ELEMENT ABUNDANCES IN STARS: CONNECTION WITH CHEMICAL EVOLUTION OF A GALAXY

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ABSTRACT. Abundaces of 17 elements in the atmospheres of 100 stars belonging to different population of the Galax y were determined. The comparing of the obtained results with the predictions of current chemical evolution models was made.

1. Introduction

The introduction of efficient high-resolution spectrographs on modern telescopes and the development of theoretical interpretation of spectra allow to define very accuracy the chemical composition of stars and to test the theories of nucleosynthesis and chemical galactic evolution.

One of the important questions of modern astrophysics is the investigation of enrichment of the chemical elements and then the construction of an adequate model of the chemical and dynamic evolution of the Galaxy. The individual elements are produced at various events and on different timescales, and the observed abundances may be used to decode the galactic evolution. However, the chemical enrichment is realised by the return of new elements into the interstellar medium (ISM) through slow and fast mass loss phenomena, whose relative importance is controlled by several parameters, like the initial stellar mass distribution, the physics of stellar winds, star formation rates, stellar lifetimes, the metal dependency of the nucleosynthesis, the galactic gas flows, the mixing processes in the ISM etc. As we cannot get this information directly from observations, it is necessary to use models of galactic evolution taking into account all these processes in detail.

The goal of this work is the determination and the analysis of several element abundances in atmospheres of the stars belonging to various subsystems of the Galaxy and the choice of sources of the contributions in the element abundances by the comparison of the observations with the predictions of some galactic models.

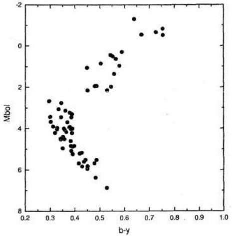

Figure1: The diagram of M_{bol} vs b-y for program stars

2. Observations

For the decision of the task we selected 100 stars (dwarfs, giants and subgiants) in a range of metallicity -3<[Fe/H]<0.3 (Fig. 1). The observations were taken from the library of spectra were collected at the Haute Provence Observatory (Soubiran et al., 1998). They had been made with the 193 cm telescope equipped ELODIE spectrometer (R = 42 000), the spectral range is 4400-6800 A, signal-to-noise rations are more 100. Spectra were previously reduced (Kats et al., 1998), the further processing of spectra (continuum level location, measuring of equivalent widths etc) was carried out by us using the DECH20 software (Galazutdinov, 1992). Equivalent widths EWs of lines were measured by means of a Gaussian fitting.

We have compared our EWs with those defined by other authors (Mishenina, Kovtyukh, 2001; Mishenina et al., 2002a, b). The agreement is sufficiently good.

3. Stellar parameters

The basic characteristics of investigated stars are given in the papers (Mishenina, Kovtyukh, 2000; Mishenina, et al., 2002a, b). The spectral classes Sp, stellar magnitude V and colour index (B-V) are taken from a database SIMBAD, parallax − from the observation of Hipparcos (ESA 1997). Bolometric magnitudes M_{bol} are calculated with use bolometric corrections from the paper of Alonso et al. (1995). Use of direct methods of definition of effective temperature T_{eff} is possible only for the limited number of stars. The used photometric and spectral methods are burdened by some additional errors. The photometric methods base on theoretical or empirical spectral calibrations and require the account of the interstellar reddening. The spectral methods require the reliable damping constant and account of probable influence of the departures from the local thermodynamic equilibrium (NLTE) require the account interstellar reddening, spectral. Therefore for T_{eff} determination we used the following iterative procedure. As the first approach, we adopted T_{eff} determinations given in the paper of Soubiran et al. (1998), they are based on a statistical method using the large number of lines in a spectrum and calibration of effective temperature T_{eff}, taken from the reference sources with certain weight. Then T_{eff} was specified on conditions that the iron abundance determined on any line is independent on its low level energy E_{low}. As the control of a choice T_{eff} we carried out the comparison of the observational profile of the Hα lines with the theoretical calculations of the Hα lines under the program STARSP (Tsymbal, 1996).

The surface gravity log g was determined on the assumption of the ionisation balance for iron lines and then it was specified under the standard formula:

$$\log g = 4\log T_{eff} + 0.4 M_{bol} + \log(M/M_{solar}) - 12.5,$$

where the following parameters for the Sun T_{eff}=5770 K and log g=4.40 are accepted.

Microturbulent velocity V_t was determined on conditions that the iron abundance determined with Fe I lines is independent on its equivalent widths EWs. As a metallicity of star [Fe/H] the iron abundance determined with the oscillator strengths from Gurtovenko, Kostyk (1989) on the program of Kurucz WIDTH9 is accepted.

The accuracy of definition of parameters is equal: $\Delta T_{eff}=\pm100$ K, $\Delta\log g=\pm0.3$ dex, $\Delta V_t=\pm0.2$ km/s, Δ[Fe/H]=±0.1 dex. The parameters of atmospheres of studied stars are given in Tab. 1. The comparing of our studies with results of some recent works was made in paper (Mishenina, Kovtyukh, 2001; Mishenina, et al., 2002a,b). The agreement between parameters of atmospheres determined by other and us authors is within the limits of determination errors. The available divergences are caused, first of all, by the various methods of parameter definitions that were used by the authors.

In order to distinguish disk stars (D) from halo stars (H) by kinematic criteria, we determined the spatial velocities and galactic orbital parameters of our target stars. The first group of stars (D) includes objects with disk-like kinematic, (nearly-cirular orbits, not reaching extreme distances from the plane and with a significant component of rotational velocity. Thick-disk stars dominate this group. The second group (H) includes all stars whose orbits reach larger distances from the galactic plane; they have larger values of ecentricities or retrograde rotational velocities. All other stars fall into an intermediate group (I) corresponding to the overlap between the thick disk and the halo (Mishenina, et al., 2002a).

Lithium. The change of any element abundance with age or with distance in the Galaxy represents undoubted interest for the theories of chemical evolution of the Galaxy and nucleosynthesis. But the lithium occupies the special place, both by amount of papers on Li abundance determination, and on that role, which it plays in building of an adequate picture of the Universe. Lithium is one of few elements formed as a result of the Big Bang and its cosmological abundance can characterize baryon-proton ratio and the baryon contribution to density of the Universe. Li abundance characterizes also physical and nuclear processes occurring inside stars.

The lithium is destroyed in nucleosynthesis at rather low temperatures (near 2.5×10^6 K) and its abundance in stellar atmospheres varies already at stages Pre Main Sequence and Main Sequence (Iben, 1965; D'Antona, 1991). Since Spite&Spite (1982) revealed that the lithium in enevolved stars of Population II shows comparable surface abundances (for stars with T_{eff} beyond 5800 K, [Fe/H] <-1.4), many Li abundance investigations were made that confirmed this result. In recent works the obtained value of log$A$(Li) is equals to 2.1 (Pilachowski et al., 1993), 2.32 (Thorburn et al., 1994), 2.24 (Bonifacio&Molaro, 1997), 2.40 (Gratton et al., 2000). The primordial abundance of Li according to the big bang models is 3×10^{-8}% on mass (Walker et al., 1991). That value is close to those observed in dwarfs and subdwarfs.

Lithium abundances for the stars of our target were derived from a fitting of observational data with a synthetic spectra computed by STARSP code (Tsymbal, 1996) in LTE assumption using the detailed structure of the lithium feature at 6707 A. Atomic and molecular line list was taken from Mishenina&Tsymbal (1997). The calculations of NLTE (Carlsson et al., 1994) departures show that the 6707 lines are slightly affected by it.

