Advances in Astronomy and Space Physics, **4**, 20-24 (2014)

Abundances in the atmosphere of the metal-rich planet-host star HD 77338

I. O. Kushniruk[1]*; *Ya. V. Pavlenko*[2,3], *J. S. Jenkins*[4], *H. R. A. Jones*[3]

[1]Taras Shevchenko National University of Kyiv, Glushkova ave., 2, 03127 Kyiv, Ukraine
[2]Main Astronomical Observatory of the NAS of Ukraine, Akademika Zabolotnoho str., 27, 03680 Kyiv, Ukraine
[3]Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield, Hertfordshire AL10 9AB, UK
[4]Departamento de Astronomía, Universidad de Chile, Camino el Observatorio 1515, Las Condes, Santiago, Chile

Abundances of Fe, Si, Ni, Ti, Na, Mg, Cu, Zn, Mn, Cr and Ca in the atmosphere of the K-dwarf HD 77338 are determined and discussed. HD 77338 hosts a hot Uranus-like planet and is currently the most metal-rich single star to host any planet. Determination of abundances was carried out in the framework of a self-consistent approach developed by Pavlenko et al. (2012). Abundances were computed iteratively by the `ABEL8` code, and the process converged after 4 iterations. We find that most elements follow the iron abundance, however some of the iron peak elements are found to be over-abundant in this star.

Key words: stars: abundances, stars: atmospheres, stars: individual (HD 77338), line: profiles

INTRODUCTION

Determining the chemical composition of stars is one of the primary goals of astrophysics. Such investigations help us to better understand the chemical enrichment of the Galaxy and to make some assumptions about the mechanisms involved in element evolution in the interstellar medium, and in stellar atmospheres in particular [12]. While studying the Sun, the problem of the abundances of certain atoms necessitated a model to explain this. It was finally explained with the introduction of the pp- and CNO- cycles in the interior of the Sun. However, this was not sufficient to explain the presence of large amounts of Helium. The next step in studying the evolution of elements was the introduction of nucleosynthesis theory. Modern scientific understanding is that chemical elements were formed as a result of the processes occurring in stars, leading to evolutionary changes of their physical conditions. Therefore, the problem of nuclide formation is also closely related to the issue of the evolution of stars and planetary systems. Recently Jenkins et al. [5] announced the discovery of a low-mass planet orbiting the super HD 77338 as part of our ongoing Calan-Hertfordshire Extrasolar Planet Search [6]. The best-fit planet solution has an orbital period of 5.7361 ± 0.0015 days and with a radial velocity semi-amplitude of only $5.96 \pm 1.74\,\mathrm{ms^{-1}}$, giving a minimum mass of $^{+4.7}_{-5.3}\,\mathrm{M_\oplus}$. The best-fit eccentricity from this solution is $0.09^{+0.25}_{-0.09}$, and is in the agreement with results of a Bayesian analysis and a periodogram analysis.

According to modern theory, the formation of the nucleus of chemical elements from carbon to iron is the result of thermonuclear reactions involving He, C, O, Ne and Si in stars. After the depletion of hydrogen reserves, a star's core starts running a 3α reaction, where it produces a number of elements as a result of the following transformations:

$$3\,{}^{4}\mathrm{He} \longrightarrow {}^{12}\mathrm{C}, \quad {}^{12}\mathrm{C} + {}^{4}\mathrm{He} \longrightarrow {}^{16}\mathrm{O} + \gamma,$$

$${}^{16}\mathrm{O} + {}^{4}\mathrm{He} \longrightarrow {}^{20}\mathrm{Ne} + \gamma.$$

After reaching a specific threshold temperature, carbon begins fusing with the formation of Ne, Na and Mg:

$${}^{12}\mathrm{C} + {}^{12}\mathrm{C} \longrightarrow {}^{20}\mathrm{Ne} + {}^{4}\mathrm{He} + 4.62\,\mathrm{MeV},$$

$${}^{12}\mathrm{C} + {}^{12}\mathrm{C} \longrightarrow {}^{23}\mathrm{Na} + \mathrm{p} + 2.24\,\mathrm{MeV},$$

$${}^{12}\mathrm{C} + {}^{12}\mathrm{C} \longrightarrow {}^{24}\mathrm{Mg} + \gamma - 2.60\,\mathrm{MeV}.$$

