NON-LTE ABUNDANCES AND CONSEQUENCES FOR THE EVOLUTION OF THE $\alpha$-ELEMENTS IN THE GALAXY

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ABSTRACT

Abundances of $\alpha$-elements such as Ca and Mg in disk and halo stars are usually derived from equivalent width lines measured on high-resolution spectra and assuming local thermodynamic equilibrium (LTE). In this paper, we present non-LTE differential abundances derived by computing the statistical equilibrium of Ca I and Mg I atoms, using high-resolution equivalent widths available in the literature for 252 dwarf to subgiant stars. These non-LTE abundances, combined with recent determination of non-LTE abundances of iron, seem to remove the dispersion of the [Ca/Fe] and [Mg/Fe] ratios in the galactic halo and disk phases, revealing new and surprising structures. These results have important consequences for chemical evolution models of the Galaxy. In addition, non-LTE abundance ratios for stars belonging to the M92 cluster apparently have the same behavior. More high-resolution observations, mainly of globular clusters, are urgently needed to confirm our results.

Subject headings: Galaxy: abundances — radiative transfer — stars: abundances — stars: atmospheres

1. INTRODUCTION

The determination of abundances of nuclear species at distinct locations in the Galaxy (e.g., halo, disk, and bulge) comes mainly from the spectra of late-type star atmospheres. Measured abundances in cool stars at different stages of evolution give not only an understanding of stellar nucleosynthesis but also provide valuable information about the process of chemical enrichment of the Galaxy.

The archaeological tracers of the chemical evolution of a star system are the elements produced by explosive nucleosynthesis in Type II (SN II) and Type Ia (SN Ia) supernova events. The interest in using such elements as tracers rests on the fact that SN II and SN Ia progenitors have different lifetimes; SN II is the final stage in the evolution of massive stars, and SN Ia is a possible final result of the evolution of a close binary system of intermediate-mass stars. SNe II contribute to the enrichment of the interstellar medium (ISM) mainly with elements produced by the capture of $\alpha$-particles ($\alpha$-elements) and from the $\beta$-process, and SNe Ia produce elements belonging to the Fe peak. Consequently, the basic tools to constrain the evolution of ISM in the Galaxy are usually the analysis of relations between ratios of heavy elements [element/Fe] and Fe abundance [Fe/H].

A first glance at the temporal behavior of $\alpha$-elements shows that the ratio [\alpha/Fe] is approximately constant for halo metal-poor stars ([Fe/H] \leq -1.5) and decreases for metal-rich stars ([Fe/H] > -1.5) belonging to the disk. This is reasonably explained by the chemical evolutionary models that assume progressive enrichment of the ISM by supernovae: the first generation of stars has in its atmospheres the signature of SN II events only (called the halo phase of the Galaxy), and the subsequent generations have signatures of both SN II and SN Ia events (disk phase).

\[ \text{[Fe/H]} = \log \left( \frac{N_{\text{Fe}}}{N_{\text{H}}} \right) - \log \left( \frac{N_{\text{Fe}}}{N_{\text{H}}} \right)_\odot. \]

However, a more precise analysis of [\alpha/Fe] versus [Fe/H] shows a pronounced scatter, mainly in the region of metal-poor stars. This scatter has been interpreted mostly as a consequence of the inhomogeneity of the matter making up the stars rather than a result of poor observational data (Audouze & Silk 1995).

The derivation of abundances based on the analysis of high-resolution stellar spectra is usually made under the assumption of local thermodynamical equilibrium (LTE). In the last 15 years, many efforts to estimate errors on abundance determinations caused by LTE assumption have been made. Recent results for Ba II (Gigas 1986, 1988; Mashonkina & Bikmaev 1996), Sr II (Belyakova & Mashonkina 1997), Na I (Mashonkina, Sakhibullin, & Shimsanskii 1993), Mg I (Gigas 1986; Mashonkina, Shimanskaya, & Sakhibullin 1996), Ca I (Drake 1991), B I (Kiselman & Carlsson 1996), Al I (Baumuller & Gehren 1997), Fe I and Fe II (Thévenin & Idiart 1999, hereafter TI99), O I (Mishenina et al. 2000), and Mg I (Zhao, Butler, & Gehren 1998) demonstrate that most lines can form far from LTE conditions. Thus, some important questions arise: what is the influence of non-LTE abundance calculations on the chemical evolution diagrams of the Galaxy? Do these computations add additional different constraints to the chemical history of enrichment of the matter in the Galaxy?

