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FULL TITLE
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Interplay between diffusion, accretion and nuclear reactions in the atmospheres of Sirius and Przybylski's star

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Abstract. The abundance anomalies in chemically peculiar B-F stars are usually explained by diffusion of chemical elements in the stable atmospheres of these stars. But it is well known that Cp stars with similar temperatures and gravities show very different chemical compositions. We show that the abundance patterns of several stars can be influenced by accretion and (or) nuclear reactions in stellar atmospheres. We report the result of determination of abundances of elements in the atmosphere of hot Am star: Sirius A and show that Sirius A was contaminated by s-process enriched matter from Sirius B (now a white dwarf). The second case is Przybylski's star. The abundance pattern of this star is the second most studied one after the Sun with the abundances determined for about 60 chemical elements. Spectral lines of radioactive elements with short decay times were found in the spectrum of this star. We report the results of investigation on the stratification of chemical elements in the atmosphere of Przybylski's star and the new identification of lines corresponding to short lived actinides in its spectrum. Possible explanations of the abundances pattern of Przybylski's star (as well as HR465 and HD965) can be the natural radioactive decay of thorium, and uranium, the explosion of a companion as a Supernova or nucleosynthesis events at stellar surface.

1. Introduction

The diffusion of chemical elements in the atmospheres of late B – early F main sequence stars is usually accepted as the major reason for the peculiar abundances in the atmospheres of these objects. One of the biggest problems is the different abundance patterns for stars with very similar temperatures and gravities. It is clear that additional phenomena can influence the chemical composition. In the 70s, nuclear reactions in stellar atmospheres were discussed as the possible mechanism responsible for such chemical peculiarities. Proffitt & Michaud (1989) pointed the possibility for these stars to have accreted *s*- or *r*-processes enriched matter. They showed that one out of 500 peculiar stars can be expected to have surface abundance anomalies due to accretion from a binary companion that exploded as a Supernova (hereafter SN). Radiative diffusion is expected to make these peculiarities undetectable after a few millions years. No observational detection of this phenomena were found for B-F main sequence stars, but it was investigated in barium stars and permit to explain the overabundances of *s*-process elements.

In this paper we show the preliminary results of investigations of several Cp stars, namely Sirius A, Przybylski's star, HD965, HR465. Accretion, natural radioactive decay of thorium and uranium, and nucleosynthesis in stellar atmospheres are discussed as the possible explanation of chemical composition of these objects.

2. Observations and Data Analysis

The chemical abundances in the atmosphere of the main component of Sirius binary system are found using Rogerson (1987) atlas (spectral resolution 0.1 A, signal to noise ratio S/N>100, wavelength region 1649-3130 Å) and spectrum obtained at 2.6 meter telescope of McDonald observatory (spectral resolving power R=60,000, S/N>600 in red region, 3525-10200 Å). The spectrum of Przybylski's star (R=80,000, S/N>300 in red region, 3040-10400 Å, UVES spectrograph) was taken from the VLT archive (Bagnulo et al. 2002). Additional observations were made at 3.6 meter ESO telescope during 4 nights in March, 2004 (R=110,000, 3780-6710 Å, HARPS). Coaddition of 13 spectra observed without iodine cell permit to reach S/N near 400-500 in red region. Observations of HD965 and HR465 were made at the 1.8 meter telescope of Boyhynsan observatory in Korea (R=80,000, S/N>150, 3780-9500 Å, BOES). The abundances of the chemical elements were obtained using the spectrum synthesis method. The description of the codes and line lists can be found in Yushchenko et al. (2004).