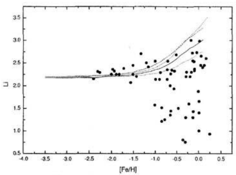

Figure 2: Comparison of Li dwarf observations (T_{eff}>5600 K) with theretical models of Timmes et al. (1995, ApJS 98, 617) (the calculated Li abundance is show as the solid line, the dotted lines show factors of two variation in the ν-process yields) and Romano et al. (1999, A&A 352, 117) (dashed line).

The study of behaviour of the Li abundance for stars with T_{eff}>5600 K, and log g>3 on various metallicities allows to estimate the contribution of various sources of the Li production in enrichment of interstellar medium (ISM). The lithium abundance raises with [Fe/H] increasing and it shows the larger dispersion on [Fe/H]>-1.3 (see Fig. 2, and also Rebolo et al., 1988; Chen et al., 2000).

Lithium evolution has already been studied in detail by several authors and some sources of the Li-production were considered. The model of chemical evolution of D'Antona and Matteuci (1991) considered classical novae and AGB stars as additional sources of Li-production. In the later model of Matteuci et al. (1995) the neutrino-process nucleosynthesis from Type II SNe and hot bottom burning in intermediate mass AGB was taken. Abia et al. (1995) has accepted the Li production from low mass AGB stars (C-stars) and Galactic cosmic ray (GCR) nucleosynthesis. We have compared our Li determination log$A$(Li) to the calculation of lithium evolution (Timmes et al., 1995) (Fig. 2). The authors used simple standard model, which accepted, that halo and disk are parts of the same system distinguished only on age. Timmes et al. (1995) have considered two sources of the Li – production: as a product of homogeneous Big Bang (Walker et al., 1991) and synthesized Li in processes of neutrino capture in massive stars (at [Fe/H]>-1). As to iron, it is delivered with two main sources – supernovae SN II and SN Type Ia. The analysis of the metallicity in the solar neighbourhood shows that of 1/3 the Solar System iron abundances arise from SN II and 2/3 from SN Ia. The calculated Li abundance is displayed as the solid line, and the dashed lines show factors of two variations in the ν-process yields. Our result is a higher (0.1 dex on the average) than Li abundance, predicted by the model. Probably, it is result of errors of Li abundance definition or there is a consequence more high cosmological value of Li abundance (larger than 2.1 dex). Models of Li dilution, taking into account various transport mechanisms (Pinsonneault et al., 1992; Proffitt, Michaud, 1991; Chaboyer, Demarque, 1994) also requires more larger primordial lithium abundances than log (Li) = 2.1. Certainly, it may be also due to unreliable choice of sources of Li-production or preconditions of model of chemical evolution.

Ryan et al. (2001) carefully studied the abundance and evolution of Li in galactic halo and disk. They draw attention to a choice of effective temperature of stars. Higher temperature conducts to the larger Li abundance. Ryan et al. (2001) also have carried out the comparison of the evolution of Li as a function of [Fe/H] with the predictions of several models of galactic evolution that is taking into account various sources of Li-production and their combination (primary nucleosynthesis, reactions cosmic ray spallation, nucleosynthesis in supernovae through ν-process, nucleosynthesis in AGB stars and novae). The main distinctions between models arise at a stage of a disk (on [Fe/H]>-1), where AGB stars and novae begin to bring the remarkable contribution to Li enrichment with interstellar medium (ISM). For halo star evolution the essential processes are primary nucleosynthesis, ν-process, and reaction of GCR spallation. We have compared our data to model Romano et al. (1999), taking into account the above-mentioned processes. This model gives the good agreement with our data (see Fig. 2, dashed line) and we may conclude, that the main sources of Li enrichment of halo stars are Li-production as a result of the Big Bang, reaction of cosmic ray spallation and H-process in massive supernovae.

Carbon. The main nuclear source of carbon is helium hydrostatic burning in massive stars (He burning before explosion, the yield depends on presupernovae model – convective criterion, processes of hashing, expiration of masses and rate of nuclear reactions) and in stars of intermediate and low masses. The supernovae Type II and Type Ia are the main producer of carbon at earlier stage of the Galaxy, then the longer lived intermediate- and low-mass stars play important role, and also at the same time metal-rich Wolf-Rayet stars eject the carbon in ISM by stellar wind.

Our determinations of the carbon abundance were made on C I lines 4817, 5052, 5380 AA. These lines are weak and they are invisible at [Fe/H]<-1. Therefore our [C/Fe] data present the small region of metallicity. For metal-poor stars the carbon abundance are determined on molecular CH lines in ul-

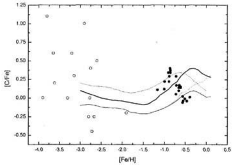

Figure 3: The trend of [C/Fe] vs [Fe/H]. Our [C/Fe] - black circles, open circles - [C/Fe] (Ryan et al., 1991, AJ 102, 303); Norris et al., 2001, ApJ 561, 1034). The dashed lines show the calculations of Timmes et al. (1995) with two factors variation in the iron yields from massive stars, dotted line shows the results when Type Ia supernovae are excluded; solid line - Liang et al. (2001, A&A 374, 936).

tra-violet (UV) range, CO lines in infra-red (IR) range, on atomic CI and [CI] lines, at that [CI] lines no effects the departures from LTE. As a whole, [C/Fe] determinations for unevolved stars show the larger dispersion from -0.5 up to + 0.5dex (Tomkin et al., 1992; Carretta et al., 2000; Gratton et al., 2000) and the average relation [C/Fe] roughly solar at [Fe/H]> -2.5. At [Fe/H]<-2.5 there are the larger scattering of [C/Fe] (from -0.7 to +1.1) with some tendency of growth of observed [C/Fe] with [Fe/H] increasing (Ryan et al., 1991; Norris et al., 2001).

The different sources of carbon-production were used in several chemical evolution models. So in model Timmes et al. (1995) the carbon yields from Supernovae II (Woosley, Weaver 1995) and the yields from stars of intermediate- and low- masses independent from metallicity (Renzini, Voli, 1981) was accepted, at that the main contribution was made the intermediate- and low- mass stars. The model Timmes et al (1995) unsatisfactorily described observable trend of [C/Fe] with [Fe/H], particularly, at low metallicities (Fig. 3, our [C/Fe] – black circles, open circles – [C/Fe] (Ryan et al., 1991; Norris et al., 2001). The dashed lines show the calculations of Timmes et al. (1995) with two variations in the iron yields from massive stars, dotted line shows the results when Type Ia supernovae are excluded. Chiappini et al., (1997) have received similar result by two-infall model. The carbon yields from the intermediate- and low- mass stars as the main source of carbon was also considered by Oberhummer et al. (2000). Marigo (2001) has analysed the carbon yields, but dependent from metallicity for the same stars.

Other source of carbon contribution to the chemical enrichment of the ISM was proposed in model Prantzos et al. (1994). The authors have assumed, that after during the near 1–2 Gyr of the halo phase, the massive stars by means of a stellar wind enriched by carbon with ISM during the further galactic evolution. Gustaffson et al. (1999), having considered evolution of carbon in a Galactic disk, have accepted, that the main source – the stellar wind from rich metal massive stars. Later Gustaffson, Ryde (2000) have concluded, that a source of carbon still is not clear. Hou et al. (2000) have united sources of carbon; they have accepted a star wind from massive stars both star of intermediate- and low-masses. Goswami, Prantzos (2000), having applied our new model considering halo and a disk as two independent systems, have concluded, that the C yields from SN II (Woosley, Weaver 1995) are not sufficient reflect an observational picture and that there are other sources, for example, Wolf-Rayet stars or intermediate- and low mass stars.