Aluminium can then be produced by:

$${}^{24}\mathrm{Mg} + \mathrm{p} \longrightarrow {}^{25}\mathrm{Al} + \gamma.$$

The combustion reaction of oxygen is a dual-channel process and causes the presence of Al, S, P, Si and Mg. One of the channels is:

$${}^{16}\mathrm{O} + {}^{16}\mathrm{O} \longrightarrow {}^{30}\mathrm{Si} + {}^{1}\mathrm{H} + {}^{1}\mathrm{H} + 0.39\,\mathrm{MeV},$$

$${}^{16}\mathrm{O} + {}^{16}\mathrm{O} \longrightarrow {}^{24}\mathrm{Mg} + {}^{4}\mathrm{He} + {}^{4}\mathrm{He} - 0.39\,\mathrm{MeV},$$

---

[*] `nondanone@gmail.com`

$$^{16}\mathrm{O} + {}^{16}\mathrm{O} \longrightarrow {}^{27}\mathrm{Al} + {}^{4}\mathrm{He} + {}^{1}\mathrm{H} - 1.99\,\mathrm{MeV},$$

With continuous temperature growth, silicon burning is initiated. This process is described by a number of reactions. As a result we can receive, for example, Ar, Ni, S, etc. ^{56}Ni, after two β decays, turns into ^{56}Fe. It is the final stage of the fusion of nuclides in massive stars, which forms the nucleus of the iron group.

The production of heavy elements is provided by other mechanisms. They are called s- and r-processes. An s-process, or slow neutron capture, is a formation of heavier nuclei by lighter nuclei through successive neutron capture. The original element in the s-process is ^{56}Fe. The reaction chain ends with ^{209}Bi. It is thought that s-processes occur mostly in stars on the asymptotic giant branch. For the s-process to run, an important condition is the ability to produce neutrons. The main neutron source reactions are:

$$^{13}\mathrm{C} + {}^{4}\mathrm{He} \longrightarrow {}^{16}\mathrm{O} + \mathrm{n},$$

$$^{22}\mathrm{Ne} + {}^{4}\mathrm{He} \longrightarrow {}^{25}\mathrm{Mg} + \mathrm{n}.$$

An examples of an s-process reaction is:

$$^{56}\mathrm{Fe} + n \longrightarrow {}^{57}\mathrm{Fe} + n \longrightarrow {}^{58}\mathrm{Fe} + n \longrightarrow {}^{59}\mathrm{Fe} \xrightarrow{\beta^-}$$

$$\longrightarrow {}^{59}\mathrm{Co} + n \longrightarrow {}^{60}\mathrm{Co} \xrightarrow{\beta^-} {}^{60}\mathrm{Ni} + n \longrightarrow \ \ldots$$

Elements heavier than H and He are usually called metals in astrophysics. Their concentration is significantly lower relative to hydrogen and helium, however, they are the source of thousands of spectral lines originating from a star's atmosphere. The abundance of iron depends on a star's age and its position in the galaxy [9]. Metal-rich stars are also known to be rich in orbiting giant exoplanets. High metallicity appears to be a major ingredient in the formation of planets through core accretion [5].

HD 77338 is one of the most metal-rich stars in the sample of [3] and in the local Solar neighbourhood in general. Its spectral type is given as K0IV in the Hipparcos Main Catalogue [17]. However, HD 77338 is not a sub-giant, as labelled in Hipparcos [5], its mass and radius are smaller than those of the Sun: $\mathfrak{M} = 0.93 \pm 0.05\mathfrak{M}_\odot$, $\mathrm{R} = 0.88 \pm 0.04\mathrm{R}_\odot$. A parallax of 24.54 ± 1.06 mas for HD 77338 means the star is located at a distance of 40.75 ± 1.76 pc. Its effective temperature and surface gravity were found $T_{eff} = 5370 \pm 80\,\mathrm{K}$, $\log g = 4.52 \pm 0.06$ [5]. More stellar parameters for HD 77338 and detailed information about its planetary system are in [5].

Using the Simbad database one can find information on the previous assessments of abundances in the atmosphere of HD 77338 (see Table 1). In most cases the authors only determine the metallicity of the star, i. e. the iron abundance. In turn, we recomputed the abundances of many elements which show significant absorption lines in the observed spectrum of HD 77338.

