Stellar abundance patterns. 
What is the possible level of completeness today?

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**Abstract.** We discuss the way of increasing of the number of chemical elements, investigated in stellar spectra. We can reach it by using spectrum synthesis method, new atomic data and observation of stellar spectra with resolution comparable to solar spectral atlases. We show two examples of this kind researches. The first is the implementation of new atomic data to well known Przybylski’s star. We show that the number of spectral lines, which can be identified in the spectrum of this star can be significantly higher. The second example is the investigation of ζ Cyg. We found the abundances of 51 elements in the atmosphere of this mild barium star.
1. Introduction

If we will try to overview the results of determinations of stellar abundances, we will find that a lot of elements with $Z>30$ are omitted. Elements heavier than iron group are synthesized primarily by means of neutron capture processes. According to the work by Burbidge et al. (1957, B2FH), in order to reconstruct the Galactic evolutionary history of heavy elements, one has to consider two major mechanisms of neutron addition: the s-process and r-process. Small amount of nuclei can be created in p-process. New process of heavy elements creation was proposed by Woosley & Hoffman (1992) - this is $\alpha$-process for heavy elements. A review of the developments of the theory of elements creation was made by Wallerstein et al. (1997). This paper was devoted to the 40th anniversary of B2FH work. The theory of element creation needs a detailed abundance pattern for comparison of theoretical predictions with observations. New data on stellar abundance patterns for stars of different types can significantly influence the theory.

The full isotopic pattern is available only for meteoritic matter. The precision of abundance determinations in stars is not so high. The best abundance samples for the stars are:

- Sun – 73 elements (Grevesse & Sauval, 1998)
- Procyon A – 55 elements (Yushchenko & Gopka, 1996a,b),
- Przybylski’s star – 54 elements (Cowley et al., 2000),
- $\chi$ Lupi – 51 elements (Leckrone et al., 1999),
- Gopka (2000) investigated the abundances of several heavy elements if the atmosphere of Sirius A. Now we are preparing a review of chemical composition of Sirius A. The abundance pattern of this star consists of 50 elements We can see a significant progress. In 1988 Reinolds et al. pointed, that the abundance pattern for Canopus (38 elements) is the third after the Sun and Przybylski’s star (Wegner & Petford, 1974 – 51 elements).

We realize, that this review is not full, but it is sufficient to make some conclusions. First of all - detailed abundance determination is a very long process. In many cases it cost a decades of efforts of many scientists. The majority of above cited papers are the review papers or the papers which are the final paper in a long series of articles on abundances in this star. What are the necessary conditions for future progress? The base of the improvement are:

1) the increasing of level/noise ratio and spectral resolution stellar spectroscopy, investigation of the chemical abundance using UV spectra;
2) the new atomic data;
3) the using of the spectrum synthesis method not only for limited number of lines in the spectrum, but for majority of lines, taking in account hyperfine and isotopic splitting, magnetic fields, spots, detailed analysis of spectral binaries, individual atmosphere models, etc.

Let us show a short overview for these three items. We will show only some aspects which, we hope, will be interesting for the community of this conference. It is difficult to point poor better observations or poor better atomic data or software influence on final results. Usually it is the combination of all three items.
2. High quality observations

The majority of cited papers, which give us the most complete stellar abundance samples, deals with the spectra obtained at the best telescopes and spectrographs. But it should be noted, that we have 2.5 meter telescope since 1917, 5 meter - since 1948, 6 meter - since 1975, 10 meters - since 1991. But while this telescopes were the single in it’s class, no significant progress were available. Only during last two decades, when the number of telescopes over 2 meters became near 50, we can see a lot of new results.

During the last decade observations with coude-echelle spectrographs were started at the 1 meter telescope of SAO RAS and 2 meter telescope of ICAMER. The last telescope is located at 3100 meters elevation. Now it is possible to obtain spectra with resolutions 45000, 80000, 125000, 190000. Now we are testing the new spectrograph which permit us to obtain the spectra of bright stars with the resolution comparable with solar spectral atlases.

In the last section of this paper we review the preliminary results of one of the first detailed investigations of stellar abundances with this spectrograph. The mild barium star ζ Cyg was observed in 2000 with relatively low resolution - near 80000. This investigation will be the base for future observation of this and other barium stars with highest spectral resolution in visual and near UV wavelengths regions.

3. New atomic data – line identification in Przybylski’s star

The more detailed review of used observations and methodologies one can find near this poster in the poster of Shavrina et al. (2002). Here we will point only important items:

1) wavelength coverage 6123-6175 Å and 6676-6732 Å – 108 Å;
2) spectral resolution R=100000, signal to noise ratio S/N>100;
3) new lanthanides lines from DREAM database (Biemont et al., 2002);
4) identification of lines and calculation of abundances were made using spectrum synthesis method. We used Kurucz (1995) SYNTHE program for calculation synthetic spectra and Yushchenko (1998) URAN program for line identification and spectrum synthesis in automatic mode. Abundances for all identified lines were found with spectrum synthesis method.