Liang et al. (2001) using the standard infall model was explored the origin of carbon by 8 different models of stellar nucleosynthesis yields. They have shown that at early stages of a Galaxy, the massive stars are the main source of carbon, then the contribution from the longer lived intermediate- and low-mass stars and from the metal-rich WR stars grows. Unfortunately, the modern nucleosynthesis calculations do not allow selecting precisely the main carbon sources. We have carried out the comparison the [C/Fe] data with of Liang et al. (2001) (Fig. 3, solid line) model, using as the basic sources of carbon production the intermediate- and low-mass stars (with the yields dependent from metallicity, Marigo, 2001) and the stellar wind from massive stars (Portinari et al., 1998). Noted, the authors do not examine observational increase of [C/Fe] (up to +1) at [Fe/H]<-2.5. We suppose, that this growth may be explain by the contribution from Supernovae II type, and the larger dispersion of [C/Fe] values at these metallicity by unhomogeneous early Galaxy.

Oxygen. The oxygen abundance does not change during burning hydrogen in traditional CNO cycle, and so both the dwarf s and the giants can be indicators of enrichment by oxygen of ISM. However, globular cluster giants show remarkable (up to 1.5 dex) scattering of [O/Fe] and anticorrelation of oxygen abundance with the sodium and aluminium abundance. On it we shall stop later.

Overabundance of oxygen to iron relative to solar [O/Fe] in stars with deficiency of metals was revealed Conti et al. (1967). The values of oxygen excess have evoked significant discussion that remains undecided till now. The question is that the oxygen abundance determined on forbidden [O I] lines, IR triplet OI lines and molecular features (OH lines) will not be come to an agreement among themselves (Nissen, Edvardsson 1992; Fulbright, Kraft 1999). The [O/Fe] value determined on lines [OI] 6300, 6360 AA is equal to near 0.4 dex (Spite, Spite 1986; Barbuy, 1988; Spissman, Wallerstein, 1991) and it is lower, than in case of use of IR triplet lines at 7770 AA, [O/Fe] = 0.9 dex (Abia, Rebolo, 1989; Cavallo et al., 1997). Furthermore the last determinations show the trend of [O/Fe] with metallicity decreasing. The first attempt to improve this situation was made by Kiselman (1991). Using NLTE calculations, he found the encouraging result – NLTE corrections were achieved 0.4dex. However, further attempts of the NLTE calculations (Tomkin et al., 1992; Takeda, 1994; Mishenina et al., 2000) have resulted in lower values of NLTE departures (up to 0.2 dex) and it has not removed the contradictions for these two groups of lines. The subsequent attempt to rule the situation has touched the change of a scale of effective temperatures for metal-poor stars (King, 1993). Later it was confirmed and accepted in works Gratton et al., 2000; Carretta et al., 2000.

But the oxygen abundance study using UV molecular lines have shown more high [O/Fe] which is agree to results on IR triplet lines (Tomkin et al., 1992, Boesgaard et al., 1999, Israelian et al., 1998). The situation is complicated by the fact, that at [Fe/H]<-2.0 the analysis of the giants [O I] lines and of the dwarfs IR triplet lines are used. At the same time the definitions of oxygen abundance on these two groups of lines for dwarfs with [Fe/H]>-1.5 has given the similar result (Spite, Spite, 1991). Tomkin et al have assumed, that the neglect of convection can be responsible for the

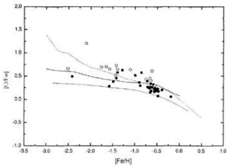

Figure 4: The trend of [O/Fe] vs [Fe/H] (black circles – this work, open circles – Mishenina et al. 2000, A&A 353, 978). Lines represent of models: Timmes et al., 1995 (solid); Shustov et al. (1997, A&A 317, 397) (dash-dotted); Chang et al.(1999, A&A 350, 38) (dashed); Qian, Wasserburg (2001, ApJ 549, 337) (dotted).

discrepancy. We have determined O abundance using the models with convection (Castelli et al., 1997) for metal poor giants (T_{eff}<4600 K) and without convection (Kurucz, 1993). We found the small difference (0.05), which has not removed the observation contradictions.

And, at last, the application of 3D models gives one more chance to solve this problem within the framework of stellar atmosphere modelling (Asplund et al., 1999). However, Israelian et al., (2001) find for a star BD+23 3130 ([Fe/H]=-2.43) high oxygen abundance ([O/Fe]=0.78), using three indicators of oxygen in frameworks of one-dimensional models, and they assumed that is not a problem of theoretical modelling of atmospheres. The question still remains open. Therefore the interpretation of a trend [O/Fe] with [Fe/H] by the theories of chemical evolution of the Galaxy has some uncertainty.

In our work the average value of [O/Fe] was obtained from [OI] lines and it is +0.46±0.12 (8 stars) in the region of -1.5<[Fe/H]<-0,7. At metallicities from -0.7 to -0.3 the <[O/Fe]> is +0.17±0.09 (15 stars). These values are lower than those were defined from IR triplet lines (Cavallo et al.,1997, Mishenina, et al., 2000) and from OH ultraviolet lines (Boesgaard et al., 1999; Israelian et al., 1998). But our present result carried out at [Fe/H]>-1.5 and it was quite concordance with our proceeding one (see Fig. 4). All remain intricate in case of cool giants. Just for these stars the forbiden oxygen lines is detectable in their spectra at low metallicities. In our example of stars there is star BD+30 2611 with the low O abundance ([O/Fe]=+0.19 from our determination), its low O abundance was noticed by Kraft et al. (1992), King (1997) and Gratton et al. (2000). As see from Fig. 4, and also see (Carretta et al., 2000; their Fig. 3) the scatter in [O/Fe] is wide at [Fe/H]<-1 from both [OI] lines and IR triplet lines. This may be as the result of determination errors or the prestellar medium scatter of oxygen abundance.

In the given research we used [OI] lines, as the spectra, examined by us, have no IR spectral region. We receive average value <[O/Fe]>=+0.46±0.12 (8 stars) in a range -1.5<[Fe/H]<-0.7 and <[O/Fe]>= +0.18±0.09 (17 stars) in a range -0.7<[Fe/H]<-0.3. The mean value of [O/Fe] does not contradict the tendency of growth [O/Fe] on lower [Fe/H]. The average value of [O/Fe], obtained in this work for dwarfs and in the paper of Mishenina, et al. (2000), for halo stars <[O/Fe]>=+0.53±0.08 (4 stars) and disk <[O/Fe]>=+0.24±0.12 (16 stars).

Hydrostatic burning of He in massive supernovae SN II (Woosley, Weawer, 1995) is the main source of oxygen. These calculations of the O yields are used in models of chemical evolution. We have carried out the comparison [O/Fe] data with several chemical evolution models (Timmes et al, 1995; Shustov et al., 1997; Chang et al., 1999). [O/Fe] near 0.4–0.5 dex was accepted in these models and it is lower, than those obtained with permitted IR triplet lines and UV molecular lines. The model which is taking into account loss of heavy elements into intracluster medium (Shustov et al., 1997) better, than other considered models, are reproduced the run of oxygen with [Fe/H], however, on low [Fe/H] is not achieved the values of [O/Fe]=1 dex and more. Three components model of Qian, Wasserburg (2001) supposing, that the first massive stars $M>100M_{solar}$ produce oxygen in an early Galaxy, reflects well enough the observation data. It is necessary to note, that there is also other opportunity to explain the larger dispersion at low metallicity, it may be due to homogeneous of the earlier Galaxy. Among stars the poor metals observe stars, which show low enough value of [O/Fe]. So in our example there is a star BD+30 2611 c by very low value of [O/Fe]=+0.19 (our definition), such low value was marked also Kraft et al. (1995); King (2000); Gratton et al. (2000). As see from Fig.4 the larger scatter of [O/Fe] is observed at low [Fe/H].

