THE ABUNDANCES OF HEAVY ELEMENTS IN RED SUPERGIANTS OF MAGELLANIC CLOUDS

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ABSTRACT. The spectra of Magellanic Clouds (MC) supergiants PMMR 23, PMMR 144 and RM_1-667 with resolving power R=30,000 and signal to noise ratio near 100 obtained at 3.6 meter telescope in Chile were analysed. We present a report on the detailed investigation of MC supergiants, with spesial attention to the thorium abundance in these stars. The abundance patterns of three supergiants show that r-process elements are clearly detected in the atmospheres of investigated stars, but the abundances of s-processes elements can vary from star to star.

Key words: Magellanic Clouds, supergiants, chemical abundances, heavy elements, r-process elements, s-process elements.

1. Introduction

The investigation of different types of stellar objects outside of the Galaxy (Milky Way) usually starts from LMC & SMC – the nearest irregular galaxies located at the distances 50 Kpc (e.g. Bekki, 2011) and 60.6 Kpc (Hilditch et al., 2005), respectively. Our Galaxy and the MCs constitute the most examined part of the larger formation, called the Local Group of galaxies that includes up to 50 galaxies. The comparative analysis of the stars in the Milky Way and other galaxies leads to better understanding of the evolution of Local Group.

Huge interest to the nearest MC galaxies is revealed both through the amount of multiwavelength observational studies and astrophysical theories which have been developed using the obtained information. Among the three galaxies (Milky Way, LMC and SMC), the SMC has the smallest mass which is 50 times less than that of our Galaxy (e.g. Novara et al., 2011) and 5 times less than the mass of LMC (Skilba et al., 2012).

It is known that the chemical composition of MCs stellar population differs from that of our Galaxy, and the SMC metallicity [Fe/H] is lower than that of the LMC. According to the study of F-supergiants (Russel & Bessel, 1989), [Fe/H]=-0.65 dex for the SMC and [Fe/H]=-0.3 dex for the LMC stars.

The investigations of abundances of heavy elements are usually performed only for Galactic stars. High resolution spectra of at least brightest extragalactic objects are available now. These spectra as well as the new atomic and molecular data, and the development of new theoretical methods allow to investigate the abundances of heaviest chemical elements in the members of closest of Local Group galaxies. It can be helpful for understanding the evolution of these galaxies and finding the possible differences in the history of stellar formation.

Relying on the observational data, Russel and Dopita (1992), concluded that the r-process is more efficient in the Magellanic Clouds than in our Galaxy. According to Rolleston (1991), the MC galaxies can serve as an example to test the evolutionary model of the average chemical composition of galaxies. The matter enriched by heavy elements in the interstellar space of these galaxies is the source material to form the new generation of stars. The enrichment of SMC member stars with heavy elements is the indicator of more evolved chemical composition in those stars in comparison with the stars of the same spectral class of our Galaxy.

To compare, let us consider the results of the chemical composition examination of a supergiant in our Galaxy, namely Canopus (α Car) which, according to Reynolds et al. (1988), does not show any overabundances of heavy elements. Reynolds et al. (1988) result shows that the chemical abundances of 21 heavy r- and s-processes elements are very similar to the solar ones. A numerous investigations of stellar objects, including 64 supergiants of our Galaxy from F- to M-type (Luck & Bond, 1989), can also be discussed. Luck & Bond

(1989) showed that the heavy elements abundances in these stars are very similar to solar ones. In contrast to MC supergiants there are no anomalies, found in the supergiants of our Galaxy.

This paper is the overview of heavy elements investigation in the atmospheres of MC supergiants PMMR 144 & RM_1-667 . The results for PMMR 23 (Gopka et al., 2005) are also shown for comparison. The chemical composition of LMC red supergiant RM_1-667 was not investigated earlier. This star was selected for careful analysis due to peculiar H_α and sodium lines, which clearly indicated the mass loss (Gopka et al. 2013). Here after we present the determination of atmospheric parameters and the analysis of chemical composition with special attention to *r*- and *s*-processes elements.