Table 1: Simbad's list of previous assessments of abundances in the atmosphere of HD 77338

T_{eff}	$\log g$	[Fe/H]	Comp. star	Ref.
5300	4.30	0.36	Sun	[18]
5290	4.90	0.22	Sun	[1]
5290	4.60	0.30	Sun	[19]

THE OBSERVATIONS

The observations of HD 77338 were carried out as part of the Calan-Hertfordshire Extrasolar Planet Search (CHEPS) program [4]. The main aim of the program is monitoring a sample of metal-rich stars in the southern hemisphere to search for short period planets that have a high probability to transit their host stars, along with improving the existing statistics for planets orbiting solar-type and metal-rich stars. The high-S/N (> 50) and high-resolution ($R = 100\,000$) spectrum of HD 77338, observed with the HARPS spectrograph [10], was reduced using the standard automated HARPS pipeline and analysed in this work in order to determine the chemical abundances and other physical parameters of the stellar atmosphere.

THE PROCEDURE

Firstly, we selected "good" absorption lines for all elements of interest that are present in spectra of the Sun and HD 77338. These lines should not be blended (see [3]) and be intense enough in both spectra. We selected lists of lines of each element that were to be used for the abundance investigations. We used line list data, which was taken from a database of atomic absorption spectra VALD [7], to compute synthetic spectra of the Sun for a plane-parallel model atmosphere with parameters $T_{eff}/\log g/[\mathrm{Fe/H}] = 5777/4.44/0.0$ [15]. The model atmosphere was used to compute the synthetic spectra using `WITA6` [13], building a grid of models with different microturbulent velocities $V_t = 0 - 3\,\mathrm{km/s}$ with a step size of 0.25 km/s. The shapes of the line absorption profiles were constructed as Voigt function profiles $H(a, v)$, and a classical approach was used to compute the damping effects [20]. To compute the rotational profile we followed the procedure described in Gray [2].

All abundance determinations were performed by the `ABEL8` code [14]. Details of the full procedure used are described in [16], see [3], also for more details on the line selection and fitting procedure.

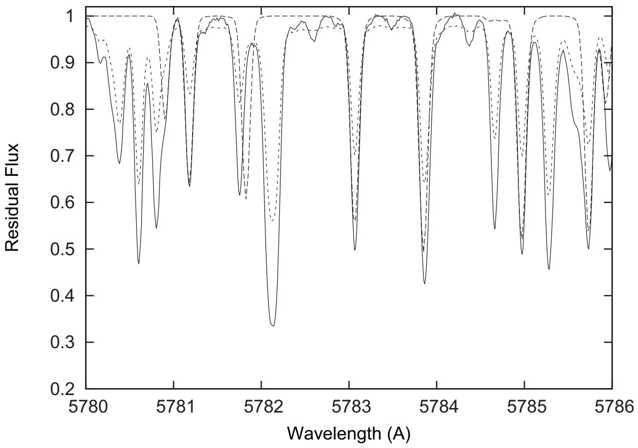

Fig. 1: The dotted line represents the observed spectrum of the Sun, the solid line is the observed spectrum of HD 77338, the dashed line shows the synthetic spectrum computed by `Wita618` with $\log \mathrm{N(Cr)} = -6.11$ for a model atmosphere of 5315/4.39. This plot was used to detect "clean" parts of Cr line profiles marked here by arrows.

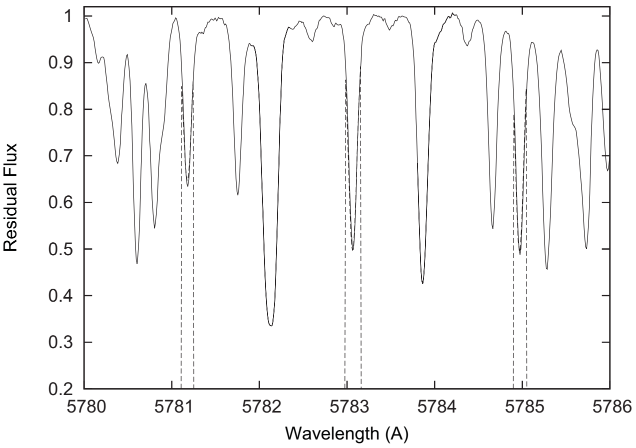

Fig. 2: Cr I absorption line profiles computed for a model atmosphere of 5315/4.39 and $\log \mathrm{N(Cr)} = -6.09$ using `ABEL8` and fitted to the observed spectrum of HD 77338 shown by dashed and solid lines, respectively. The vertical lines show the fitted parts of Cr sc i line profiles.

