ABUNDANCES OF r-PROCESS ELEMENTS IN THE PHOTOSPHERE OF RED SUPERGIANT STAR PMMR23 IN SMALL MAGELLANIC CLOUD

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ABSTRACT. Detailed analysis of chemical abundances determined from high-resolution CCD-spectrogram of supergiant star PMMR23 (K5 I) in SMC is presented. The observation were obtained at 3.6 meter ESO La Silla telescope by Hill (1997). Spectral resolving power is near R=30,000. The wavelength coverage is 5050-7200 A. The abundances of iron and 15 r-, s-processes elements are found. The abundances of Cu, Zr, Mo, Ru, Pr, Sm, Gd, Dy, Er are found for the first time. The abundances of elements with atomic numbers less than 55 are deficient with respect to the Sun. The mean underabundance is near 0.7 dex. The abundances of barium and lanthanides are near solar values. The overabundances of these elements with respect to iron are in the range from 0.4 tp 0.9 dex. The abundances of heavy lanthanides are higher than the abundances of light lanthanides. The abundance pattern of PMMR23 can be fitted by scaled solar r-process distribution. The atmosphere of PMMR23 is enriched by r-process elements.

Key words: Stars: fundamental parameters; stars: abundances; stars: kinematics; stars: atmospheres; stars: individual: PMMR23; r-process nucleosynthesis; galaxies: stellar content; galaxies individual: Small Magellanic Cloud

1. Introduction

The Magellanic Clouds and our Galaxy are the members of Local Group galaxies. The Magellanic system is composed of two small irregular galaxies, the Large (LMC) and Small (SMC) Magellanic Clouds, in orbit around Galaxy. Tidal interactions between these galaxies and Milky Way have produced several high-velocity gas complexes connected to the clouds, namely the Magellanic Bridge (MB), the Magellanic Stream. The Magellanic Clouds are optimal targets for investigations of stellar formation histories in local galaxies. The Magellanic Clouds have often been used as a laboratories to test the validity of the theories of evolution of our Galaxy. These are the nearest galaxies to our Galaxy. The high resolution spectral observations of the brighest stars of these galaxies became available in the last decade.

In previous work the abundances of chemical elements in nine K-supergiants in the SMC were investigated by the method of model atmospheres (Komarov et al. 2001). High-resolution CCD-spectrograms obtained at 3.6 meter ESO telescope were used - R=30,000 for the stars with magnitudes 12.4^m-13.5^m (Hill 1997). The wavelength coverage was 5050-7180 A. It was shown that all stars have a deficit of iron from -0.4 to -0.97 dex relative to the Sun. Some differences in the abundances of the elements of α-process (Si, Ca, Ti), s-process (Y, Zr) and e-process (Sc, V, Cr, Ni, Mn) relatively to the iron abundances were found in the atmospheres of the stars in the SMC and comparison star (Sun).

In this investigation we reanalyze the abundances of iron and r-, s-processes elements in one of the stars, PMMR23 (star number 23 from the catalogue by Prevo et al. 1983), using the spectrum synthesis method for identification of the lines and for calculating the abundances.

2. Methodics

The observed spectrum of PMMR23 was compared to synthetic spectrum generated using the Kurucz's numeric code SYNTHE. URAN code (Yushchenko 1998) was used for identification of the lines in observed spectrum. The examples of the spectrum are shown in the Figs. 1, 2.

The first iteration was made with the parameters of atmosphere model taken from Hill (1997). Synthetic spectrum was calculated for the whole observed