3. Sirius

Sirius system consists of a main sequence star and a white dwarf (WD). The orbital period is about 50 years. The atmosphere of the main sequence star can be contaminated by s-process enriched matter at the time the WD was a red giant. The contamination of Sirius A by the companion was pointed by Lambert et al. (1982) as a reason of anomalous CNO abundances. We calculated the abundances of elements with atomic numbers Z≥29 in the atmosphere of Sirius A. Atlas12 atmosphere model was built with parameters T_{eff}=9900, logg=4.3, microturbulent velocity 1.85 km/s, and Qiu et al. (2001) abundances. Rotational velocity was accepted to be equal *vsini*=16 km/s. We estimated the abundances of Cu I (1 spectral line), Zn I (3), Sr II (2), Y II (11), Zr II (13), Ba II (5), La II (2), Ce II (11), Pr III (1), Nd III (2), Gd II (1), Os II (1), Pb II (1) using McDonald observatory spectrum and abundances of Ga II (1 spectral line), Mo II (1), Cd II (1), Hf II (1), W II (1), Re II (2), Os II (4), Pt II (2), Hg II (1), Pb II (2) using Copernicus UV spectrum. Preliminary results are shown in Fig. 1 where the contamination of the atmosphere is clearly seen. As it was noted by Proffitt and Michaud (1989) the peculiarities of this type should be destroyed by diffusion in few millions years.

We can point three estimates of the age of Sirius WD: near $160 \cdot 10^6$ years (standard theory of WD: Holberg et al. 1998), less than $1\text{-}5 \cdot 10^6$ years (our abundance analysis and diffusion theory), and $1\text{-}2 \cdot 10^3$ years (historical researches: See 1927, Whittet 1999 and references therein).

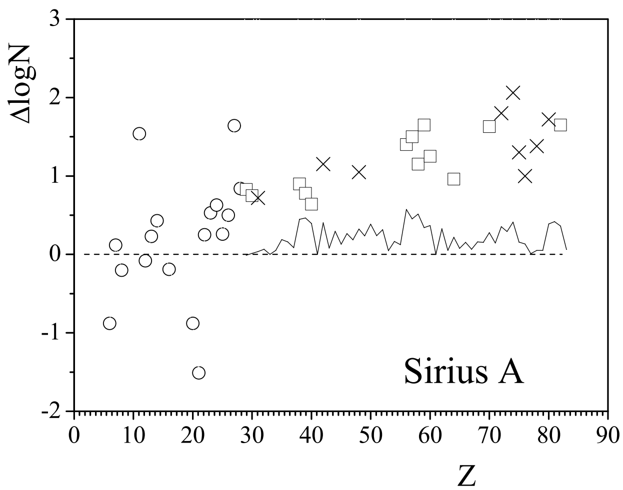

Figure 1. Chemical composition of Sirius A. The axes are atomic numbers and logarithmic abundances with respect to solar values. Abundances of elements with Z<29 (from Qiu et. al (2001)) are marked by circles. Our results are shown by squares (values obtained from visual spectrum) and crosses (from UV spectrum). The line corresponds to calculated s-process-rich abundances obtained from the wind accretion model for mild barium star ζ Cyg A (Yushchenko et al. 2004). The extremums of this curve coincide with extremums of observed abundances

To check the third possibility, we tried to find the lines of Tc (Z=43) in the optical and UV spectra of Sirius A. No sign of Tc lines was found. So, if Tc was produced at the final stages of evolution of red giant, the age of WD should significantly exceed the decay time of the Tc isotopes, i.e about 10^5 years.

The discrimination between the first two cases needs additional investigation. If the contamination should be destroyed by diffusion, what is the final abundance pattern? The contaminated abundances are observed in barium stars. Is it possible to observe similar patterns in Sirius type binaries with age of WD more than few millions years?

4. Przybylski's star (HD101065)

Cowley et al. (2004) found the lines of Tc and Pm in the spectra of Przybylski's star (hereafter PS) and HD965. Gopka et al. (2004) and Bidelman (2005) found the lines of short-lived elements with atomic numbers 83<Z<100 in the spectrum of PS. The lines of all elements except At and Fr (Z=85 & 87) were identified in both studies. Gopka et al. (2004) proposed some explanations for the existence of these elements in the stellar atmospheres. Gopka et al. (2006) reported the identification of Tc, Pm, and lines of short lived elements with 83<Z<100 in the spectra of PS, HR465, and HD965. The above-mentioned investigations were based on the NIST wavelengths data for elements with Z>83 (Sansonetti et al. 2004). Of course, these identifications needs additional justifications.