In tables 1,2 we give the summary of results. In table 1 one can find the total number of lines of different elements and ions in DREAM database. The numbers in the last column of this table - the part of these lines, which were present in our previous line list. The total number of lanthanides and thorium lines in DREAM database is 56150.

We tried to use these lines to find the abundances in Przybylski’s star. We used 108 Å wavelength interval in red part of the spectrum. In table 2 we show our mean abundances, errors and number of lines from 108 Å interval in red region of the spectrum and the corresponding values from 2693 Å interval in blue-red parts of the spectrum according to Cowley et al. (2000).

The brief inspection of the abundances show, that the results are similar in the range of uncertainties. In the last column of this table we give the ratio of lines, identified in the work of Cowley et al (2000) and in this work.
From the ratio of wavelengths coverage in two studies we can expect that the ratio of numbers of identified lines will be near 25 or more, if we take in account, that the majority of lanthanides lines are located in the blue part of the spectrum. But only one value in the last column of the table exceeds 10.

It means that the lanthanides lines from DREAM database give us a powerful instrument for examination of the atmospheres of peculiar stars.

It should be noted that not only lanthanides show the overabundance in the atmosphere of Przybylski’s star, but all heavy elements. Unidentified lines can be the lines of other heavy elements.

4. Chemical composition of ζ Cyg

ζ Cyg is one of the brightest middle barium stars. The spectrum was obtained at ICAMER 2 meter telescope with resolving power R=80000 in the wavelength range 3495-10000 Å with signal to noise ratio in visual and infrared region more than 100. As a first step we tried to find atmosphere parameters. We tested the parameters used by Zacs (1994) and Boyarchyk et al. (2001). We analyzed iron lines in the spectrum and found that following atmosphere parameters are valid:

\[ T_{\text{eff}} = 5050 \text{ K}, \quad \lg g = 2.8, \quad v_{\text{micro}} = 1.45 \text{ km/s}, \quad v_{\text{macro}} = 3-3.5 \text{ km/s}. \]

We interpolated Kurucz (1995) atmosphere model with these parameters and calculated synthetic spectrum for all observed region. This spectrum was used for identification of spectral lines. Abundance calculations for all elements except iron were made with spectrum synthesis method. We used Kurucz (1995) SYNTHE program for calculation of synthetic spectra and Yushchenko (1998) URAN program for approximation of the observed program by calculated one in automatic mode.

We tried to obtain abundances by direct comparison with the solar spectrum. We found solar oscillator strengths for majority of the used lines. We used Liege Solar atlas (Delbouille et al., 1974), Holweger-Muller atmosphere model, microturbulent velocity 1.0 km/s, macroturbulent velocity 1.8 km/s. SYNTHE and URAN codes were used for approximation of observed solar spectrum by synthetic one.

In tables 3,4 we show the results of abundance determinations. The results of Gratton (1985), Zacs (1994), Boyarchuk et al.(2001) are displayed for comparison. The chemical elements with lines, that have no counterparts in the solar spectrum are marked by asterisk.

We found the abundances of 48 elements in the atmosphere of ζ Cyg. The abundances of Li, N, Ba are known from previous investigations of this star. The total abundance sample consist of 51 elements. Detailed analysis of these results will be made later.

5. Conclusion

We show that the abundances of 50-55 elements are the best results for stellar abundance samples in sharp-lined stars. We can point some ways how to increase these number for several types of the stars. First of all F stars of main sequence.
The detailed chemical composition of Procyon is a summary of many papers, and significant part of this papers were used Griffin’s (1979) atlas of this star. New atlas of the star observed with higher signal to noise ratio and spectral resolution will help to find several new elements.

The other way is the observations of UV spectrum of Procyon or Procyon type stars. We have no determinations of chemical composition of Procyon from UV spectral data.

For barium stars additional abundances can be obtained from observations in the near UV wavelengths region - 3100-3500 Å.

And let we will not forget about the Sun. There are a dozen of chemical elements with unknown abundances in the solar atmosphere. For example Gopka et al. (2001) found the abundance of arsenic in the Sun. The spectral atlases of solar spots can be used for abundance determinations, if the good model of the spot will be made.

It should be noted that all these ways will lead us to very crowded spectral regions. Usual model atmosphere method is not available in this case. It is necessary to use spectrum synthesis and automatic spectrum synthesis. The programs for automatic spectrum synthesis were described by Cowley (1995), Valenty and Piskunov (1995), Tsymbal & Cowley (2000), Erspamer & North (2002), Yushchenko (1998). These programs are very different, but all of them can help us to obtain detailed abundance samples for different type stars.