Using our [O/Fe] and executed by us early, including recalculation NLTE of [O/Fe], obtained in work Cavallo et al. (1997) we have estimated the scattering of [O/Fe] values for stars with [Fe/H]<-1 and [Fe/H]>-1, it is equal ±0.29 (43 stars) and ±0.17 (33 stars), correspondingly. Thus the determination errors are equal accordingly ±0.19 and ±0.15. Thus, observation dispersion for stars with [Fe/H]>-1 is caused, for the most part, of measurement errors, but in case of stars with [Fe/H]<-1 parts of an errors may be due to ungemogenous prestellar matter.

Sodium. Sodium is synthesized during hydrostatic burning of carbon and partially, during hydrogen burning shell through the NeNa cycle.

The observational situation for sodium abundance in metal-poor stars is not quite clear. Pilachowski et al.(1996) studied halo stars and found a slight mean deficiency <[Na/Fe]>=-0.17±0.22 and a slight tendency for [Na/Fe] to increase with advancing evolutionary stage. Investigation of Na abundance of halo stars on extreme orbits (Stephens, 1999) exhibits the [Na/Fe] decrease (up to -0.7 dex) at [Fe/H] from -1 to -2. Study of thick disk stars displays mildly enhanced Na with an average <[Na/Fe]> is 0.087±0.014, there is a mild trend with metallicity (Prochaska et al., 2000). The determination of Na abundance was carried out by Carretta et al.(2000). They found for stars with [Fe/H]<-0.6, that the average [Na/Fe] is -0.09±0.19.

Lines of a doublet Na I 6154 and 6160 AA, and line 5682 A, (other component of this doublet is blended by telluric spectrum line) were chosen for definition of the sodium abundance. Not LTE departures for 6154 and 6160 AA lines are insignificant, but it is more important for a 5682 A line as was

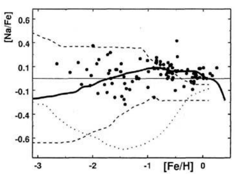

Figure 5: The trend of [Na/Fe] vs [Fe/H] Our [Na/Fe] data – black circles; dotted line – Timmes et al. (1995); solid line – Samland (1998, ApJ 496, 155); dashed lines – Goswami, Prantzos (2000, A&A 359, 191).

shown earlier for stars of various types (Mashonkina et al., 2000; Korotin, Mishenina, 1999; Baumuller et al., 1998; Gratton etc. 1999), but for D of Na I lines, they achieve -0.5 dex (Baumuller 1998).

We determined Na abundance with taking into account the NLTE corrections (Mishenina et al., 2002b). NLTE calculations were made under the program MULTI (Carlsson, 1986), modified (Korotin, Mishenina, 1999). In our case the corrections for 6154, 6160 lines are slightly and they are higher (up to 0.2 dex) for 5682 line.

Let's consider the behaviour of [Na/Fe] with [Fe/H] and compare it to the predictions of models of chemical evolution of the Galaxy (Timmes et al., 1995; Samland, 1998; Goswami, Prantzos, 2000) (Fig. 5). All these models as the main source of Na production consider massive stars and a Na yields take from nucleosynthesis calculations of Woosley, Weaver (1995). The authors specify, that on [Fe/H]>-1.0 some synthesis of sodium in intermediate mass stars can occur in the hydrogen burning shell through the neon-sodium cycle (Denissenkov, 1989). Mass loss of the stellar envelopes would enrich the interstellar medium. However, they did not it take into account in model calculation. Note, that the important question concerning synthesis of Na is a question on that, primary it is an element or secondary. In the first case it syntheses directly burning carbon and the Na yields is independent from metallicity. In a case of its production during neutron or proton capture the Na yields depends on neutron excess (Woosley, Weaver, 1995) and, correspondingly, from metallicity (Samland, 1998). In last case Na abundance should demonstrate deficiency in relation to iron in metal – poor stars.

As see from a Fig 5., the calculations of Timmes et al. (1995) (dotted line) and Goswami, Prantzos

(2000) (dashed lines) do not reproduce an observation run of [Na/Fe] with [Fe/H]. At that Timmes (1995) consider the Na yields independent from [Fe/H] and accepting, that halo and disk are parts of the same system, differing only on age. Gosvami, Prantzos (2000) take the Na yields dependent from metallicity and considers halo and disk, as two independent subsystems. It is interesting, that in case of the Na yields independent from metallicity (upper dashed line), the behaviour [Na/Fe] in model Gosvami, Prantzos (2000) is similar to the behaviour of alpha-elements (Mg, Si), this case is marked by the authors as not realistic. Model Samland (1998) (solid line) better describes the trend of Na with [Fe/H], than other models. This model using the metal dependency of stellar nucleosynthesis, and taking into account the large number of free model parameters (gas flows in the galaxy, mixing processes in ISM, energy release of supernovae etc.), have a great influence on the distribution of chemical elements, and, in particular, Na.

The average values of [Na/Fe] for stars with [Fe/H]>-1 is equal to 0.07±0.09 (60 stars) and slightly larger than for stars with [Fe/H]<-1, it is equal − 0.02±0.14 (38 stars). NLTE corrections reduce the dispersion (in LTE assumption the sigma is ±0.14 and ±0.20, accordingly), but the scattering is larger for stars of lower metallicity. We suppose that the larger dispersion is due to the larger determination errors at [Fe/H]<-1, though the Na dispersion in prestellar medium can also do its part for total dispersion.

Aluminium. The aluminium is a product of hydrostatic burning of carbon and neon in massive stars, and partially, hydrogen burning in MgAl a cycle. Al a yield is strongly effect to influence of a shock wave depends on model pre-supernovae and power of a shock wave.

The Al abundance determination is made in LTE approach with lines Al I 6696, 6698 AA. For these lines NLTE corrections do not exceed 0.15 dex (Baumuller, Gehren, 1997). At [Fe/H]=-1.0−-1.5 lines of aluminium weaken in stellar spectra depending on temperature and surface gravity of a star. The obtained values of [Al/Fe] are in the good concordance with those obtained in some papers (Edvardsson et al., 1993; Baumuller, Gehren, 1997; Prochaska et al., 2000) for stars with [Fe/H]>-1.5.

To examine the evolution of aluminium at lower metallicities we have taken the result of works (Ryan et al., 1996b; Norris et al., 2001). These determinations are carried out on a resonance line of Al I 3961.5, very effected to influence of NLTE departures (-0.65 on [Fe/H] ~ -3, Baumuller, Gehren, 1997). If to correct [Al/Fe] data for NLTE, we shall get [Al/Fe] on 0.2−0.3 over solar relation at [Fe/H]>-1.5 and on -0.2−0.3 below solar relation with a wide scatter at [Fe/H] ~ -3. As [Al/Fe] data were found without the NLTE departures the comparison observation data to calculation of models

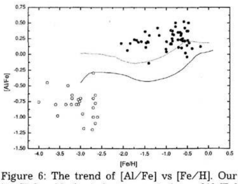

Figure 6: The trend of [Al/Fe] vs [Fe/H]. Our [Al/Fe] − black circles, open circles − [Al/Fe] (Ryan, 1991; Norris et al., 2001). The solid and dashed lines show the calculations of Timmes et al. (1995) with two factors of variation in the iron yields from massive stars.

of chemical evolution is not enough correct. We carry out such comparison as a first approximation. In a fig. 6 the comparison [Al/Fe] with models (Timmes et al., 1995 − solid line, our [Al/Fe] − black circles, open circles − Ryan et al., 1996b; Norris et al. (2001) is displayed. We see underproduction of aluminium at higher [Fe/H], especially if to take into account the NLTE corrections. The calculations of Goswami, Prantzos (2000) for aluminium yields independent from metallicity predict the trend of [Al/Fe] with [Fe/H] similarly the trend of alpha-elements (with [Al/H] overabundance up to 0.5 on [Fe/H] ~ -3). The authors consider this model only for illustration. Samland (1998), using Al yields dependent from metallicity and enlarged on the factor 5, achieves the quite good concordance between observational data and model calculation. Additional source of Al can be Al-production through AlMg cycle. There is another source of Al-production. There is another source of Al-production. The origin of a radioactive isotope ^{26}Al became interesting problem with the discovery of an excess of ^{26}Mg in the Allende meteorite (Lee et al., 1977). The presence of array line due to the decay of ^{26}Al in ^{26}Mg in the Galaxie pointed to the production of ^{26}Al in a Galaxy at present time, since the half-life of ^{26}Al is $7.2{\times}10^5$ years.