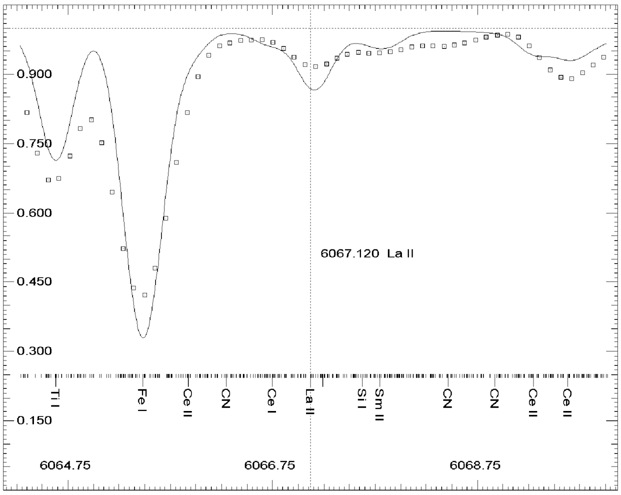

Figure 1: The example of the spectrum of PMMR23 in the vicinity of La II line 6067.12 Å . The axes are the wavelengths in angstroms and relative fluxes. The solid line is the synthetic spectrum, the open squares - observed spectrum. The positions of the lines, taken into account in the calculation of synthetic spectrum are shown in the bottom part of the figure. Part of the strong lines are identificated. Hill (1997) parameters of the atmosphere model and abundances of the elements were used for calculation of the synthetic spectrum.

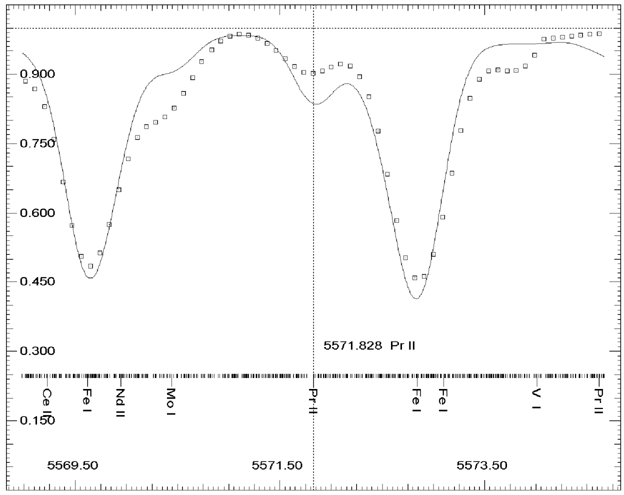

Figure 2: The same as in Fig. 1 in the vicinity of Pr II line 5571.828 Å.

wavelength region. The used list of spectral lines includes all atomic and molecular lines from Kurucz (1995), DREAM database (Biemont et al. 2002), VALD database (Piskunov et al. 1995), Hirata & Horaguchi (1995) and other sources.

This spectrum was used for identification of clean spectral lines in the observed spectrum. 88 clean lines of neutral iron and 7 lines of ionized iron were selected. Equivalent widths of these lines were used for testing of the atmosphere model. Kurucz (1995) WIDTH9 program was used for calculation of iron abundances. Hill (1997) parameters were adopted, only small change in microturbulent velocity was necessary.

The final set of atmosphere parameters is: effective temperature $T_{\rm eff}$=4200 K, surface gravity log g=0.2, microturbulent velocity $v_{\rm micro}$=3.95 km s^{-1}, the abundance of iron [Fe/H]=-0.65. The value of projected rotational velocity was estimated to be equal $v \sin i$ =3.5 km s^{-1}. This value includes all possible effects of broadening of spectral lines, for example macroturbulent velocity, magnetic broadening.

We found the numerous lines of lanthanides: La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Er in the spectrum of PMMR23. We identified also the lines of Cu, Y, Zr, Mo, Ru, Ba. The abundances were estimated using model atomosphere method with WIDTH9 program (Kurucz 1995). The next step was the calculation of abundances of these elements using the spectrum synthesis method. Kurucz (1995) SYNTHE and Yushchenko (1998) URAN codes were used for calculating of synthetic spectra and for fitting the observed spectrum by calculated one. Hyperfine and isotopic splitting data from Kurucz (1995) were taken into account for lines of Cu and Eu. More detailed description of methodic can be found in Yushchenko et al. (2005).

3. Results

The results are summarized in Table 1. The first three columns of the table are the numbers of the investigated elements, its identifications and atomic numbers. The next two triplets of columns are the abundance results of this investigation and that of Hill (1997). The relative abundances (with respect to the Sun), rms errors and number of used lines are shown in these columns. The last column is the abundances in the atmosphere of the Sun in accordance with Grevesse & Sauval (1998). The abundance on Ni from Hill (1997) is also included in the table.