Here before we have showed the significance of new atomic data for lanthanides. But it should be noted that Corliss & Bozman (1961) oscillator strengths are still in use for several elements. We have zero or very limited information about the abundances of elements with Z=50-55, 33-36. One of the peaks of solar system abundances is near Z=50-55. And we have zero information about this peak in the Sun and in other stars. One of the first attempts to find the abundance of tellurium (Z=52) (Yushchenko & Gopka, 1996a,b) lead us to possible overabundance of this element in Procyon.

Maybe a decade later, when 50-70 elements will be a common number of elements in every paper on chemical abundance in sharp-lined stars, we will be able to resolve a lot of modern problems in this field and to ask new questions.

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Table 1. Number of lines of different elements in DREAM database

| Element | Number of lines in Dream | Which are common in Dream and in our old line list |
|---------|-------------------------|--------------------------------------------------|
| La III  | 137                     | 9                                                |
| Ce II   | 14970                   | 1663                                             |
| Pr III  | 18401                   | -                                                |
| Nd III  | 51                      | 51                                               |
| Tb III  | 923                     | -                                                |
| Ho III  | 1324                    | -                                                |
| Er III  | 1307                    | 304                                              |
| Tm II   | 7954                    | 474                                              |
| Tm III  | 1478                    | -                                                |
| Yb II   | 5484                    | 311                                              |
| Yb III  | 278                     | -                                                |
| Yb IV   | 2769                    | -                                                |
| Lu II   | 106                     | 74                                               |
| Lu III  | 58                      | 3                                                |
| Th III  | 901                     | -                                                |
Table 2. Abundances of lanthanides in Przybylski’s star

| Element | $\lg N$ | $\sigma$ | N1 | $\lg N$ | $\sigma$ | N2 | N2/N1 |
|---------|---------|----------|----|---------|----------|----|--------|
| La II   | -8.32   | 0.25     | 4  | -8.17   | 0.29     | 28 | 7      |
| Ce II   | -7.58   | 0.06     | 28 | -7.60   | 0.26     | 46 | 1.6    |
| Pr I    | -6.40   | 0.21     |    |         |          |    |        |
| Pr II   | -9.45   | 0.13     | 3  | -8.80   | 0.21     | 31 | 10     |
| Pr III  | -8.25   | 0.52     | 3  | -7.46   | 0.16     | 12 | 4      |
| Nd I    | -6.39   | 0.35     |    |         |          |    |        |
| Nd II   | -7.62   | 0.09     | 10 | -7.65   | 0.28     | 71 | 7      |
| Nd III  | -6.89   | 0.09     | 7  | -7.31   | 0.30     | 7  | 7      |
| Sm II   | -7.65   | 0.07     | 10 | -7.75   | 0.29     | 41 | 4      |
| Eu II   | -9.15   | 1        | 8  | -8.58   | 0.19     | 5  | 5      |
| Gd II   | -7.61   | 2        | 2  | -7.62   | 0.25     | 35 | 18     |
| Tb II   | -8.84   | 1        | 3  | -8.89   | 0.16     | 3  | 3      |
| Dy II   | -7.68   | 2        | 16 | -7.88   | 0.23     | 16 | 8      |
| Ho I    | -6.60   | 1        |    |         |          |    |        |
| Er I    | -6.24   | 1        |    |         |          |    |        |
| Er II   | -8.17   | 2        | 18 | -8.09   | 0.22     | 18 | 9      |
| Er III  | -6.83   | 0.04     | 4  |         |          |    |        |
| Tm II   | -8.20   | 0.28     | 15 |         |          |    |        |
| Yb II   | -8.99   | 0.33     | 9  |         |          |    |        |
| Lu II   | -8.80   | 1        | 6  | -8.65   | 0.14     | 6  | 6      |
Table 3. Chemical composition of $\zeta$ Cyg