As a whole, the theories of nucleosynthesis and chemical evolution do not yet describe the trend of [Al/Fe] with [Fe/H].

α-elements. The so-called α-elements are formed due to capture of α-particles in the processes of hydrostatic neon and oxygen burning. Oxygen, magnum, silicon, sulfur, calcium and titanium traditionally belong to this group (though Ti is an element of iron peak). Supernovae SN II and, partially, SN Ia are producer of silicon and calcium.

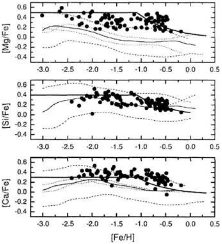

Figure 7: Our relative abundance of the б-elements, Mg, Si, Ca and the tracks for these elements computed by Timmes et al. (1995) (thin solid line) and by Pagel&Tautvaisiene (1995, MNRAS 276, 505) (thick solid line).

The Si, Ca yields depend on pre-supernovae model and power of a shock wave.

We carried out Mg, Si, Ca abundance determination using the lines of neutral atoms of these elements and LTE approximation. Some authors (Gratton et al., 1999; Thevenin, Idiart, 1999; Shimanskaya, Mashonkina, 2000) have estimated the departures from LTE for lines of Mg. The NLTE corrections for Mg I lines (for example, Shimanskaya, Mashonkina 2000) have not change the trend of [Mg/Fe] with [Fe/H] and the average value of [Mg/Fe]=0.45±0.05. Estimations of the departures from LTE for lines Mg at [Fe/H]<-0.6.

The effects of non-LTE for Fe and Mg lines were investigated by Gratton et al. (1999). They shown that the size of the model atom impact on results of non-LTE computations. Using 60-level model of the iron atom, they found negligible departures from the LTE in high gravity stars and slightly pronounced in low gravity stars, which is evidently due to the less efficient thermalization by collisions in giants. Non-LTE corrections for Fe lines are very small in dwarfs, and only small corrections (<0.1 dex) are expected for giant stars. The main non-LTE effect for Mg is overionization, but for high excitation lines these corrections are small in cool dwarfs (T_{eff}≤6000K) and larger in warmer dwarfs (-0.15 dex). Corrections are larger also in giants due to collisions less efficiently complete.

In Fig.7 we plotted our [Mg/Fe], [Si/Fe] and [Ca/Fe] vs [Fe/H] abundances together with the tracks computed by Timmes et al. (1995) and by Pagel, Tautvaisiene (1995). The thick solid line represents the results of Pagel, Tautvaisiene (1995). The thin solid line corresponds to the data from Timmes et al. (1995), the dashed line shows variation of the iron yield by a factor of two and dotted line reflects variation in an exponent by 0.3 in the initial mass function. For [Si/Fe] vs [Fe/H] and for [Ca/Fe] vs [Fe/H] plots observations are in the reasonable agreement with both models, and [Mg/Fe] vs [Fe/H] – with the model of Pagel, Tautvaisiene (1995), as one can see from Fig. 7. But, the discrepancy between the tracks for Mg of two models is evident, «for reasons which are not yet clear» (Pagel, Tautvaisiene, 1995). Both models assume that magnesium is a pure product of massive supernovae SNII. The best fit the model of Timmes et al. (1995) to the [Mg/Fe] observations may be a systematic reduction of the iron yields from massive stars by a factor of two and a small magnesium contribution originating from another source (Timmes et al., 1995).

The model of Goswami, Prantzos (2000) describes well the behaviour of α-elements, except Mg. Samland (1998) accepts, that the main source of Mg are massive stars (SN II) and 1.5% of Mg – production come out from SN Ia. The complicated model of Samland (1998) describes well the trend of [Mg/Fe] vs [Fe/H].

Iron. The main nuclear source of iron is explosive nucleosynthesis in supernovae SN II and SNIa. 2/3 of solar abundance of iron is a product of explosion of white dwarfs in double systems (SN Ia), supernovae SN II is producteur of 1/3 of iron solar abundance.

The abundance of iron relative to solar one [Fe/H] = lg(Fe/H) star – lg(Fe/H) is used as parameter metallicity of a star.

The iron abundance was obtained on similar set of lines for all study stars, in LTE approximation. From 50 up to 150 lines depending on metallicity were used in our analysis. The influence of NLTE effects on the neutral and ionized iron lines was investigated in some works (Thevenin, Idiart, 1999; Gratton et al., 1999; Schukina, Bueno, 1998). Unfortunately, the construction of complex model of atom (as iron, for example) is difficult task, especially in absence of physical parameters with satisfactory accuracy.

Other problem concerning the iron abundance in metal-poor stars, there is a diffusion of atoms of iron, which can result in lower iron abundance in giants (Chaboyer et al., 2001). The observation of dwarfs and giants in globular clusters do not support this assumption – Fe abundance in dwarfs and giants coincide among themselves.

n-capture elements. Two main mechanisms are responsible for the production of these elements: the *r*-process (for rapid neutron capture and the *s*-process for slow neutron capture depending on the magnitude of the neutron flux available, and in some cases the p-process (Burbidge et al., 1957). The *r*- and *s*-process syntheses are supposed to occur at different stages of star's lifetime. The *r*-process nuclei are synthesized in massive stars, that explode as Type II supernovae (SNe) (Cowan et al., 1991). The *s*-process is traditionally divided into two types: the weak *s*-component and the main *s*-component. The weak *s*-component is responsible for the production of lighter elements (Sr, Y, Zr) during the core He burning in massive stars (Lambd et al., 1977; Raiteri et al., 1991). The main *s*-component elements (heavier than Ba) can be synthesized during the termal pulses in the AGB phase of intermediate- and low-mass stars (Iben, Renzini, 1982; Hollowell Iben, 1989).In the works concerning n-capture elements determinations (Spite, Spite, 1978; Gilroy et al., 1988) the pattern of an element relative to iron ratio has been found not to follow that of α- or iron-peak elements at [Fe/H]<-2. Truran (1981) speculated that for low metallicity stars this might be due to the dominant role of the *r*-process. Later Gratton Sneden (1994) found that the relative contribution of the s-process is smaller in the metal-poor stars than in the solar system but that it is not at all negligible, even in stars as metal-poor as [Fe/H]=-2.5. McWilliam et al. (1995) confirmed the slump for [Sr/Fe], [Ba/Fe] vs [Fe/H] at a unique metallicity, about of [Fe/H]=-2.4 early detected by Spite, Spite (1978). This observation implies that a distinct phase of nucleosynthesis occurred before the Galaxy reached [Fe/H]= -2.4. McWilliam et al. (1995), Ryan et al. (1996) found also that the dispersions in some heavy element abundances (Sr for example) represent a scatter in the original stellar compositions at [Fe/H]< -2.5. This signature may have arisen from the weak s-process in massive stars or by *r*-processing. McWilliam (1998), Sneden et al. (1998), Burris et al. (2000) confirmed the significant scatter in n-capture elements at low metallicities.

In our study Sr,Y, Ba, La, Ce, Nd and Eu abundance analysis was carried out in the LTE approximation using the oscillator strengths log *g* from the paper of Gurtovenko, Kostyk (1989). Oscillator strengths from this source for some of the elements (including Ba, Eu) allow for the effect of hyperfine structure.