RESULTS

THE SUN

The solar spectrum is well-studied, and abundances for the Sun are known to very high accuracy; therefore it represents a very good template. Fig. 1 and Fig. 2 illustrate the presence of spectral lines of Cr in the observed spectrum of the Sun as a star [8]. Arrows on the plot show the spectral range which was selected to compute profiles of two Cr I lines to be used later by `ABEL8` [14] in the determination of the abundance of chromium. We employ a similar selection in the solar spectrum Sun, and in the spectrum of HD 77338 for lines of Fe I, Si I, Ni I, Ti I, Na I, Mg I, Cu I, Zn I, Mn I, Cr I, Al I, and Ca I.

We verified whether our input data were of sufficient quality and quantity to reproduce the abundances in the atmosphere of the Sun. We computed abundances for the Sun using the fits of the theoretical spectra to the profiles of the selected lines. In that way we can test our method and estimate the accuracy of our abundance determination. Then, we investigated the dependence $E_a = \partial a/\partial E''$, where a and E'' are the iron abundance and excitation potential of the corresponding radiative transition forming the absorption line. Best fits of the selected lines of Fe I in the computed spectra, when compared to their observed profiles in the solar spectrum, provide the min E_a of $V_t = 0.75$ km/s. The abundances of iron and other elements were then obtained using this adopted value for the microturbulence; the results are shown in Table 2. It is worth noting that our abundances agree with the reference values within an accuracy of ±0.1 dex.

HD 77338

The model atmosphere for HD 77338 was computed using the parameters determined by Jenkins et al. [5] using the `SAM12` code [15]. Again, as the first step of our analysis, we determined the microturbulent velocity in the atmosphere of HD 77338. The minimum of the slope of E_a provides $V_t = 0.75$ km/s for $\log \mathrm{N(Fe)} = -4.120 \pm 0.07$ or $\mathrm{[Fe/H]} = 0.281$ (iteration 1). For other elements we used the same value ($V_t = 0.75$ km/s).

We carried out 4 iterations to determine all abundances. In each next step the abundances from the previous determination were used to recompute the model atmosphere by `SAM12` [15] and the synthetic spectra. Each time we are approaching self-consistency by computing the model atmosphere that relates to the final metallicity of the star.

In Table 2 we present our results for 12 different ionic species. We compare our abundances with the solar values, obtained using a model atmosphere of 5777/4.44/0.00. They are in good agreement with each other. Fig. 2 and Fig. 3 show the line profiles of Cr and Mg calculated using a $V_t = 0.75$ km/s.

In Fig. 4 we show the dependence of [X/H] on atomic number of each element for every iteration. The presence of errors can be explained by the presence of noise in the selected spectral lines, along with only having a small number of lines to work with for some elements. In Fig. 5 we present the dependence of [X/Fe] for the final iteration, where different elements are shown using different plotting shapes, depending on their mechanism of formation.

Table 2: Abundances in the atmosphere of HD 77338, iteration 4.

Iron	log N(X)	log N(X)$_{\odot}$, `ABEL8`	*log* N(X)$_{\odot}$	[X/H]	[X/Fe]	$v \sin i$, km/s	N$_l$
Al I	-5.403 ± 0.000	-5.767 ± 0.033	-5.551	$+0.148$	-0.095	2.33 ± 0.44	3
Ca I	-5.376 ± 0.029	-5.588 ± 0.023	-5.661	$+0.285$	$+0.042$	1.25 ± 0.13	14
Cr I	-6.085 ± 0.032	-6.345 ± 0.026	-6.441	$+0.356$	$+0.113$	1.91 ± 0.14	22
Cu I	-7.670 ± 0.058	-8.133 ± 0.067	-7.941	$+0.271$	-0.028	2.17 ± 0.44	3
Fe I	-4.158 ± 0.038	-4.439 ± 0.023	-4.401	$+0.243$	$+0.000$	2.06 ± 0.11	27
Mg I	-4.228 ± 0.058	-4.367 ± 0.095	-4.441	$+0.213$	-0.030	1.50 ± 0.50	3
Mn I	-5.957 ± 0.097	-6.600 ± 0.046	-6.641	$+0.684$	$+0.441$	2.69 ± 0.21	8
Na I	-5.387 ± 0.048	-5.789 ± 0.054	-5.721	$+0.334$	$+0.091$	1.94 ± 0.31	9
Ni I	-5.367 ± 0.033	-5.756 ± 0.027	-5.821	$+0.454$	$+0.211$	2.29 ± 0.15	17
Si I	-4.111 ± 0.054	-4.469 ± 0.058	-4.401	$+0.290$	$+0.047$	2.39 ± 0.13	23
Ti I	-6.897 ± 0.040	-7.064 ± 0.028	-6.981	$+0.084$	-0.159	1.88 ± 0.13	24
Zn I	-7.028 ± 0.065	-7.375 ± 0.048	-7.441	$+0.413$	$+0.170$	2.25 ± 0.25	4

