THORIUM LINES IN THE SPECTRA OF SEVERAL SMC SUPERGIANT STARS

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ABSTRACT. We present the results of identifications of the Th II lines in the spectra of four stars in the Small Magellanic Cloud: PMMR 23, PMMR 39, PMMR144, and PMMR 145. We report about detection of the lines of Th II in the visible part of spectra of K-supergiants. Thorium lines in the spectra of these stars are stronger than the thorium lines in the spectra of HD221170 and Arcturus. The thorium abundances in the atmospheres of four SMC stars are scattered from +0.05 to -0.69 in the scale where logN(H)=12.

Key words: stars: abundances; stars: individual (PMMR23, PMMR39, PMMR144, PMMR145); nucleosynthesis; galaxies: stellar content; galaxies: individual (Small Magellanic Cloud).

1. Introduction

Investigation of the thorium abundance in the atmospheres of different stars in our Galaxy has a long history. Only strongest line of Th II λ 4019.129 Å was used before. But new values of oscillator strength of the thorium lines (Nilsson et al, 2002.) permit us to increase significantly the list of measurable thorium lines in stellar spectra. For example, thorium halo star HD 221170 has the thorium lines in the visible part of its spectrum (Yushchenko et al. 2005).

Determination of the elemental abundances in SMC stars is very usefull for construction of the theory of evolution of this galaxy. It is very important to investigate the heavy elements. Surveys of the heavy element abundances were made by Russell and Bessel (1989) and Spite et al. (1991). It was shown that the heavy neutron-capture elements in the Magellanic Clouds were formed similarly to the formation of these elements in the Galactic halo, but not in the Sun (Russell, 1991).

The apparent overabundances of the neutron-capture elements heavier than Ba in the atmospheres of supergiants, that was found earlier in several investigations, permits us to suppose that the search for thorium lines in these stars can be fruitful.

We used high-resolution CCD-spectra of SMC red K-supergiants, obtained by V. Hill from 1989 to 1993 at ESO (La Silla, Chile), using the New Technology Telescope equipped with the ESO Multi-Mode Image EMMI and the 3.6 meter telescope with the CASPEC spectrograph. (Hill, 1997).

2. Investigation of thorium lines

The underabundance of elements heavier than barium was found in F-supergiants of both Magellanic Clouds by Russel and Bessell (1989). Russell (1991) outlined that one of the important areas of futher researches can be the acquiring the data about spectral lines of heavy neutron-capture elements in these stars.

The distribution of the abundances of these elements indicates that they were produced by the r-process (Russell, 1991). Hill (1997) and Hill et al., (1997) analysed the chemical compositions of K-supergiants in Magellanic Clouds and found that in all investigated stars, except PMMR144, s- and r-process elements heavier than Ba are enhanced by +0.4 dex. The abundances of 35 and 20 chemical elements in the atmospheres of PMMR23 and PMMR39 were obtained by Gopka et al. (2005).

For elements with atomic numbers less than 56 we found the underabundances with respect to the Sun near -0.7 dex. The abundances of elements heavier than barium are similar to the solar abundances of these elements.

The main goal of this investigation is the identification of all lines of ionized thorium in visible part of the spectra of K-supergiant stars in the Small Magellanic Cloud: PMMR23, PMMR39, PMMR144, and PMMR145.

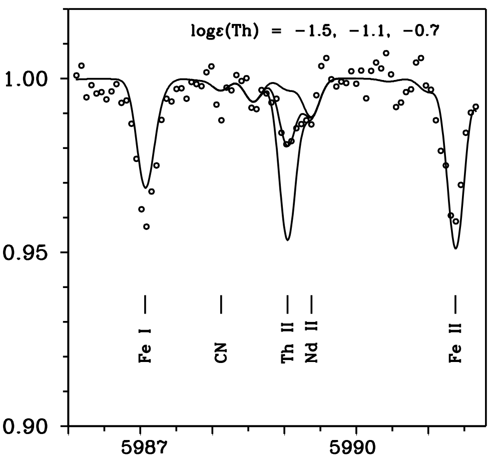

Figure 1: Spectrum of HD221170 near λ 5989.045 Å. Circles - observed spectrum, lines - synthetic spectra calculated with different thorium abundances.