Non-LTE calculations for Ba were performed in the work by Mashonkina et al. (1999). They showed that corrections are small for subordinate lines (<0.08 dex) and increase to 0.20 for the Ba II resonance line lambda 4554 A. Departure from the LTE gets stronger with lower metallicity, depends on temperature and microturbulence but is insensitive to surface gravity and EW. However, the observed underabundance of Ba at the considered low metallicities is 1−1.5 dex, and this amount can't be removed completely by accounting for these corrections only. Therefore, we consider our analysis to be quite robust against non-LTE effects.

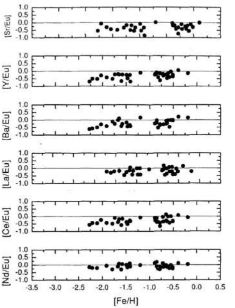

Figure 8: Relative abundances of Sr, Y, Ba, La, Ce, Nd to Eu versus [Fe/H].

The study of the trends of relative abundances vs [Fe/H] is important to investigate of the influence of the *n*-capture elements in enrichment of the Galaxy (Mishenina, Kovtyukh 2001). Investigation of *r*-, *s*-processes in the Solar System was carried out by Kappeler et al. (1989) and Raiteri et al. (1991). They conclude that more than 90% of Eu should come from the *r*-process. Relative abundances of Sr, Y, Ba, La, Ce, and Nd to Eu may indicate the efficiency of the *s*-process at the epocs of different metallicities (see Fig. 8). [Nd/Eu] exhibits larger contribution of the *r*-process than other elements. [Y/Eu], [Ba/Eu] and [Ce/Eu] show trend with [Fe/H] that may be the evidence of the *s*-process enrichment growth with increasing metallicity. Mashonkina et al. (1999), by direct determination of the odd-to-even isotopic ratio from the Ba II resonance line, showed at the instance of two stars that they have been formed from material whose barium content originated mainly in the *s*-process ([Fe/H]>-2.2). This result agrees with our conclu-

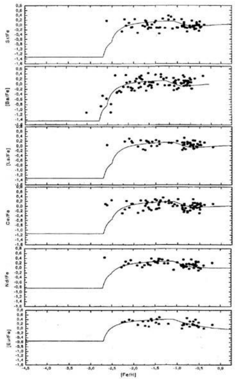

Fig. 9. Relative abundances of Sr, Y, Ba, La, Ce, Nd, and Eu versus [Fe/H] and the tracks for these elements computed by Pagel&Tautvaišiene (1997, MNRAS 288, 108) (solid line).

sion. Relative abundances to iron of [Sr/Fe], [Y/Fe], [Ba/Fe], [La/Fe], [Ce/Fe], [Nd/Fe], [Eu/Fe] vs [Fe/H] and comparison with the tracks of the model of Pagel Tautvaisiene (1997) are given in Fig. 9. The run of [Ba/Fe] vs [Fe/H] confirms the well-known jump of Ba abundances at [Fe/H] about of -2.5 dex (Spite Spite, 1978). Unfortunately, the lack of more stars in our sample with metallicities <-2.5 does not permit to trace the behavior of Ba abundances at earlier times and check if there is a plateau at [Fe/H]<-2.5 predicted by the model of Pagel Tautvaisiene (1997). But inside the available range of metallicities -0.5>[Fe/H]>-2.5 agreements with these model calculations is pretty good. These theoretical abundances have been computed assuming two separate time delays in s-elements production of the order of 37 Myr and 2.7 Gyr, corresponding to progenitor masses of about 8 Msolar and 1.5 Msolar respectively. Now, let's compare our results with the chemical evolution theory of Travaglio et al. (1999), which considers AGB stars of different masses and low mass SN as the sauces of production of r- and s-elements. Ba, La, Ce, Nd, and Eu that contain species of very different origin (mostly r-process production for Eu and s-process for Ba) were analyzed by these authors. Fig. 10 represents the behavior of these elements among the three populations of the Galaxy (the solid line corresponds to thin disk, the dotted line – thick disk, the dashed line – halo). For La, Nd, and Eu the agreement between observations is good, while for Ce and, especially, Ba it clearly breaks down. The model of Travaglio et al. (1999) predicts the appearence of s-enrichment at lower [Fe/H] than it follows from our observation data (for Ba, for example). It may be due to that at [Fe/H]<-2.5 the inhogeneous models of chemical evolution are required. Analysis of our data and matching with various evolutional models testifies to s enrichment at [Fe/H]>-2.5 by a wind from AGB stars of small masses. Some our target stars show that r-process contributes into Ba, Y and Ce abundances at [Fe/H]<-2.0. Sr shows larger scatter. McWilliam et al. (1995), Ryan et al. (1996) found larger dispersion in [Ba/Fe] and [Sr/Fe] at lower metallicities ([Fe/H]<-2.5) and have interpreted it as the evidence of the formation of our Galaxy at early times by mergers of the fragments with various proper enrichments (Searle, Zinn, 1978). Recently, the inhomogeneous chemical evolution models have been constructed by Raiteri et al. (1999) – for the run of [Ba/Fe] vs [Fe/H], by Travaglio et al., (2000) – for the run of [Eu/Fe] vs [Fe/H] and Tsujimoto et al. (2000) – the run of [Ba/Mg] vs [Mg/H], [Eu/Mg] vs [Mg/H]. We compared our [Eu/Fe] vs [Fe/H] data with the calculations of the inhomogeneous chemical evolution models by (Travaglio et al., 2000 (schematically, Fig. 11, 12). A Monte Carlo model by Travaglio et al. (2000) is based on the idea of fragmentation and coalescence between interstellar gas clouds, taking into account the effects of local enrichment and mixing of the halo gas, and accentuating on elements like Eu produced by r-process from low-mass SN. In case of Eu production from high-mass SN (15-25M), the time delay in the enrichment of Eu with respect to Fe will be too small and it is not enough to explain the observed spread in [Eu/Fe] at -3.5<[Fe/H]<-2.5. Our data are overlapped with the model dots partially in common region of [Fe/H]. Never the less, inhomogeneous models are very perspective for the interpretation of the behavior of r- and s-elements at early times of galactic evolution (at [Fe/H]<-2.5).

Cooper and zinc. Cu and Zn, two elements immediately following the iron peak. The first schematic description of the chemical evolution of Cu and Zn was proposed by Sneden et al. (1991), who suggested that they might be ascribed mainly to the weak s-process. Their conclusions were subsequently questioned by Raiteri et al. (1992) and by Matteucci et al. (1993). In this last work evidence was presented in favor of a large contribution from relatively long-lived processes, tentatively identified as Type Ia supernovae. Contrary to this, Timmes et al. (1995), using the copper and zinc yields of Type II supernova explosion from Woosley, Weaver (1995), suggested that these elements might be synthesized in significant amounts by the major nuclear burning stages in massive stars. These contrasting explanations are an example of the large uncertainties one meets when an incomplete picture of stellar yields and a simplified chemical evolution scheme have to be used for interpreting the data.