2. Observational data and atmospheric parameters

We used the high-resolution spectra of RM_1-667 and PMMR 144 obtained in 1989 and 1993 by V. Hill at the 3.6 m telescope of ESO in La Silla, Chile. The EMMI spectrometer with spectral resolving power R=30,000 was used in 1989 to obtain the data in spectral range from 5900 Å to 6100 Å. The observations with CASPEC spectrometer (R=20,000) in the spectral range from 5900 Å to 6700 Å were made in 1993. The initial reduction of images were made by V. Hill. It is necessary to note that the visual magnitudes of RM_1-667 and PMMR 144 are V=13.124, and V=12.82 respectively (Hill, 1997). The signal to noise ratio of the spectra is only near S/N=100.

The parameters of atmospheric model of RM_1-667 were specified using the absorption lines of neutral and ionized iron: $T_{\rm eff}$= 3750 K, log g=–1.5, v_{micro} =2.4 kms^{-1}, v_{macro} = 9 kms^{-1}. The individual model atmosphere with these parameters and plane-parallel geometry was calculated using SAM12 code (Pavlenko, 2003), which is a modification of ATLAS12 code (Kurucz, 1995).

The effective temperature and other parameters of PMMR 144 were also determined using the lines of iron in the spectrum of this star. We adopted the values $T_{\rm eff}$= 4100 K, log g=–0.7, v_{micro} =4 kms^{-1}, v_{macro} = 9 kms^{-1}. Our values of effective temperature and surface gravity of the star are in good agreement with those determined by Hill (1997), only the microturbulent velocity is higher by 0.5 kms^{-1}.

The first approximation of abundances in PMMR 144 were used by R. E. Luck to create the individual atmosphere model with ATLAS12 code (Kurucz, 1995). The relations between iron abundances, equivalent widths and excitation energies of iron lines calculated with our individual atmosphere model support the derived parameters of PMMR 144.

3. Investigation of n-capture elements in the atmospheres of RM_1-667 and PMMR 144

Since the end of 80th of the former century we developed a method which allows to increase the reliability of identification of lines of chemical elements in stellar spectra. The main idea of this method is the comparison of observed and calculated spectra in wide spectrum region. The calculations of synthetic spectra should be made using the extended database of atomic and molecular lines and the observed spectra of different type stars should be compared. The more detailed description of the method and the examples of results can be found in Gopka et al. (2004), Yushchenko et al. (2005), Kang et al. (2012, 2013). The use of this method allowed us to find the identifications of lines of neutron-capture elements in the spectra of MCs supergiants and to calculate the abundances of these elements in the atmospheres of RM_1-667 and PMMR 144.

To increase the validity of results we used also the last version of SYNTHV code (Tsymbal, 1996), The last version of input list of atomic lines from VALD (Piskunov et al., 1995) and the model atmosphere 3750/-1.5 were used to create the synthetic spectra. The abundances of chemical derived using the equivalent widths of lines in observed spectra were applied as a first approximation for calculation of synthetic spectra. These spectra were used for comparison with observations and refining initial abundances in the next iterations.

First of all the abundances of C, N, O, Mg and Ti which define the intensity of predominant lines of TiO, CN, MgH and other molecules were specified before the analysis of other elements. The lines with maximum sensitivity to abundance changes were selected for final estimates.

PMMR 23. In 2005 we presented the investigation of this SMC supergiant (Gopka et al., 2005). One of the results was the determination of thorium abundance using the spectral lines in wavelength range from 5300 to 7100 Å in the observed spectra of several stars. Gopka et al. (2005) also derived the abundances of chemical elements in the atmosphere of PMMR 23, located in the region of low-velocity neutral hydrogen flow. It was found that the abundances of heavy (Z>56) elements such as La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Er, Lu, Hf, Tl, and Th in the atmosphere of PMMR 23, the star with iron abundance [Fe/H]=-0.51, are close to [el/Fe]=0.8 dex.