We compared the lines of Th II in the spectra of SMC stars with these lines in the spectra of halo star of our Galaxy HD221170 and Arcturus. Observed spectra were taken from Yushchenko et all. (2005) and from Hinkle et al. (2000) for HD221170 and for Arcturus respectively. Thorium line λ 5898.045 Å in the spectra of HD221170, Arcturus and SMC supergiant stars is shown in Figures 1-3. Thorium line λ 6044.433 Å in the spectra of PMMR23, PMMR39, and PMMR144 can be found in Fig. 4.

We can see that thorium lines in the spectra of SMC supergiants (Fig. 3) are stronger that the lines in the spectra HD221170 and Arcturus (Fig. 1-2). It should be noted that line λ 5898.045 Å is blended by Nd II line. In the case of PMMR144 the blending is not significant since the Nd is underabundant with respect to the Sun approximately by -1 dex.

Other thorium lines are not so strong in the spectra of SMC stars, but they are still strong in comparison with the spectra of HD221170 and Arcturus. It seems reasonable to search for thorium lines in the spectra of K-supergiants of our Galaxy with similar to SMC stars temperatures and gravities.

The equivalent widths of thorium lines were estimated by fitting their profiles with a Gaussian function. The thorium abundance was calculated using the model atmosphere method on the basis of the Kurucz (1995) WIDTH9 program. Parameters of atmosphere models were taken from prevoius investigations of these stars. The results for individual lines can be found in Table 1, where for all used lines we pointed the wavelength, the oscillator strength, and the pairs (equivalent width – abundance) for four program stars.

The mean abundances of thorium in the atmospheres of PMMR23, PMMR39, PMRR144, and PMMR145 are found to be equal to $\approx -0.10 \pm 0.13, -0.63 \pm 0.13, -0.69 \pm 0.09$, and $+0.05$ dex (in the scale logN(H)=12), using 6, 2, 4, and 1 thorium lines respectively.

The blend of λ 5989.045 of Th II line with line of Nd II at λ 5989.378 Å has equivalent width which exceeds 100 mÅ in the spectra of SMC K-supergiants. It is better to use synthetic spectra method to find the precise abundances of thorium (Gopka et al. 2005). The weaker thorium lines shows similar values of abundances, the scattering is smaller than 0.2.

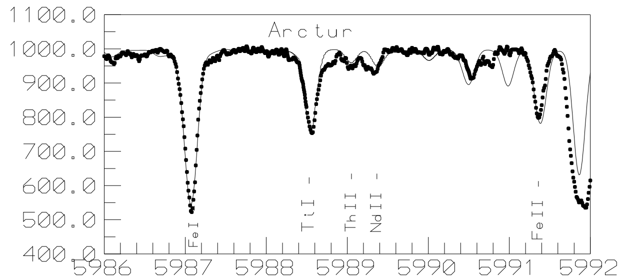

Figure 2: Spectrum of Arcturus near λ 5989.045 Å. Thin line is synthetic spectrum, filled circles - observed one.

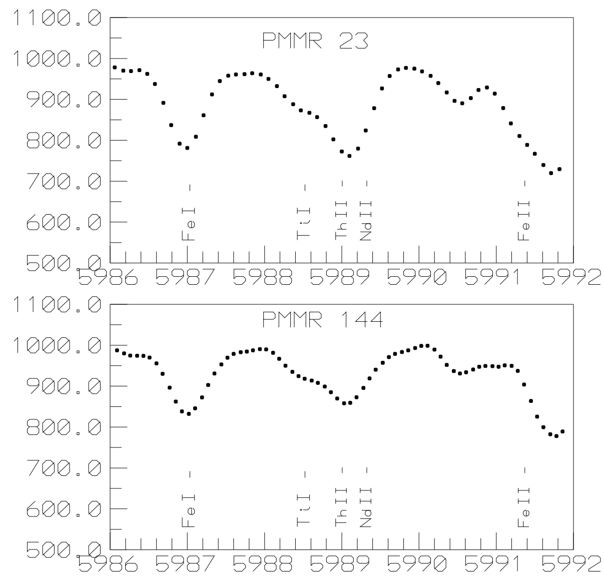

Figure 3: Spectra of PMMR23, and PMMR144 in vicinity of λ 5989.045 Å.