The number of unidentified lines in the spectra of PS and similar stars is of the order of several lines per angstrom. In the 70s of the last century there was a hope that new laboratory data for lanthanides will help to identify these lines. After 3 decades we have a lot of additional line data. The largest new set of lanthanides lines is DREAM database (Biemont et al. 2002a). But available lines of stable elements are still not sufficient for identification of unknown lines. If unstable elements exist in the atmosphere of PS it is quit natural to expect that the analysis of line lists of these elements will permit to find new identifications.

We tried to find new lines using atomic spectra of actinides by Blaise & Wyart (2005). 52 new lines of unstable actinides are found in the spectrum of PS. Oscillator strengths for these lines are not known, even ionization stages are not pointed for einsteinium. Let us consider only lines of the second spectra of the elements with at least four identifications in the spectrum of PS. These are 10, 6, 23, 5, and 4 lines of Ac II, Pa II, Pu II, Am II, and Bk II respectively. Note, that 23 lines is found for Pu. The decay time of ^{244}Pu is $80{\cdot}10^6$ years – the longest among actinides, after Th and U, and not negligible in comparison with stellar evolution time scale. One of Pu lines is shown in Fig. 3.

Three scenarios can be called for to explain the existence of short-lived radioactive elements in stellar atmosphere. Gopka et al. (2004) pointed that due to diffusion in stellar atmospheres layers with Th and U overabundances should exist. Due to the Th and U natural radioactive decay elements with 83<Z<92 can be produced. Elements with Z>92 are created by reactions on lighter elements with neutrons and α-particles produced in the decay chains. All these elements are found in terrestrial radioactive ores. The ores with concentration of Th and U near one percent are considered as the best ores for industry.

Abundance pattern of PS can be fitted by scaled solar r-process pattern (Cowley et al. 2000). It goes along the old idea that the PS abundances originate from the SN explosion of its binary component. Gopka et al. (2004) found the upper limits of Pb and Bi abundances. These limits are smaller than scaled r-process values. Kuchowicz (1973) pointed, that it is a sign of recent SN event.

Finally, nuclear reactions at the stellar surface can naturally be called for to explain the formation of radioactive elements. The large magnetic field observed in Ap stars can be the origin of a significant acceleration of charged stellar energetic particles (SEP), mainly protons and α-particles, that in turn can by interaction with the stellar material modify the surface content. External sources from cosmic rays or jet-like accelerated particles could also be considered. Due to the unknown characteristics of the accelerated particles, a purely parametric

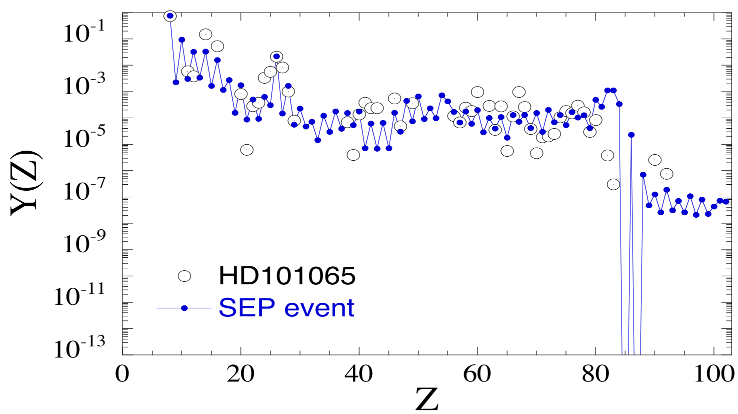

Figure 2. Comparison of Cowley et al. (2000) abundances (circles) with those obtained for one of the possible nucleosynthesis events (see text).