In this work, we present non-LTE abundances derived from the computation of statistical equilibrium of Ca and Mg atoms, using published equivalent widths (§ 3). The atomic data and stellar atmospheric models used are presented in § 2. $\alpha$-elements such as Mg and Ca have well-known enhanced abundances in atmospheres of F–G metal-poor dwarf stars as a result of cumulative stellar generations. Recently, Nissen & Schuster (1997) and Jehin et al. (1999) proposed the existence of two sequences of stars having two different [$\alpha$/Fe] ratios for intermediate stars ([Fe/H] \approx -1). Their works are based on highly accurate observations of stars having approximately the same tem-
temperatures and surface gravities. Based on our non-LTE computations, we found different branches or sub-populations of stars not only for intermediate metallicities; consequences for chemical evolution models of the Galaxy are presented in § 4. We draw our conclusions in § 5.

2. ATOMIC DATA AND STELLAR ATMOSPHERIC MODELS

The code we used to solve the equations of statistical equilibrium and radiative transfer is version 2.2 (1995) of MULTI (Carlsson 1986). This code allows us to obtain theoretical spectra of Mg I and Ca I for given stellar atmospheric models and atomic data.

The atomic models used are shown by Grotrian diagrams presented in Figures 1 and 2, for Mg I and Ca I, respectively. We included all the fine-structure levels of Mg I below 6 eV: 103 levels + continuum and 980 radiative transitions. For calcium, the model has 83 levels + continuum and 483 radiative transitions. We used the atomic energy level tables given by Hirata & Horagushi (1995, hereafter HH95) and Martin et al. (1985). Oscillator strengths are from HH95, Kurucz (1993), and Thévenin (1989, 1990). We followed the procedure described in TI99 for the remaining atomic data: radiative and collisional damping coefficients, excitation, and ionization collisional cross sections. Photoionization cross sections are from TopBase. The van der Waals damping for all Mg lines was calculated using the approximation given by Unsöld (1955) and multiplied by a factor 1.3 as in TI99. For Ca we followed Cayrel et al. (1996). Note that the factor 1.3 is important only for strong saturated lines. As will be seen in § 3, we always tried to use lines lying on the linear part of the curve of growth, where this factor does not play an important role.
| Star       | $\theta_{\text{eff}}$ | log $g_{\text{NLTE}}$ | [Fe/H]$_{\text{NLTE}}$ |
|-----------|----------------------|----------------------|----------------------|
| HD 3158   | 0.790                | 4.20                 | 0.08                 |
| HD 3268   | 0.820                | 4.10                 | -0.13                |
| HD 3567   | 0.827                | 4.20                 | -1.05                |
| HD 4307   | 0.890                | 3.90                 | -0.17                |
| HD 5015   | 0.810                | 4.10                 | 0.10                 |
| HD 6582   | 0.950                | 4.67                 | -0.56                |
| HD 6920   | 0.870                | 3.90                 | -0.05                |
| HD 7476   | 0.770                | 4.15                 | -0.09                |
| HD 7570   | 0.830                | 4.30                 | 0.18                 |
| HD 9562   | 0.870                | 3.80                 | 0.20                 |
| HD 9826   | 0.830                | 4.00                 | 0.08                 |
| HD 10307  | 0.850                | 4.00                 | 0.08                 |
| HD 12042  | 0.810                | 4.20                 | -0.22                |
| HD 14214  | 0.830                | 4.10                 | 0.15                 |
| HD 15335  | 0.860                | 4.20                 | -0.08                |
| HD 15798  | 0.780                | 3.95                 | -0.10                |
| HD 16673  | 0.800                | 4.40                 | 0.10                 |