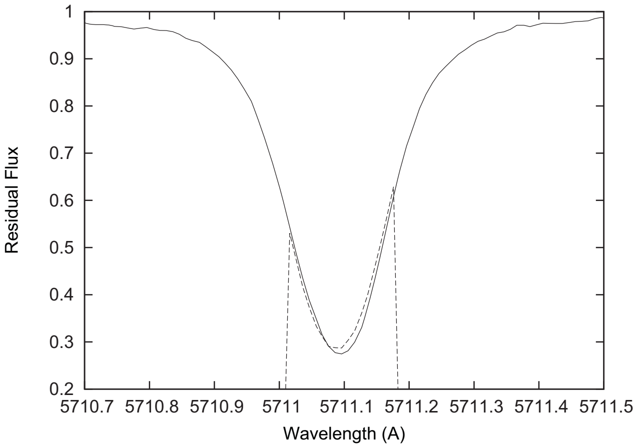

Fig. 3: Computed by ABEL8 and observed line profiles of Mg in the spectrum of HD 77338 with a model atmosphere of 5315/4.39, *log*N(Mg) $= -4.23$ shown by dashed and solid lines, respectively. The vertical lines show the fitted part of Mg I line profile.

DISCUSSION

We determined abundances for 12 ionic species in the atmosphere of the Sun and the metal-rich exoplanet host star HD 77338. Our values for the solar abundances are in good agreement with results from previous authors, proving the validity of our method. We used the solar spectrum as a reference to select the proper list of absorption lines to be used later in the analysis of the HD 77338 spectrum.

Our [X/H] correlates well with the condensation temperature of the ions (T_{cond}), see discussion in [11]. This may indicate the presence of a common shell (in the past) and can be an additional criterion for the existence of a planetary system around metal-rich stars.

We also computed $v \sin i$ for both stars. It is worth noting that we determined all parameters in the framework of a fully self-consistent approach (see [15] for more details). In general, lines of Mn, Cu can not be used to obtain $v \sin i$ because these lines usually have several close components, but in our case the parameter $v \sin i$ was used to adjust theoretical profiles to get the proper fits to the observed special features. We believe that fits to Fe I lines provide reasonable measures of the rotational velocity.

Our results show that the abundances of most elements in the atmosphere can be described well by the overall metallicity. However, we found an overabundance of some of the iron peak elements (e. g. Mn, Cu). Interestingly, Cu is an element formed through the s-process and its abundance follows that of Fe, whereas Zn and elements formed through the p-process, e. g. Ni[1], show a noticeable overabundance compared to iron. It would be interesting to compare these results for HD 77338 with other metal rich stars to see if this is a common trend for super metal-rich stars. We plan to investigate this issue in a following paper (Ivanyuk et al. 2015, in preparation).

ACKNOWLEDGEMENT

JSJ acknowledges the support of the Basal-CATA grant. YP's work has been supported by an FP7 POSTAGBinGALAXIES grant (No. 269193; International Research Staff Exchange Scheme). Authors thank the compilers of the international databases used in our study: SIMBAD (France, Strasbourg), VALD (Austria, Vienna), and the authors of the atlas of the spectrum of the Sun as a star. We thank the anonymous Referee for some reasonable remarks and helpful comments.