approach was followed, taken as free parameters the proton and α-particle flux amplitude and energy distribution, and the time of irradiation. To estimate the resulting nucleosynthesis, a nuclear reaction network including all nuclei heavier than oxygen up to $Z = 102$ and located between the proton drip line and the neutron-rich side of the valley of stability is used. Proton, α and neutron captures, as well as α-, β- and spontaneous fission decays are considered. This includes some 240000 reactions on 3940 different species. The initial abundance distribution is assumed to be solar. Our calculation shows that many aspects of the composition of PS and other chemically peculiar stars can be explained. As an example, we compare in Fig. 2 the PS abundances with those obtained for a given irradiation event characterized by a proton flux of $\Phi_p = 100$ mb^{-1} s^{-1}, and α-particle flux $\Phi_\alpha/\Phi_p = 0.2$, both with energies per nucleon ranging uniformly between 40 and 50 MeV. The irradiation time is 24 min. Note that we also consider here the possibility that the observed abundances is a mix (for example by diffusion) between the irradiated material and part of the ambient unaffected surface matter. For a 3-to-1 ratio between unaffected and irradiated material, the pattern show in Fig. 2 is obtained. As can be seen, a significant production of $Z > 30$ heavy elements is found, and can be explained through secondary neutron captures. Another attractive feature of the proposed process is the systematic production of Tc and Pm, and the possible production of actinides and subactinides, as suggested by our observations. More details on these calculations will be published somewhere else.

To select one of these scenarios we need the data on stratification and abundances of chemical elements in the atmosphere of PS. We found the stratification of barium using the profile of the strong Ba II line at λ 6141 Å (Fig. 3). Similar result for barium was published by Ryabchikova et al. (2003). It should be noted that Cowley et al. (2000) abundances and atmosphere model with flat abundances can fit the observed spectrum in red and visual wavelength regions but fail in near UV (Fig. 3). The stratification of chemical elements in the atmosphere of PS is very plausible hypothesis to reach an agreement.

Analysis of equivalent widths of Fe, Th, and U permits to find the distribution of these elements in the atmosphere of PS (see Fig. 4). Test calculations show an evidence of strong stratification for iron group elements, lanthanides