| HD 17288  | 0.882                | 4.32                 | -0.75                |
| HD 17820  | 0.868                | 4.21                 | -0.54                |
| HD 19994  | 0.830                | 4.10                 | 0.18                 |
| HD 20807  | 0.840                | 4.50                 | -0.05                |
| HD 22001  | 0.740                | 4.10                 | -0.01                |
| HD 22454  | 0.840                | 4.20                 | 0.00                 |
| HD 22879  | 0.861                | 4.35                 | -0.67                |
| HD 23754  | 0.750                | 4.10                 | 0.16                 |
| HD 24339  | 0.854                | 4.31                 | -0.48                |
| HD 25621  | 0.800                | 4.00                 | 0.16                 |
| HD 25704  | 0.856                | 4.35                 | -0.68                |
| HD 26491  | 0.880                | 4.20                 | -0.08                |
| HD 29645  | 0.840                | 4.10                 | 0.16                 |
| HD 30562  | 0.860                | 4.00                 | 0.22                 |
| HD 30743  | 0.780                | 4.20                 | -0.21                |
| HD 33256  | 0.780                | 4.00                 | -0.14                |
| HD 33608  | 0.760                | 4.10                 | 0.37                 |
| HD 34411  | 0.860                | 4.10                 | 0.09                 |
| HD 35296  | 0.790                | 4.30                 | 0.10                 |
| HD 38393  | 0.790                | 4.30                 | 0.00                 |
| HD 41330  | 0.850                | 4.10                 | -0.07                |
| HD 43042  | 0.770                | 4.30                 | 0.12                 |
| HD 43318  | 0.790                | 4.10                 | -0.03                |
| HD 45701  | 0.870                | 4.20                 | 0.20                 |
| HD 49933  | 0.760                | 4.20                 | -0.27                |
| HD 50223  | 0.760                | 4.10                 | -0.04                |
| HD 55575  | 0.850                | 4.00                 | -0.21                |
| HD 59984  | 0.860                | 4.02                 | -0.62                |
| HD 60532  | 0.820                | 3.92                 | -0.07                |
| HD 61902  | 0.832                | 4.11                 | -0.59                |
| HD 63077  | 0.880                | 4.33                 | -0.66                |
| HD 65998  | 0.872                | 4.15                 | -0.73                |
| HD 67228  | 0.870                | 4.20                 | 0.14                 |
| HD 68456  | 0.770                | 4.10                 | -0.15                |
| HD 70110  | 0.850                | 4.40                 | 0.12                 |
| HD 76151  | 0.880                | 4.50                 | 0.10                 |
| HD 78747  | 0.888                | 4.02                 | -0.61                |
| HD 76932  | 0.860                | 3.75                 | -0.73                |
| HD 79028  | 0.860                | 4.20                 | 0.00                 |
| HD 79601  | 0.882                | 4.01                 | -0.53                |
| HD 83220  | 0.777                | 4.20                 | -0.40                |
| HD 86728  | 0.880                | 4.00                 | 0.20                 |
| HD 87141  | 0.790                | 4.20                 | 0.15                 |
| HD 88737  | 0.820                | 4.10                 | 0.26                 |
| HD 88966  | 0.870                | 4.00                 | 0.04                 |
| HD 89125  | 0.820                | 4.30                 | -0.24                |
| HD 89744  | 0.800                | 4.10                 | 0.28                 |
| HD 91752  | 0.780                | 3.90                 | -0.13                |
TABLE 1—Continued