Fig. 1 shows one of the thorium lines in the spectrum of PMMR 23. Fig. 2 is the abundance pattern of PMMR 23, and Fig. 3 compares the abundances in the atmosphere of PMMR 23 with scaled solar *r*- and *s*-process distributions. For this and next figures the solar *r*- and *s*-processes distributions were taken from

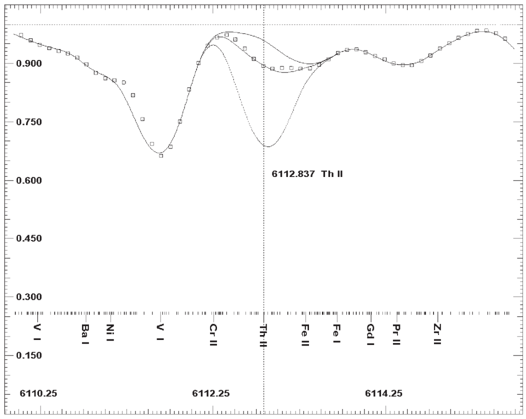

Figure 1: The fitting of observed spectrum (open squares) of PMMR 23 by synthetic spectra (lines) in the vicinity of Th II line λ 6112.837 Å. The axes are wavelength in angstroms and relative fluxes. Three synthetic spectra are shown near center of thorium line. One of these spectra fit the observations, the other two are calculated for under and overabundance of thorium by ±0.5 dex from the best value. The position of thorium line is marked by vertical dotted line. The wavelengths of atomic and molecular lines used for calculations of synthetic spectra are shown in the bottom part of the figure. The identifications are shown for the strongest of them.

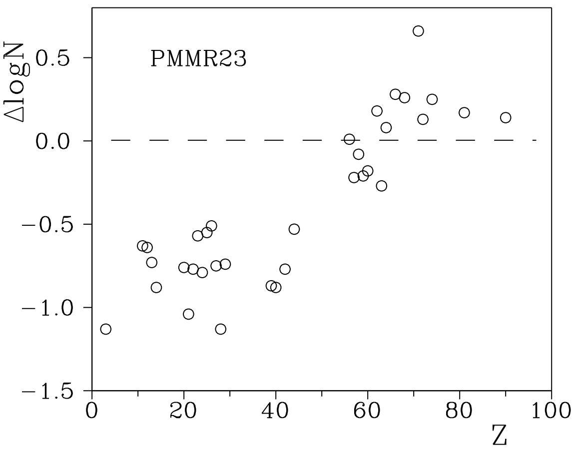

Figure 2: The plot of relative abundances of chemical elements in the atmosphere of PMMR 23 with respect to atomic numbers of these elements. Horizontal dotted line designates the solar abundances.