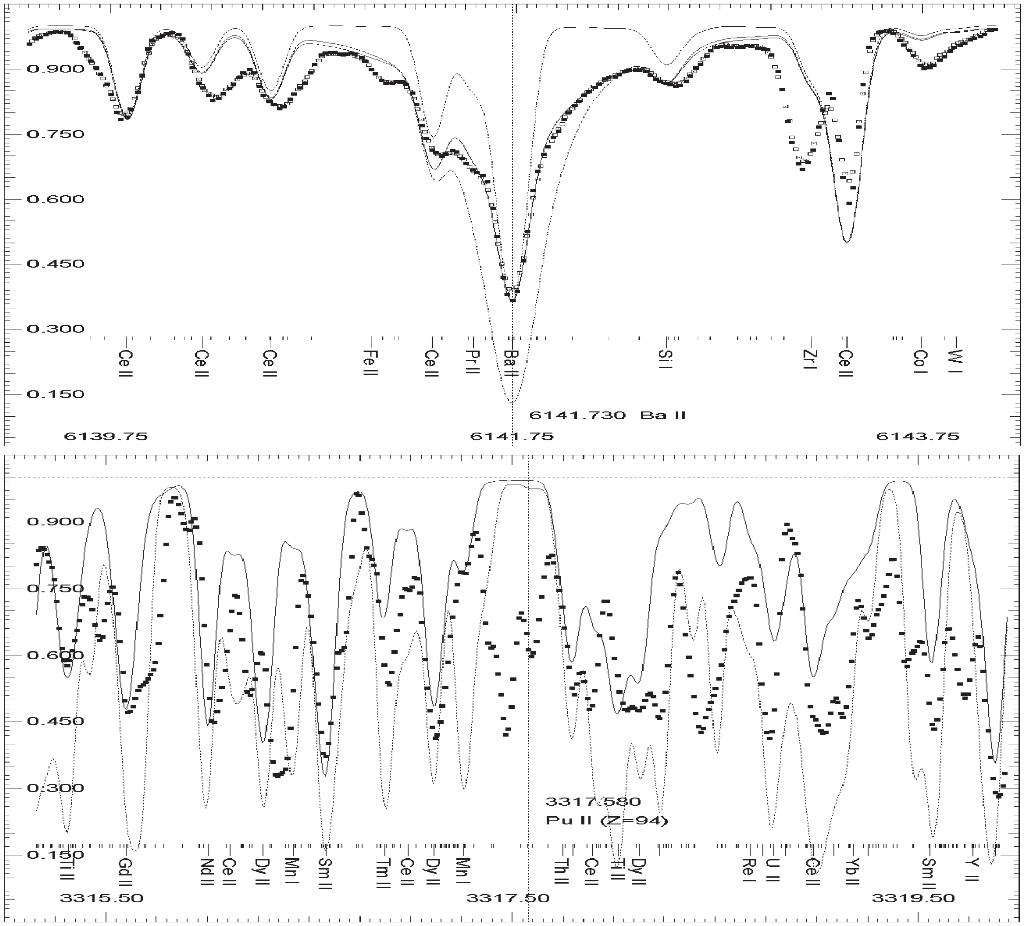

Figure 3. *Upper:* Spectrum of PS in the vicinity of Ba II line 6141 Å. Filled and open squares – VLT and HARPS spectra. For this and other spectral regions the difference between the observed spectra is within the noise level. Three synthetic spectra are shown. Two spectra are calculated with flat barium distribution using $N(Ba)/N_{total}$=$10^{-7.65}$ and $10^{-9.95}$ to fit the wings and the core. The third one – with stratified barium abundances to fit the profile of the line. *Bottom:* Spectrum of PS in the vicinity of Pu II line λ3317.58 Å. Points - VLT spectrum. Lines – synthetic spectra. Dotted line – Cowley at al. (2000) flat abundances, solid line – stratified abundances (preliminary values). Shavrina et al. (2003) atmosphere model is used. Part of the strongest lines are marked.

and other elements in the atmosphere of PS. The influence of such a stratification on the spectrum is shown in Fig. 3. The abundances of practically all elements are increased at the bottom of the atmosphere. Abundances can differ by several orders of magnitudes at different optical depths, reaching up to 6 dex for Th in particular. The abundances of Th at the bottom of atmosphere of PS is near N/N_{total}=$10^{-4.5}$, i.e only two orders of magnitude lower, than that in the best radioactive ores. So, spectroscopic registration of short-lived isotopes in the spectrum of PS seems reliable, the abundances of these isotopes should