| Star | θ_{eff} | log g_{NLTE} | [Fe/H]_{NLTE} |
|------|---------|-------------|--------------|
| HD 199623 | 0.800 | 4.20 | -0.21 |
| HD 200790 | 0.820 | 4.10 | 0.03 |
| HD 203608 | 0.824 | 4.51 | -0.52 |
| HD 210855 | 0.810 | 3.90 | 0.18 |
| HD 213657 | 0.830 | 3.94 | -1.75 |
| HD 215257 | 0.873 | 4.01 | -0.67 |
| HD 216385 | 0.820 | 4.10 | -0.18 |
| HD 217014 | 0.870 | 4.20 | 0.16 |
| HD 218470 | 0.770 | 4.20 | -0.04 |
| HD 241253 | 0.854 | 4.45 | -0.87 |
| BD +20 3603 | 0.840 | 4.30 | -2.04 |
| BD +80 245 | 0.933 | 3.70 | -1.78 |
| BD −21 3420 | 0.848 | 4.31 | -0.88 |
| CD −33 3337 | 0.850 | 4.02 | -1.16 |
| CD −45 3283 | 0.890 | 4.58 | -0.72 |
| CD −47 1087 | 0.879 | 4.33 | -0.64 |
| CD −57 1633 | 0.850 | 4.30 | -0.73 |
| CD −61 0282 | 0.853 | 4.45 | -0.97 |
| G005 −040 | 0.859 | 4.22 | -0.68 |
| G046-031 | 0.837 | 4.43 | -0.61 |
| G088-040 | 0.845 | 4.18 | -0.64 |
| G09-3 | 0.876 | 4.27 | 0.95 |
| G102-020 | 0.935 | 4.50 | -0.93 |
| G125-64 | 0.892 | 5.45 | -2.16 |
| G190-15 | 1.008 | 5.20 | -2.65 |
| G182-31 | 0.840 | 4.38 | -2.18 |
| W7547 | 0.804 | 3.99 | -0.30 |
| M92-18 | 0.845 | 4.33 | -2.45 |
| M92-21 | 0.848 | 4.29 | -2.38 |
| M92-34 | 0.864 | 4.18 | -2.43 |
| M92-46 | 0.846 | 4.23 | -2.41 |
| M92-60 | 0.831 | 4.33 | -2.40 |
| M92-350 | 0.851 | 4.28 | -2.38 |

Stellar atmospheric models are generated using the grids of Gustafsson et al. (1975) and Bell et al. (1976), in order to be consistent with T199, using T_{eff} from Thévenin (1998) and log g and [Fe/H] corrected for non-LTE effects from T199. We also estimated non-LTE log g and [Fe/H] values for an additional sample of stars not analyzed in T199 (see Table 1). For some objects, for which more accurate equivalent widths were recently available, non-LTE surface gravities and [Fe/H] were reestimated (see Table 1). We emphasize that we do not intend to obtain absolute abundance values (see §3); thus in a first approximation we can use LTE atmospheric models and perform our analysis just estimating non-LTE effects in statistical equilibrium.

3. NON-LTE CALCULATION AND RESULTS

To estimate Ca and Mg non-LTE abundances we used published equivalent widths (EWs) for 252 stars, including dwarfs, subdwarfs, and some subgiants. Sources of EW data are listed in Table 2 with the respective wavelengths of lines used in our analysis. Since we chose to work with one or two lines at maximum, we selected unsaturated and not very weak lines in order to have a more precise abundance determination.

To obtain non-LTE abundances we iterate MULTI with different abundance values until we reproduce the measured EW. This kind of procedure has two basic problems: (1) our atomic model is not perfect since, for example, we do not take into account all the levels and line transitions of all spectroscopic terms and certainly there are uncertainties in oscillator strengths and in collisional processes with neutral H and He (see T199, for a discussion); and (2) there are observational errors in EW measurements and inhomogeneity of EWs from different sources (e.g., observations with

TABLE 2

| EW References | Ca I Lines (Å) | Mg I Lines (Å) |
|---------------|---------------|---------------|
| Edvardsson et al. 1993 | 6166.44 | 8717.82 |
| Nissen & Schuster 1997 | 6166.44 | 5711.1 |
| Jehin et al. 1999 | 4578.56 | 4571.10 |
| Zhao & Magain 1990 | 4578.56 | 4571.1 |
| Ryan, Norris, & Bessell 1991 | 4283.01, 4302.52 | 4167.27 |
| Perrin 1986 | 4435.69 | ... |
| North, Berthet, & Lanz 1994 | 6717.69 | ... |
FIG. 5.—Percentage errors in EW in function of variations of 0.15–0.2
dex in the abundance ratios \([\text{Ca/Fe}] = +0.25\) and \([\text{Mg/Fe}] = +0.225\) for
the same lines as in Fig. 4.

different instruments and different placement of the
continua).

