf studies. IV. Abundance ratios in extremely metal-deficient stars // Astron. J. – 1991. – **102**. – P. 303–322.

[18] *Sneden C.* Carbon and Nitrogen Abundances in Metal-Poor Stars // Ph.D. Thesis, Univ. of Texas at Austin, 1973.

[19] *Straniero O., Gallino R, Cristallo S.* *s*-process in low-mass asymptotic giant branch stars // Nuclear Physics. – 2006. – **777**. – P. 311–339.

[20] *Travaglio C., Gallino R., Arnone E., et al.* Galactic evolution of Sr, Y, and Zr: a multiplicity of nucleosynthetic processes // Astroph. J. – 2004. – **601**, N 2. – P. 864–884.

[21] *van Eck S., Goriely S., Jorissen A., Plez B.* More lead stars // Astron. and Astrophys. – 2003. – **404**, N 1. – P. 291–299.

[22] *Venn K. A., Irwin M., Shetrone M. D., et al.* Stellar Chemical Signatures and Hierarchical Galaxy Formation // Astron. J. – 2004. – **128**, N 3. – P. 1177–1195.

[23] *Zacharias N., Monet D. G., Levine S. E., et al.* The Naval Observatory Merged Astrometric Dataset (NOMAD) // Bull. Amer. Astron. Soc. – 2004. – **36**. – P. 1418.