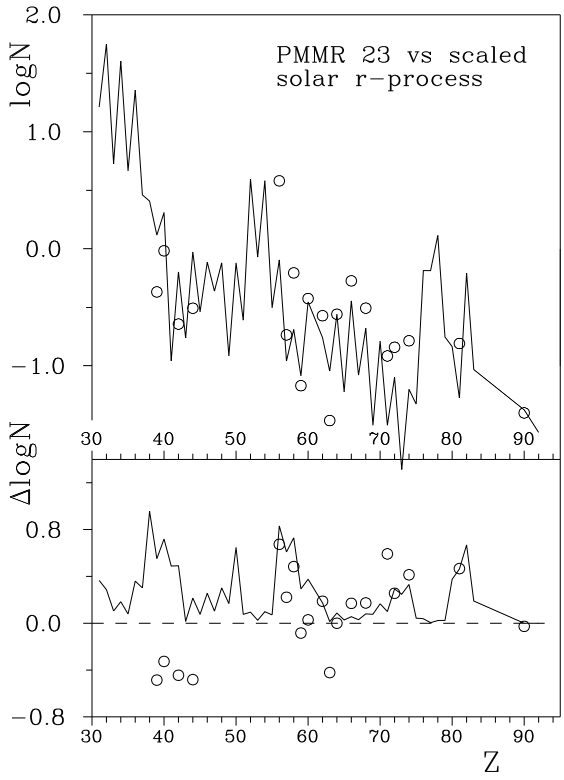

Figure 3: The upper panel shows the comparison of the surface abundances in PMMR 23 (circles) with the solar system $r-$process abundance distribution scaled at the observed Gd abundance (line). The bottom panel shows the differences of the observed abundances in PMMR 23 and the scaled solar system $r-$abundances (circles). The line is the deviations of solar photosphere abundances from solar $r-$process abundance distribution. The maximums of this curve are expected for the elements with highest relative $s-$process contributions.

Simmerer et al. (2004).

Two subsequent triplets of figures, namely Figures 4, 5, & 6 and Figures 7, 8, & 9 exhibit the similar information for next two stars: PMMR 144 and RM_1-667 respectively.

PMMR 144. In the sample of six SMC stars investigated by Hill (1997) PMMR 144 demonstrated the most deficient iron abundance with respect to other stars. It was supposed that the object was likely to have second component with magnitude of 16-17^m. The lanthanum and europium were not overabundant relative to iron (Hill, 1997). In the present study, like in earlier works devoted to the investigation of chemical composition of MC stars, we focus our attention on the identification of the heavy elements lines.

Each line in the spectrum range from 5790 to 6835 Å was analyzed by synthetic spectrum method to determine the major contributors to line absorption coefficient. It was found that thorium, lutetium, europium, neodymium, cerium, lanthanum, zirconium, yttrium, and other heavy elements lines can be identified in the visible spectrum. The equivalent widths of these lines can be as high as 80-100 mÅ.

Using the synthetic spectrum method the abundances of 31 chemical elements, including 15 neutron-capture elements, were estimated. For most of the investigated elements, the abundance pattern of PMMR144 shows a deficiency of about 1.0 dex with

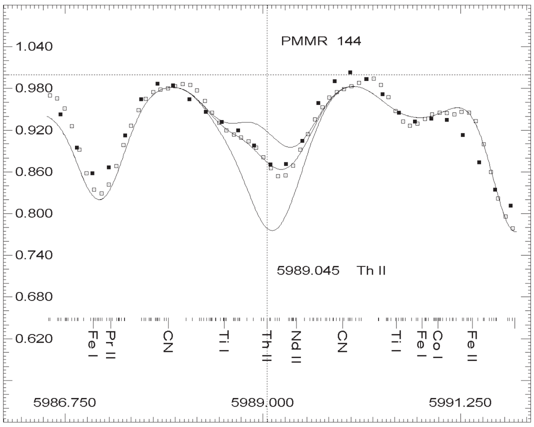

Figure 4: Similar to Fig. 1, but the star is PMMR 144, and the thorium line is λ 5989.045 Å. Open and filled squares are different observed spectra.

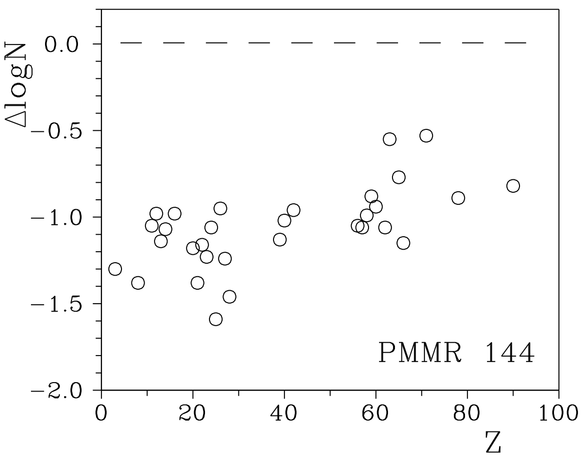

Figure 5: Similar to Fig. 2, but for PMMR 144.

respect to the solar values. Elements heavier than barium are enhanced with respect to iron by +0.5 dex.