The 5105.54, 5218.20, 5782.12 AA lines of Cu I were used for abundance definition (Mishenina et al., 2002a). Synthetic spectra were calculated taking into account the hyper-fine structure of Cu I components (Steffen, 1985). The abundance of zinc was obtained from the 4722.16,4810.53, 6362.35 AA lines of Zn I. We used the EWs of these lines and Oscillator strengths for Zn I lines were taken from Gurtovenko, Kostyk (1989). The abundance definition was made in LTE assumption. Concerning Cu and Zn, computations of NLTE-effects on their abundances are complex and so far a good estimate of NLTE-corrections has not been presented. A posteriori, obtaining different abundances from lines with different low-level excitation potentials can be an empirical demonstration that departures from LTE are present. In the case of Cu, the lines 5105 AA and 5782 AA occur from meta-stable levels E_{low}=1.39 and 1.64 eV, respectively, unlike the line at 5218 AA E_{low}=3.82 eV. We have estimated that the discrepancy in Cu abundance, as determined from the lines at 5105 A and at 5218 A, is $<[Cu/H]_{5105} - [Cu/H]_{5218}> = 0.04 \pm 0.10$. The difference is well within the uncertainty of the estimate, and does not provide reasons for assuming that departures from LTE are of any importance. Unfortunately, Zn I lines have similar potentials and we cannot perform a similar analysis for the Zn abundance. We can however note that we used solar oscillator strengths for Zn I lines from Gurtovenko, Kostyk (1989), which implicitly include departures from LTE. We thus consider that our results can be affected only marginally by NLTE-effects.

Our values of [Cu/Fe], [Zn/Fe], and [Cu/Zn] are shown as a function of [Fe/H] in Fig. 13, and compared to abundances available in the literature. In the figure we prefer to use different points for measurements of the same star made by different authors, instead of making averages: in this way the scatter related to the heterogeneous composition of the database can be better appreciated. The trends for Cu and Zn are remarkably different, suggesting that differences in the dominant stellar

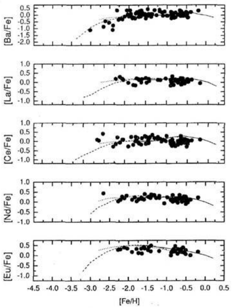

Figure 10: Relative abundances of Ba, La, Ce, Nd, and Eu versus [Fe/H] and the tracks for these elements computed by Travaglio et al. (1999, ApJ 521, 691) (the solid line corresponds to thin disk, the dotted line – thick disk, the dashed line – halo).

mechanisms controlling the production of these elements must exist. Observational trends of [Cu/Fe], [Zn/Fe], and [Cu/Zn] versus [Fe/H] are shown. Symbols are for: H stars, D, and I stars from this work; Sneden et al. (1991); Westin et al. (2000); Hill et al. (2002) and Cowan et al. (2002). Thin dotted lines connect the points representing observations of the same stars by different authors. Error bars for individual objects are shown only when reported in the original papers. Fig. 14 shows indeed that fitting their relative trends requires at least a polynomial function with a quartic term. The line in the figure has no special meaning other than minimizing the sigma of the fit; it however shows that any reasonably accurate interpolation curve must necessarily assume relationships more complex than expected from purely primary or purely secondary processes. A purely secondary element would have a linear trend with slope +1. On the contrary, in the region where an almost linear trend exists ($-2<[Fe/H]<-0.5$) the observed slope is about 0.6. Hence, already in early times of galactic evolution (the halo phases) Cu cannot be considered as a purely secondary element. In such phases it might be explained as the superposition of (at least) two independent processes, one of primary and one of

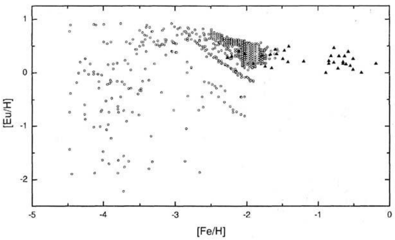

Figure 11: [Eu/Fe] versus [Fe/H], the filled triangles represent our data, the small open circles correspond schematically to the calculations of Travaglio et al. (2001, ApJ 549, 346). The r-process yields of Eu are derived from SN II in the mass range 8-10 M_{solar}.

secondary origin. A parabolic relation does in fact hold for the Cu abundance data in the shown metallicity interval, and Cu can have contributions from both primary and secondary processes in short-lived (i.e. massive) stars. The importance of secondary mechanisms can be quantitatively estimated by considering Cu production compared to the s-only isotope 80Kr. This nucleus is known to be produced at about 12% of its abundance in the main component of the s-process (Arlandini et al., 1999) and to have possibly a 10% p-process contribution. The rest is due to neutron captures in massive stars. Let us use for these last the recent models by Hoffman et al. (2001), where the overproduction of isotopes up to A=100 is given. Those models have to produce 80Kr at the 78% level of its solar abundance, then summing over the isotopes of Cu one gets for this element a contribution from sec-

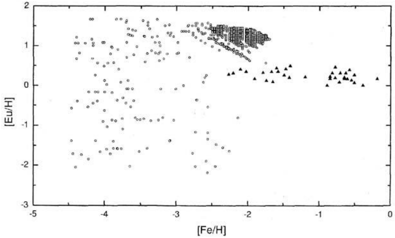

Figure 12: [Eu/Fe] versus [Fe/H], the filled triangles represent our data, the small open circles correspond schematically to the calculations of Travaglio et al. (2001). The r-process yields of Eu are derived from SN II in the mass range 15-30 M_{solar}.

ondary processes in massive stars of about 23% (assuming no primary contribution from the same stars). Below [Fe/H]= -2.5, [Cu/Fe] reaches an apparent plateau (though this conclusion is uncertain due to the limited data) around -0.6 dex. As 70% of iron comes later from type Ia Supernovae, this implies a primary contribution by population II massive stars of $10^{-0.6}\times 0.3$, which gives a total contribution as small as 7.5%. From the recent work by Heger et al. (2002) we also see that pre-galactic very massive stars cannot give remarkable contributions to Cu.

We can also exclude that the primary massive star contribution be dominated by the r-process. The comparison with Ba (Fig. 15), which galactic evolution in early phases is due to r-process (Travaglio et al., 1999) confirms it. Summing up, inspection of the observed data, comparisons with other elements and isotopes of known origin, and a very rough scheme for the chemical enrichment of the galactic halo allows us to predict that Cu receives a primary contribution by massive stars of about 7.5% of its abundance, while something around 25% should come from secondary processes in the same stars (slow neutron captures, or the weak s-process). Another 5% have been already attributed to the main s-component from AGB stars of long lifetime. We cannot avoid the suggestion that the remaining part (formally 62.5%) comes from the less known processes we have so far neglected, i.e. explosive nucleosynthesis in Type Ia supernovae. A similar reasoning can be repeated for Zn, which however shows a trend very close to Fe itself, so that the conclusion is more straightforward. Attributing 3% of its production to the main s-process component in AGB stars, the rest should come either from primary nucleosynthesis in massive stars (30%), or from Type Ia supernovae (something around 67%, like for Fe). The massive star yield cannot be dominated by the r-process, but some contribution from this last remains possible. For this «test» we make use of a metallicity distribution and a Star Formation Rate previously obtained (Travaglio et al., 1999) through an evolutionary model suitable for reproducing a large set of Galactic and extragalactic constraints (for details on the code see Ferrini et al., 1992; for its application to galactic heavy element enrichment see also Travaglio et al., 2001). The model considers the Galaxy as divided in three zones, halo, thick disk and thin disk. For Cu and Zn, we simply mimic the input stellar yields by imposing the tentative production sites derived in the previous section for the primary and secondary contributions in massive stars, in Type Ia supernoave and in AGB stars. Fig.15 and Fig. 16 show the resulting chemical enrichment, through plots of [Cu/Fe], [Zn/Fe], [Cu/Zn] and [Cu/Ba], [Zn/Ba] versus [Fe/H]. Chemical evolution predictions for Ba are from

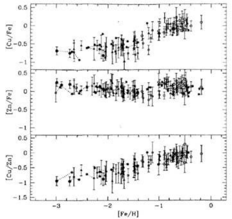

Figure13: Observational trends of [Cu/Fe], [Zn/Fe], and [Cu/Zn] versus [Fe/H] are shown. Symbols are for: H stars (open triangles), D (open circles), and I stars (open squares) from this work; Sneden et al. (1991, A&A 246, 354) (stars); Westin et al. (2000, ApJ 530, 783), Hill et al. (2002, A&A 387, 560), and Cowan et al. (2002, ApJ 572, 861) (filled circles)). Thin dotted lines connect the points representing observations of the same stars by different authors. Error bars for individual objects are shown only when reported in the original papers.