The last version of database of lanthanides lines (DREAM, Biemont et al. 2002) and using the synthetic spectrum for identification of the lines permit to increase the number of investigated lines. The number of lines of heavy elements is approximately ten times exceeds the number of lines analyzed by Hill (1997). It permits us to investigate more elements and to obtain more reliable result.

The light elements are deficient in PMMR23 and the level of blocking of the spectrum by lines of these elements is not so high as in the similar stars of our Galaxy. That is why we can find more clean lines of heavy elements in the spectrum of PMMR23.

Fig. 3 shows the abundance pattern of PMMR23. The overabundances of barium and lanthanides with respect to iron are in range from 0.4 to 0.9 dex. The

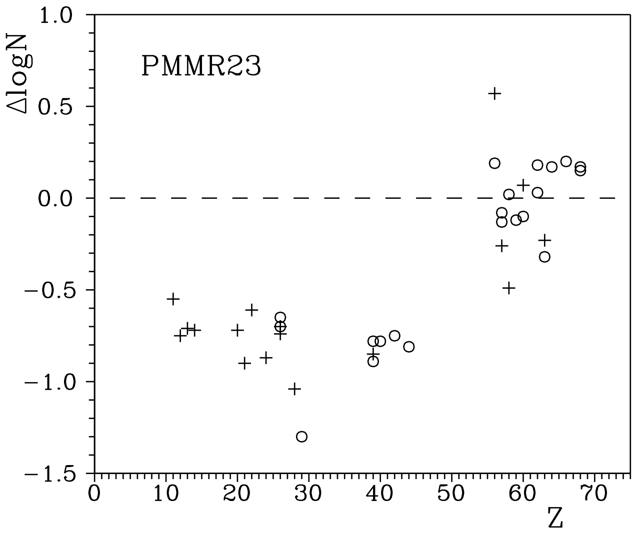

Figure 3: The chemical composition of PMMR23. The axes are the atomic numbers of the elements and relative abundances with respect to the solar values from Grevesse & Sauval (1998). The results of this paper are marked by open circles, Hill (1977) abundances – by crosses. Light elements in accordance with Hill (1997) are also shown at this picture.

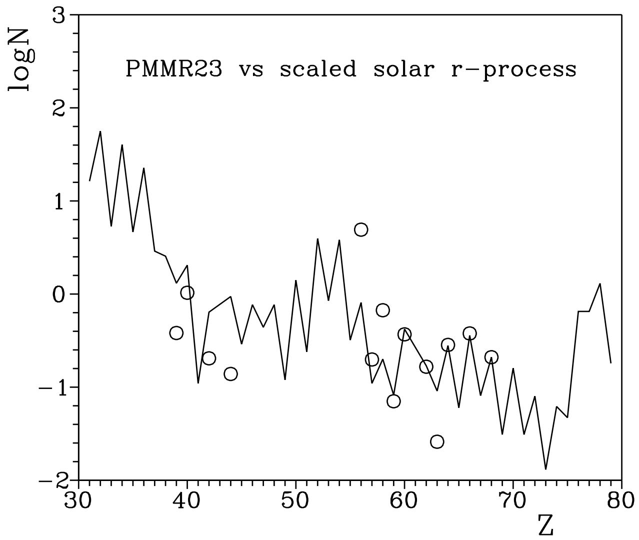

Figure 4: Comparison of the surface abundances in PMMR23 (circles) with the solar system r-abundance distribution scaled to the observed Er abundance (solid line). The solar system abundances corresponds to the photospheric determination of Grevesse & Sauval (1998) with the solar r-process distribution estimated by Burris et al. (2000)

overabundances increased with atomic number for elements after barium. Lighter r-, s- processes elements are deficient with respect to iron. All above mentioned elements exept Y, Ba, La, Ce, Nd, and Eu are identified for the first time in the spectrum of the star.

It should be noted that we detected the lines of the first spectra of La, Sm, Er. The ionization equilibrium for these elements confirms the value of surface gravity, selected from the investigation of iron lines.