RM_1-667. The detailed identification of the absorption lines in the RM_1-667 spectrum was carried out. It was found that the lines of several post-lanthanides, namely Hf, Pt, and Th can be detected in the visible spectrum. The identification of thorium lines in the visible spectrum of RM_1-667 is an important result of our study (Fig. 7). The coincidence of observed and laboratory wavelengths as well as the abundances derived for different lines are the undeniable proof of the presence of r-process elements in the atmosphere of this star.

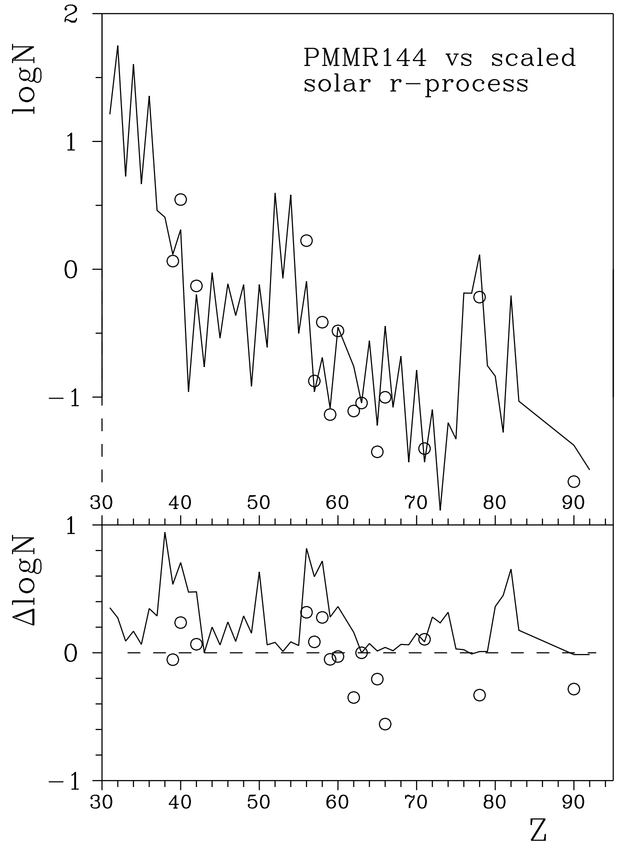

Figure 6: Similar to Fig. 3, but for PMMR 144. Solar r-process abundance distribution is scaled to the observed europium abundance.

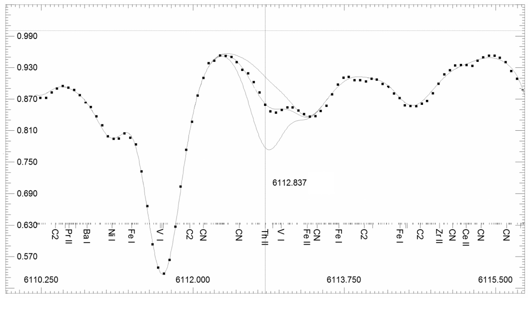

Figure 7: Similar to Fig. 1, but the star is RM_1-667. Observed spectrum is shown by filled squares.

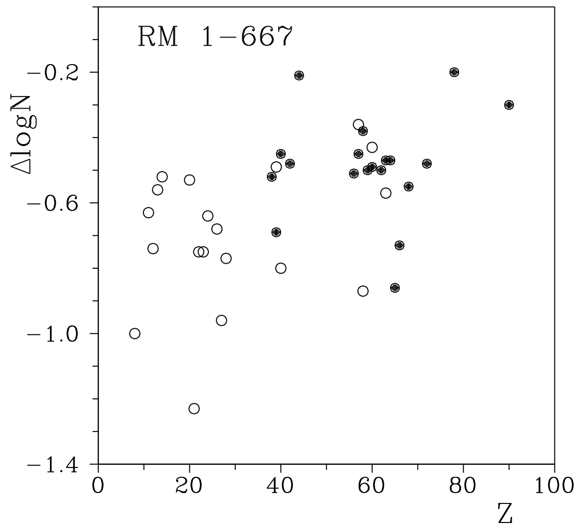

Figure 8: Similar to Fig. 2, but the star is RM_1-667. Open and filled circles are the values calculated using model atmospheres and spectrum synthesis methods respectively.