---

[1] see `http://www.mao.kiev.ua/staff/yp/TXT/prs.png`

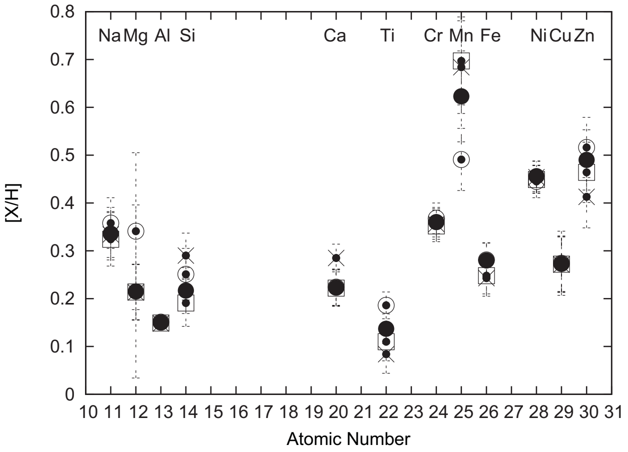

Fig. 4: Dependence of [X/H] on atomic number of each element for HD 77338. Open circles show values found in the first iteration, filled circles are for iteration 2, open squares are for iteration 3, and finally the stars show the results for iteration 4.

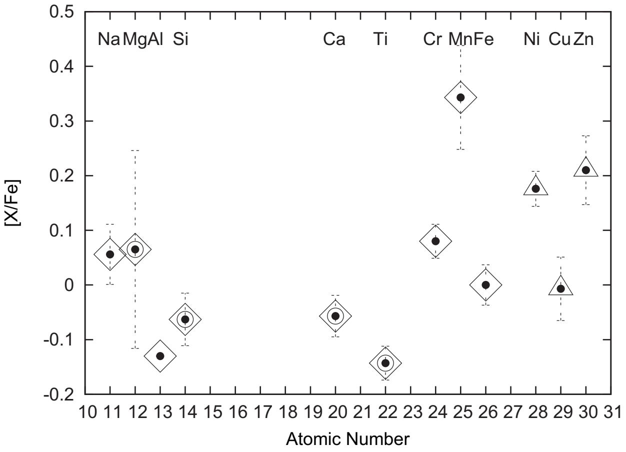

Fig. 5: Dependence of [X/Fe] on the atomic number of each element. The different plotting shapes represent the different formation mechanism of each element. Open circles are for α-elements, diamonds show the thermonuclear elemental production, and s-process is shown by triangles.

REFERENCES

[1] Feltzing S. & Gustafsson B. 1998, A&AS, 129, 237

[2] Gray D. F. 1976, *'The observation and analysis of stellar photospheres'*, Wiley-Interscience, New York

[3] Jenkins J. S., Jones H. R. A., Pavlenko Y. et al. 2008, A&A, 485, 571

[4] Jenkins J. S., Jones H. R. A., Goździewski K. et al. 2009, MNRAS, 398, 911

[5] Jenkins J. S., Jones H. R. A., Tuomi M. et al. 2013, ApJ, 766, 67

[6] Jenkins J. S., Jones H. R. A., Rojo P. et al. 2013, EPJ Web of Conferences 47, 05001

[7] Kupka F., Piskunov N., Ryabchikova T. A., Stempels H. C. & Weiss W. W. 1999, A&AS, 138, 119

[8] Kurucz R. L., Furenlid I., Brault J. & Testerman L. 1984, *'Solar flux atlas from 296 to 1300 nm'*, National Solar Observatory, New Mexico

[9] Lyubimkov L. S. 1995, *'Chemical composition of stars: method and result of analysis'*, Astroprint, Odesa

[10] Mayor M., Udry S., Naef D. et al. 2004, A&A, 415, 391

[11] Meléndez J., Asplund M., Gustafsson B. & Yong D. 2009, ApJ, 704, L66

[12] Mishenina T. V., Kovtyukh V. V., Soubiran C., Travaglio C. & Busso M. 2002, A&A, 396, 189

[13] Pavlenko Ya. V. 1997, Astrophys. and Space Science, 253, 43

[14] Pavlenko Ya. V. 2002, Kinematika i Fizika Nebesnykh Tel, 18, 1, 48

[15] Pavlenko Ya. V. 2003, Astron. Rep., 47, 59

[16] Pavlenko Ya. V., Jenkins J. S., Jones H. R. A., Ivanyuk O. & Pinfield D. J. 2012, MNRAS, 422, 542

[17] Perryman M. A. C., Brown A. G. A., Lebreton Y. et al. 1997, A&A, 331, 81

[18] Prugniel Ph., Vauglin I. & Koleva M. 2011, A&A, 531, A165

[19] Thorén P. & Feltzing S. 2000, A&A, 363, 692

[20] Unsold A. 1956, *'Physics der Sternatmospharen'*, American Institute of Physics, NY