| n | Z  | Boyarchuk et al. 2001 | Zacs, 1994 $\sigma$ | Gratton 1985 $\sigma$ | This work $\sigma$ | Element |
|---|----|----------------------|---------------------|----------------------|---------------------|---------|
| 1 | 3  | -0.14                | 1                   |                      |                     | Li I    |
| 2 | 6  | -                    | -0.10              | -0.00               | 0.21                | C I     |
| 3 | 7  | -                    | +0.61              |                      |                     | N I     |
| 4 | 8  | -                    | -0.34              | -0.46               | 1                   | O I     |
| 5 | 11 | +0.19                | -0.35              | -0.37               | 0.16                | Na I    |
| 6 | 12 | -0.51                | 2                   | +0.22               | 0.22                | Mg I    |
|    |    |                      |                     | +0.26               | 2                   | Mg II   |
| 7 | 13 | +0.16                | -0.11              | -0.11               | 0.06                | Al I    |
| 8 | 14 | +0.09                | +0.14              | 0.13                | -0.05               | Si I    |
| 9 | 15 |                      | +0.10              | 0.1                  |                     | P I     |
| 10| 16 |                      | +0.20              | 0.26                | 5                   | S I     |
| 11| 19 |                      | +0.00              | 0.26                | 3                   | K I     |
| 12| 20 | -0.03                | +0.08              | 0.19                | 0.13                | Ca I    |
| 13| 21 | -0.02                | +0.04              | 0.30                | 4                   | Sc I    |
|    |    |                      |                     | +0.15               | 0.06                | Sc II   |
| 14| 22 | -0.11                | -0.17              | 0.22                | 21                  | Ti I    |
|    |    |                      |                     | -0.07               | 0.06                | Ti II   |
| 15| 23 | -0.04                | -0.13              | 0.18                | 16                  | V I     |
| 16| 24 | -0.08                | -0.06              | 0.18                | 11                  | Cr I    |
|    |    |                      |                     | -0.11               | 0.06                | Cr II   |
| 17| 25 | -0.30                | 0.13               | 5                   | 26                  | Mn I    |
| 18| 26 | -0.03                | +0.12              | 0.23                | 51                  | Fe I    |
|    |    |                      |                     | +0.06               | 0.08                | Fe II   |
| 19| 27 | -0.13                | -0.22              | 0.12                | 6                   | Co I    |
| 20| 28 | -0.09                | -0.05              | 0.25                | 10                  | Ni I    |
| 21| 29 |                      | +0.44              | 0.45                | 3                   | Cu I    |
| 22| 30 |                      | +0.00              | 0.24                | 4                   | Zn I    |
| 23| 32 |                      | +0.28              | 0.28                | 1                   | Ge I    |
| 24| 37 |                      | -0.12              | 0.12                | 1                   | Rh I    |
| 25| 38 |                      | +0.22              | 0.10                | 3                   | Sr I    |
| 26| 39 | +0.30                | +0.37              | 0.24                | 3                   | Y I     |
|    |    |                      |                     | +0.15               | 0.15                | Y II    |
| 27| 40 | -0.08                | 0.20               | 5                   | 8                   | Zr I    |
|    |    |                      |                     | +0.24               | 0.04                | Zr II   |
| 28| 41 |                      | +0.13              | 0.13                | 1                   | Nb I *  |
| 29| 42 |                      | +0.13              | 0.12                | 3                   | Mo I    |
| 30| 44 |                      | -0.02              | 0.02                | 2                   | Ru I    |
| 31| 45 |                      | +0.36              | 0.36                | 1                   | Pd I *  |
| 32| 46 |                      | -0.12              | 0.12                | 1                   | In I    |
| n  | Z  | Boyar-Zacs, 1994 | Gratton 1985 | This work | Element |
|----|----|-----------------|-------------|-----------|---------|
| 34 | 56 | +0.54, +0.41    | -0.13, 3    | 0.13, 3   | Ba II   |
| 35 | 57 | +0.45, +0.38    | 0.15, 3    | +0.51, 0.20 | 12 La II |
| 36 | 58 | +0.33, +0.55    | 1, 1       | +0.36, 0.16 | 43 Ce II |
| 37 | 59 | +0.43, +0.32    | 0.13, 3    | +0.19, 0.19 | 6 Pr II |
| 38 | 60 | +0.23           |            | +0.42, 0.17 | 70 Nd II |
| 39 | 62 |                |            | +0.31, 0.15 | 14 Sm II |
| 40 | 63 | +0.22, -0.05    | 2          | +0.45, 0.05 | 4 Eu II |
| 41 | 64 |                |            | +0.27, 0.19 | 4 Gd II |
| 42 | 65 |                |            | +0.12, 1    | 1 Tb II * |
| 43 | 66 |                |            | +0.28, 0.19 | 5 Dy II |
| 44 | 68 |                |            | +0.35, 1    | 1 Er II |
| 45 | 69 |                |            | <+0.2, 1    | 1 Tm II |
| 46 | 72 |                |            | +0.45, 1    | 1 Hf II * |
| 47 | 76 |                |            | +0.30, 2    | 2 Os I * |
| 48 | 77 |                |            | <+0.5, 2    | 2 Ir I * |
| 49 | 78 |                |            | <+0.5, 1    | 1 Pt 1 * |
| 50 | 81 |                |            | <+0.5, 1    | 1 Tl I * |
| 51 | 82 |                |            | <+0.2, 2    | 2 Pb I * |