Travaglio et al. (1999). Being an outcome of the very crude estimates previously discussed, the results illustrated by the figures are not bad, and confirm that our suggestions for the stellar yields should be roughly correct. However, while they can interpret the general trends, they cannot explain the spread of abundances at very low metallicity. This is in particular related to the oversimplification of attributing massive star yields of Cu and Zn to generic explosive phenomena, in the absence of a criterion for distinguishing different processes occurring in different masses. In the galactic evolution results presented by Travaglio et al. (1999), the r-process was attributed to moderately massive (8-10 Msolar stars, ejecting their nucleosynthesis contribution after some delay compared to the typical products of very massive objects; this was adopted as a possible explanation for the delay in the appearance of Eu and Ba with respect to oxygen and iron (Travaglio et al., 1999). Making use of this same separation of massive star yields in two groups with different time scales for enrichment, we might improve our suggestions on the origin of Cu and Zn, trying to disentangle their r-process contribution from the rest. Actually, if the r-process becomes well mixed in the Galaxy only after [Fe/H] has reached the value -2.5 or so, we can tentatively interpret the

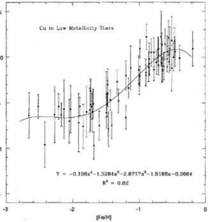

Figure 14: [Cu/Fe] vs [Fe/H]: filled squares are the observations of Fig. 12. The fit (continuous line) shows that the dependency of [Cu/Fe] on [Fe/H] is more complex than implied by purely primary or purely secondary mechanisms.

scattered Cu and Zn abundances in very metal-poor stars as an indication that these last were born out of clouds selectively contaminated by different supernova types, sometimes carrying the signature of the r-process, sometimes that of NSE

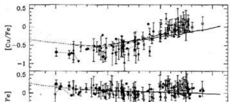

Figure15: Galactic evolution of [Cu/Fe], [Zn/Fe], [Cu/Zn] according to the chemical evolution prescriptions described in the text (including primary processes from massive stars, secondary processes from SNII, s-processes from AGB stars, and SNIa contributions). Symbols are the same as in Fig. 12.

or other explosive nucleosynthesis phenomena, in a poorly mixed early Galaxy.

Results and conclusions

We have determined the stellar parameters and abundances of 17 chemical elements in the atmospheres of 100 stars of various metallicities. The comparison of obtained data with current chemical evolution model was made. In summary, we found the following results.

Lithium. The main sources of Li enrichment of ISM are the Li yieds as a result of the Big Bang, the reaction of cosmic ray spallation and ν-process in massive supernovae. At disk metallicities there are additional sources of Li-production, these are SN Ia and AGB stars. Some dispersion of Li at low [Fe/H] nevertheless is observed. It can be due to intrinsic scatter of Li in ISM or presence of physical processes, what change the lithium abundance.

Carbon. The description of behaviour of carbon, as a whole, is unsatisfactory. The increasing [C/Fe] with decreasing [Fe/H] may be to explain by grow of the contribution from Supernovae type II and larger scatter at low metallicities may be due to unhomogeneous of early Galaxy.

Oxygen. The trend of [O/Fe] with [Fe/H] at [Fe/H]<-2 remains conflicting, as the observation data give not agree result through different indicators of oxygen. Probably, the main source of oxygen on early times of the Galaxy is the very massive stars (about 100 Msolar).

Sodium. The complicated model of Samland (1998) describes well the Na trend with [Fe/H]. This model uses the Na yields dependent from [Fe/H] and it accounts of the large number of parameter appreciably changing distribution of chemical elements. The larger scatter of [Na/Fe] at [Fe/H]<-1 than at [Fe/H]> – may be due to larger uncertainties of Na determination at [Fe/H]<-1 or intrincic sodium dispersion at low metallicities.

Aluminium. The observation of Al is unsatisfactory. The resonance lines of Al I are affected by strong NLTE departures. The nucleosynthetic theories and chemical evolution models do not describe well the behaviour of aluminium.

α-elements. As a whole, the evolution of [Si/Fe] and [Ca/Fe] with [Fe/H] is well described within the framework of various models of chemical evolution. The main sources of this element production are SN type II and, partially, SN Ia. The evolution of [Mg/Fe] is less certain, because not all models describe well the trend Mg with [Fe/H], though everyone accepts the same source of Mg production.

Neutron captures elements. R-process of the contribution of Ba abundance leaves from 8-10 M_{sol} SN II and this component dominates on low metallicities. S-process becomes dominant above r-process only after 1 Gyr of galactic evolution

([Fe/H]~-1) and it is connected to a long scale of evolution of stars of small weights and efficiency of s-production in AGB stars on different metallicities. The larger scatter of abundance at low metallicities is interpreted within the framework of unhomogeneous galactic models (Ba – Raiteri et al., 1999; Ba, Sr, Eu – Travaglio et al., 2000; Tsujimoto et al., 2000).

Cooper and zinc. Using our analysis the observation data, we have carried out the calculation of chemical evolution for Cu and Zn (Travaglio et al., 1999; Ferrini et al., 1992; Travaglio et al., 2001). The model of the Galaxy has three zones – halo, thick disk, and thin disk. We suggest that about 25% of Cu is produced by secondary phenomena in massive stars, and only 7-8% is due to primary phenomena in the same environment (either explosive or from a primary n-process). The bulk of Cu abundance (at least 62 – 65%) should be instead contributed on long time scales by type Ia supernovae. For Zn, its trend with respect to iron implies similar percentage yields for the two elements: 1/3 from primary processes in massive stars and 2/3 from type Ia supernovae. These rough indications were shown to roughly account for the Cu and Zn enrichment in the Galaxy. This approach was however found to be too schematic for interpreting the details of the database, including the scatter at very low metallicity. We argued that this last might be due to poorly mixed different contributions from massive stars in a non-homogeneous early stage (perhaps also complicated to the non-uniqueness of the r-process). A more quantitative analysis must therefore wait for a clarification of the underlying physical processes in evolved stars.

Examined element abundances show the scatter at low metallicities ([Fe/H]<-2.0). On the one hand it may be due to the low accuracy of the observatinal data, on the other hand it may be the evidence of the unhomogeneous of early Galaxy. The last may be due to the accretion of dwarf galaxies – satellites, or merging of separate fragments, on which has desintegrated primary uniform protogalaxy (Searle, Zinn, 1978). The scatter in element abundances in metal-poor stars may be also as result of small number supernovae (about 20), with various masses and, accordingly, different yields of heavy elements (Audouze, Silk, 1995) at earle Galaxy. The stochastic halo formation models (Argast et al., 2000) investigated the dispersion of the relative abundances as result of enrichment of ISM by single core-collapse supernovae. At [Fe/H]<-3, representative an early phase, the halo ISM is unmixed and dominated by local inhomogeneities caused by individual supernovae events. In the range -3<[Fe/H]<-2 the dispersion noteceablly decreases, ISM becomes better mixed and at [Fe/H]>-2 the halo ISM is well mixed.

The comparison of the thrends of [El/Fe] vs [Fe/H] with calculations of the theories of chemical evo-

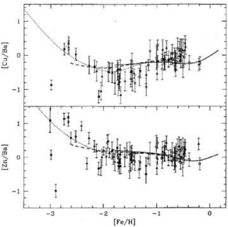

Figure16: The same as Fig. 14 for the ratio [Cu/Ba], and [Zn/Ba]. Symbols are the same as in Fig. 12.

lution and nucleosynthesis shows that many elements are described unsatisfactorily, it requires new investigations in the theories and the observations.

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