4. Discussion

In this paper we confirmed the main features of abundance pattern of the star found by Hill (1997). These are the deficiency of chemical elements with atomic numbers Z<55 and near solar values of abundances for barium and lanthanides. The number of identificated lines of heavy elements is significantly higher than in previous investigations. It is the result of using the synthetic spectrum for line identification and for abundance calculations. The abundances of nine r-, s- processes elements are found for the first time. The higher precision of our results permit us to claim that the abundances of light lanthanides are usually less than the abundances of heavy lanthanides.

Supergiant stars are very young objects, so this chemical composition should reflect the present day chemical abundance of Small Magellanic Cloud. Fig. 4 shows the comparison of abundances in PMMR23 with scaled solar system r-abundance distribution. The distribution of abundances in the investigated star can be fitted by r-process distribution. It means that the interstellar gas in the place of formation of PMMR23 was enriched by *r*-process elements. Maybe it was supernovae explosion or other event.

Usually this fitting is made for halo stars of our Galaxy. In this case, in accordance with traditional Big-Bang cosmology, the number of stellar generations before the creation of investigated object is significantly less, than for young stars. In our case we can expect that PMMR23 was born in the place, where previous stellar generations were not very active. In this case the level of contamination of interstellar gase by *s*-process elements should be not very high.

The largest deviations are observed for Ba, Ce, and Eu. It should be noted that for Ba we did not take into account hyperfine and isotopic splitting of the lines. The deviations for Ce and Eu can be real, but need to be confirmed.

Recently Yushchenko et al. (2005) showed that the *r*-process in the Milky Way is not universal or more exactly the astrophysical site(s) hosting the r-process do(es) not always lead to a unique relative abundance distribution of the elements. The abundance of Eu in HD221170 (Yushchenko et al. 2005) also lower than the predicted scaled solar abundance. Maybe more complete investigation of the spectrum of PMRR23 and other supergiants observed by Hill (1997), as well as the new observations of the brightest stars in Magellanic Clouds and other galaxies will help to investigate the production of the elements in *r*-process outside of the Milky Way.

Table 1: Abundances of iron and r-, s-processes elements in PMMR23

	Z	Ident.	This work Δlog N	σ	n	Hill, 1997 Δlog N	σ	n	log $N_\odot$
1	26	Fe I	-0.65	0.13	88	-0.74	0.21	60	7.50
		Fe II	-0.70	0.07	7	-0.70	0.19	10	7.50
	28	Ni I				-1.04	0.26	10	6.25
2	29	Cu I	-1.30		1				4.21
3	39	Y I	-0.78	0.05	3				2.24
		Y II	-0.89	0.12	5	-0.85	0.21	2	2.24
4	40	Zr I	-0.78	0.19	13				2.60
5	42	Mo I	-0.75	0.01	2				1.92
6	44	Ru I	-0.81		1				1.84
7	56	Ba I	0.19	0.02	3				2.13
		Ba II				0.57	0.24	2	2.13
8	57	La I	-0.08		1				1.17
		La II	-0.13	0.13	14	-0.26	0.16	2	1.17
9	58	Ce II	0.02	0.14	22	-0.49	0.10	4	1.58
10	59	Pr II	-0.12	0.12	10				0.71
11	60	Nd II	-0.10	0.14	46	0.07	0.13	3	1.50
12	62	Sm I	0.18		1				1.01
		Sm II	0.03	0.22	16				1.01
13	63	Eu II	-0.32	0.02	3	-0.23		1	0.51
14	64	Gd II	0.17	0.05	5				1.12
15	66	Dy II	0.20	0.10	3				1.14
16	68	Er I	0.15		1				0.93
		Er II	0.17		1				0.93

It should be noted that in this paper we did not tried to calculate the abundances of light elements and the abundances of elements with atomic numbers higher than Z=68. Our preliminary results show that the abundance pattern of PMMR23 can be significantly more complete.

The derived abundances will be used to build the individual model of the star. The calculation of the abundances of all chemical elements using the synthetic spectrum method will be made in the next paper.

Acknowledgement. We use data from NASA ADS, SIMBAD, CADC, VALD, NIST, and DREAM databases and we thank the teams and administrations of these projects. Work by AY was supported by the Astrophysical Research Center for the Structure and Evolution of the Cosmos (ARCSEC) of Korea Science and Engineering Foundation (KOSEF) through the Science Research Center (SRC) program.

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