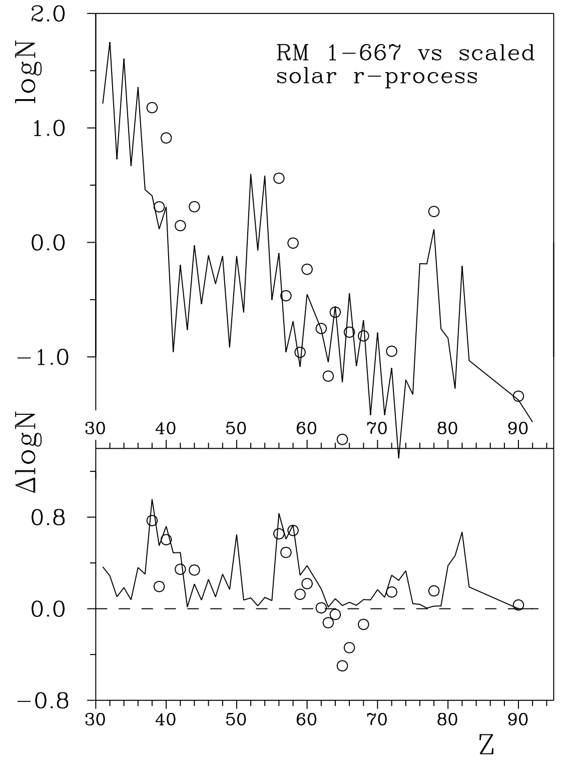

Figure 9: Similar to Fig. 3, but the star is RM_1-667. The solar system $r-$process abundances are scaled at the observed abundance of gadolinium.

4. Discussion

The knowledge of actinides abundances in extragalactic objects now is restricted by Local Group members. Only few papers were devoted to this observational problem. One of the first was the investigation of metal-poor red giant COS 82 in Ursa Minor dwarf galaxy (Aoki et al, 2007). The thorium abundance was found using the line Th II λ 5989.045 Å, which was first identified in stellar spectrum by Yushchenko et al. (2005).

We identified thorium lines in the spectra of three MC supergiants, find the chemical composition of these stars, and compared the abundance patterns with solar system r-, and s-processes abundance distributions. Analysis of Figures 3, 6, and 9 allows to conclude that the abundance patterns can not be explained by only r-process contribution. The influence of s-process is clearly visible at the bottom panels of these figures, but it is also clear that the input of s-process can not be easily estimated – it differs from star to star.

As it was discussed by Yushchenko et al. (2013) not only the nonuniversality of r-process, but also the accretion of interstellar gas also can be important to understand the chemical anomalies in stellar atmospheres. Kang et al. (2012, 2013) show that the signs of accretion of interstellar gas can be found not only in hot stars with radiative atmospheres, but also in cooler stars if the accretion is strong enough.

Our preliminary results shows that the possibility of accretion can not be neglected for explanation of abundance anomalies in the atmospheres of these three MC supergiants. The detection of signs of accretion can be additional confirmation of high density of interstellar gas in MC.

5. Conclusion

In present investigation we demonstrated the detectability of thorium lines in the spectra of MC supergiants.

The comparison of the theoretical curves of r-process and the abundance patterns, obtained in present study for MC supergiants, show resemblance that enables us to assume that the matter, from which the target stars were formed, was enriched by main r-process elements. But some percents of s-process elements are present in these stars. The elements with important contribution of s-process elements clearly deviate from solar system r-process abundance distribution, but the deviations are different from star to star.

It is necessary to discuss the possibility of additional scenarios to explain the chemical anomalies of these stars.

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