Table 1: Thorium lines and the abundances of thorium in the atmospheres of PMMR23, PMMR39, PMMR144, and PMMR145.

λ	*loggf*	Equivalent widths and abundances							
		23		39		144		145	
5488.630	-2.61	18	-0.16			12	-0.80		
5989.045	-1.41	130	0.07			102	-0.56		
6044.433	-1.87	16	-0.30	16	-0.76	20	-0.76		
6112.837	-1.83	50	-0.15	30	-0.50			49	0.05
6619.944	-1.81	29	-0.10			11	-0.65		
6993.037	-1.57	26	0.06						

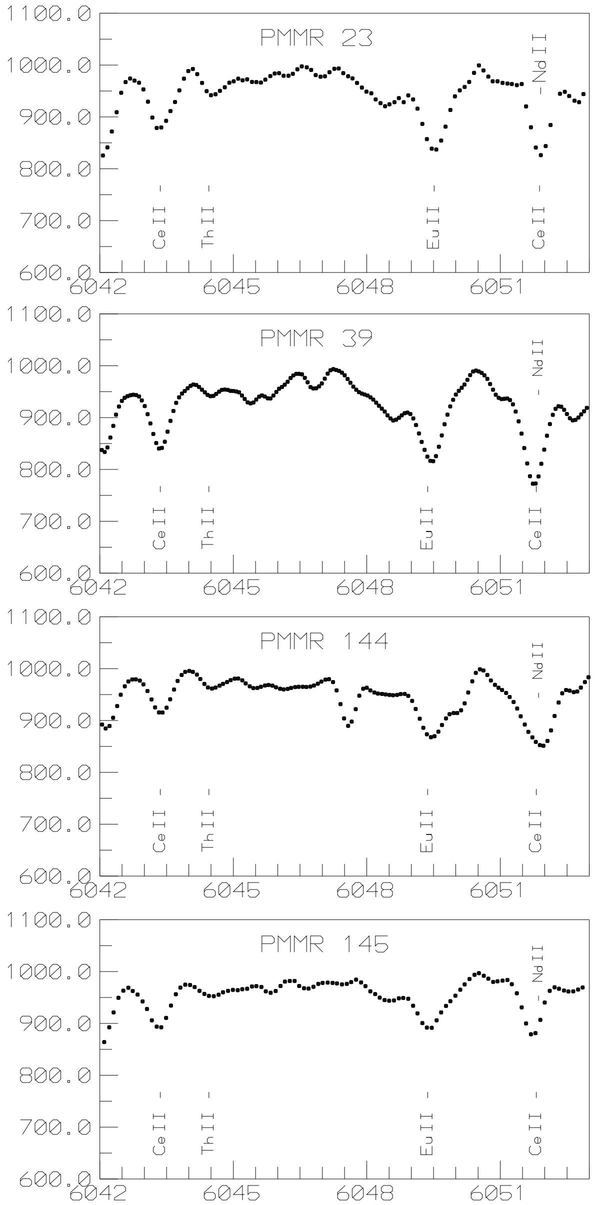

Figure 4: Spectra of PMMR23, PMMR39, and PMMR144 in vicinity of λ 6044.433 Å.

3. Discussion

We hope that the discovery of strong thorim lines in the visible part of the spectrum permits to investigate the abundance of thorium in supergiant stars of our Galaxy, Magellanic Clouds and dwarf satellites of the Galaxy. As it was pointed here before, only the strongest line of ionized thorium λ 4019.129 Å was used in numerous investigations of thorium abundance in galactic stars. It was the base of all important results concerned the evolution of the Galaxy, ecspesially its halo stars.

The brief overview of the best investigations of halo stars was made by Yushchenko et al. (2005). It was pointed out that only five galactic $r-$process-rich halo stars (GS31082-001, GS22892-052, HD115444, BD+17^{o}3248, and HD221170) have detailed abundance patterns that permit to have some imagination about the history of formation of the heavy elements in these stars.