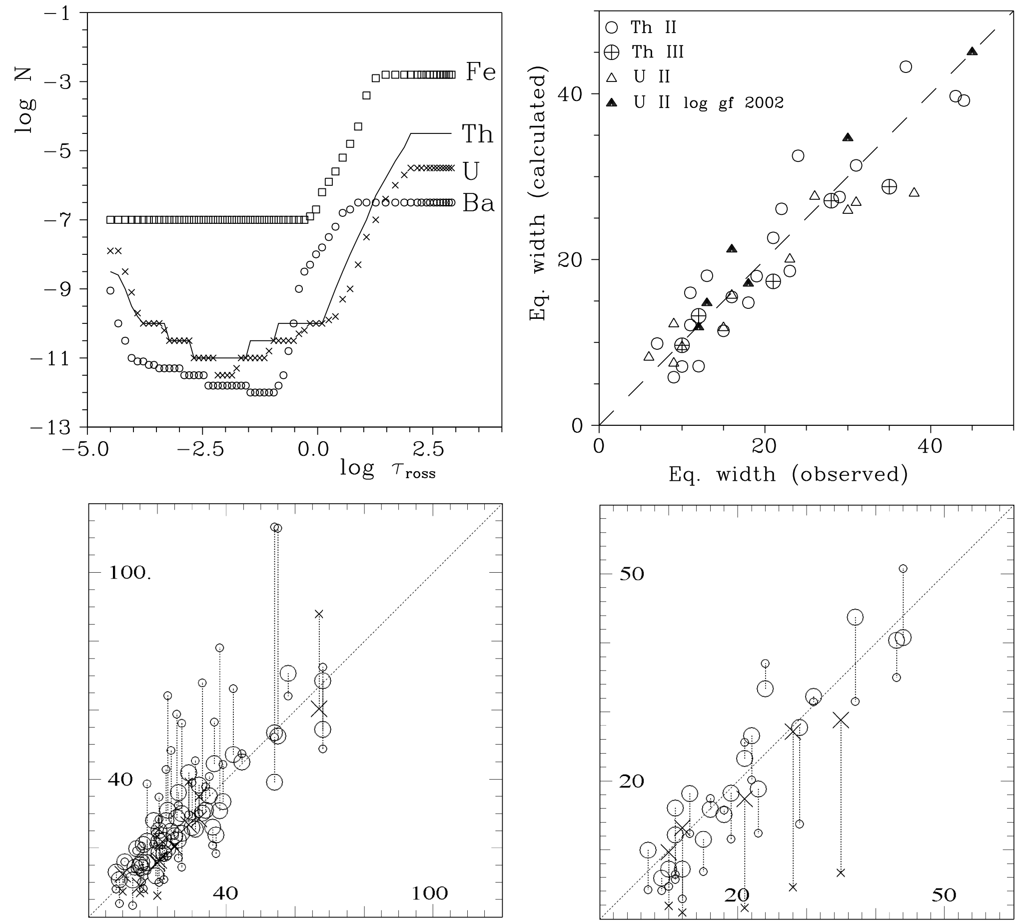

Figure 4. *Upper left:* Stratification of Fe, Ba, Th, and U in the atmosphere of PS. The axes are optical depth and abundance in the scale logN(H)=0 . *Upper right:* Comparison of observed equivalent widths of Th and U lines in the spectrum of PS (in mÅ) with theoretical values calculated with stratified abundances. Oscillator strengths are taken from Nilsson et al. (2002a) for Th II, from Biemont et al. (2002b) for Th III, from Nilsson et al. (2002b) for U II. We used 17 lines of U II, for 6 lines oscillator strengths from Nilsson et al. (2002b) are available. 38 out of the 45 Th and U lines have wavelengths longer than 5000 Å, 7 lines are in the 4700-5000 Å wavelength region. *Bottom left:* Comparison of observed and calculated equivalent widths of Fe lines. Calculated values are shown for flat and stratified (small and large symbols) iron distribution. Dotted lines connect the points calculated for flat and stratified abundances. Circles - neutral iron, crosses - ionized iron. *Bottom right:* The same for Th. Circles and crosses – second and third spectra.

be several orders lower than the abundances of Th & U. The oscillator strengths for actinides lines (except Th & U) are not known, but it is possible to estimate low limits of abundances. If we set the logarithms of oscillator strengths of identified lines of second spectra of Ac, Pa, Pu, Am, and Bk to be zero, the mean $log(gf \cdot \epsilon)$ values are equal 1.2, 1.7, 1.6, 1.3, 1.1 respectively. Similar values for Th and U are 1.1 and 1.1 (scale logN(H)=12 is used). So the abundances of unstable actinides can be close to that of Th & U. It is the strong argument to choice second or third of above mentioned hypotheses. The first one can be true only if the heaviest stable elements in stellar atmospheres are not Th & U, but that near island of stability, as it was proposed by Kuchowicz (1973).

All the three scenarios described here still need to be investigated in more details. The combination of different physical mechanisms, like nuclear reaction and diffusion, may also have contributed to the presently observed stellar surface of HD101065 and similar stars.

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