The ratio of thorium and europium abundances in three of these stars is close to -0.6, while in two stars (GS31082-001 and HD221170) it is near -0.2. Later, Ivans et al. (2006) using the spectra of HD221170 obtained at KECK telescope reanalysed the abundance pattern of HD221170. It was found that the mean difference between the abundances of chemical elements found by Yushchenko et al. (2005) using 2-m Terskol Observatory telescope and Ivans et al. (2006) using 10-m KECK telescope and 2.7-m Mc-Donald Observatory telescope is as small as $+0.04\pm0.19$ dex, but the difference in Th/Eu ratio is significant, and this ratio is close to -0.6 for HD221170.

It permitted Ivans et al. (2006) to claim that the production of $r-$process elements in different supernova explosions is similar. The only exception is GS31082-001. Ivans et al. (2006) proposed that anomalous Th/Eu ratio for this star can be explained by a contamination from a nearby SN II event, sufficiently nearby, like in the binary system.

In accordance with Ivans et al. (2006) there are 5 $r-$process-rich halo stars with detailed abundance patters, and the peculiarity of one of these stars should be explined by close supernova event.This explanations was first proposed by Qian & Wasseburg (2001) to explain the chemical composition of GS 31082-001 only.

But can we expect that 20 percents of this type of stars have been influenced by the nearby explosions? Is it really possible that all the stars with a non-standard Th/Eu ratio suffered close SNe event?

Honda et al. (2004) investigated 22 very metal-poor stars with [Fe/H]<-2.5 and found that Th/Eu abundance ratios log(Th/Eu) are distributed over the range -0.10 to -0.59 with typical error of 0.10 to 0.15 dex. It seems that this result indicates real star-to-star scatter, not contamination by close SN event. We hope that thorium lines in the red part of spectrum will be useful to resolve this and other problems of stellar evolution.

4. Conclusion

The main results of our investigation are:

1. The lines of Th II in the spectra of PMMR23, PMMR39, PMRR144, and PMMR145 are stronger than thorium lines in the spectra of other stars that were investigated earlier. We obtained, that the intensity of Th II line λ 5898.045 Å in the spectra of these stars are also stronger than in the spectra of halo star HD221170 and Arcturus (Fig. 1-6).

2. The abundances of thorium in the atmospheres of PMMR23, PMMR39, PMMR144, and PMMR145 are scattered from +0.05 to –0.69 in the scale where logN(H)=12.

3. Six thorium lines were identified in the spectrum of PMMR23. Equivalent widths of these lines are in the range from 16 to 130 mÅ.

4. Detection of of thorium lines in the visible part of the spectrum is very important for the future investigations of $r-$, $s-$process elements and for the cosmochronology. These identifications can give a possibility to investigate the thorium abundances in other stars of Magellanic Clouds, our Galaxy, dwarf satellites of the Galaxy.

References

Nilsson H., Zang Z.G., Lundberg H., Johansson S., and Nordstrom B.: 2002, *A&A*, **382**, 368.

Russell S. and Bessel M.: 1989, *ApJ Suppl. Ser.*, **70**, 865.

Spite F., Spite M., Francois P.: 1989, *A&A*, **210**, 25.

Russell S.: 1991, *Irish Astron. J.*, **20**, 42.

Hill V.: 1997, *A&A*, **324**, 435.

Hill V., Barbuy B., Spite M.: 1997, *A&A*, **323**, 461.

Hinkle K., Wallace L., Valenti J., Harmer D.: 2000, Visible and Near Infrared Atlas of the Arcturus Spectrum 3727-9300 Å, *Astron. Soc. Pacific*

Honda S., Aoki W., Kajino T., Ando H., Beers T.C., Izumiura H., Sadakane K., Takada-Hidai M.: 2004, *ApJ*, **607**, 474

Gopka V.F., Yushchenko A.V., Goriely S., Vasil'eva S.V., Kang H.: 2005, *IAU Symp. No 228.*, **228**, 535.

Ivans I.I., Simmerer J., Sneden C., Lawler J.E., Cowan J.J., Gallino R., Bisterzo S.: 2006, *ApJ*, **645**, 613.

Qian Y.-Z., Wasseburg G.J.: 2001, *ApJ*, **552**, L55.

Yushchenko A., Gopka V., Goriely S., Musaev F., Shavrina A., Kim C., Kang Y. Woon, Kuznietsova J., Yushchenko V.: 2005, *A&A*, **430**, 255.