In order to avoid systematic effects between EWs existing
in the literature we renormalized our resulting abundances
using common stars (comparison objects) present in the
data sets of different authors. Of course, a standard pro-
cedure of renormalization requires a choice of comparison
objects according to each spectral type of the analyzed stars.
In our case this step was not necessary since our selected
stars have roughly the same surface gravities (dwarfs and
subgiants) and a narrow range of not very cool effective
temperatures \((5300 < T_{\text{eff}} < 6300)\).

All the stars were renormalized to a given reference
system, to which we refer here as the Ed93 system (which is
based on abundances derived from the published EW set of
Edvardsson et al. 1993). First, we recalculate solar Ca, Mg,
and Fe abundances using MULTI and EWs taken from
Ed93. These values are our solar references. Then we esti-
mate the relative abundances \([\text{Ca/H}]\) and \([\text{Mg/H}]\) for Ed93
stars. In principle, this differential procedure also allows us
to minimize the imperfections of the atomic models used
here. To renormalize the data from other sources we used
observed common stars, as mentioned in the preceding
paragraph. For example, for Mg abundance and mean
metallicity \(<[\text{Fe/H}] > \approx -1\), to include the data of Jehin et
al. (J99) into the Ed93 system, nine common stars between
these two data sets were taken and the average of the differ-
ences between estimated abundances was calculated. This
averaging procedure was used to transform J99 data to the

Ed93 system. The same procedure was performed on data
given by Nissen & Schuster (NS97). For metal-poor stars
more steps were performed. For the Zhao & Magain
(ZM90) data, for example, we renormalized ZM90 into J99
(one common star) and ZM90 into NS97 (two common
stars); then, as J99 and NS97 have common stars with the
Ed93 system, these two sequences gave us a renormaliza-
tion ZM90-Ed93.

FIG. 6.—Chemical abundance ratios in function of effective tem-
perature \((T_{\text{eff}} = 5040/T_{\text{eff}})\). Different symbols follow the same legend as in
Fig. 3.

FIG. 7.—Relation between Mg and Ca abundances. Different symbols
follow the same legend as in Fig. 3.
### Table 3

Non-LTE Abundances for 252 Stars

| Star          | \([\text{Fe/H}]_{\text{NLTE}}\) | \([\text{Ca/H}]_{\text{NLTE}}\) | \([\text{Mg/H}]_{\text{NLTE}}\) | EW Reference |
|---------------|----------------------------------|----------------------------------|----------------------------------|--------------|
| BD +80 245    | −1.78                            | −2.14                            | −2.13                            | C97          |
| BD +20 3603   | −2.04                            | −2.13                            | −1.84                            | C97          |
| G 125-64      | −2.16                            | −2.38                            | −2.07                            | C97          |
| G 182-31      | −2.18                            | −1.96                            | −1.95                            | C97          |
| G 90-3        | −1.95                            | −1.89                            | −1.90                            | C97          |
| G 190-15      | −2.65                            | −2.72                            | −2.51                            | C97          |
| HD 400        | −0.15                            | −0.26                            | −0.06                            | Ed93         |
| HD 739        | −0.02                            | 0.1                              | −0.05                            | Ed93         |
| HD 2454       | −0.21                            | −0.32                            | −0.16                            | Ed93         |
| HD 2615       | −0.45                            | −0.42                            | −0.36                            | Ed93         |
| HD 3158       | 0.08                             | 0.04                             | 0.02                             | Ed93         |
| HD 3268       | −0.13                            | −0.19                            | −0.09                            | Ed93         |
| HD 4307       | −0.17                            | −0.21                            | −0.22                            | Ed93         |
| HD 5015       | 0.10                             | 0.06                             | 0.14                             | Ed93         |
| HD 6434       | −0.38                            | −0.32                            | −0.19                            | Ed93         |
| HD 6920       | −0.05                            | −0.17                            | −0.02                            | Ed93         |
| HD 7439       | −0.19                            | −0.29                            | −0.08                            | Ed93         |
| HD 7476       | −0.09                            | −0.28                            | −0.14                            | Ed93         |
| HD 7570       | 0.18                             | 0.12                             | 0.13                             | Ed93         |
| HD 9562       | 0.2                              | 0.13                             | 0.27                             | Ed93         |
| HD 9826       | 0.08                             | −0.02                            | 0.20                             | Ed93         |
| HD 10307      | 0.08                             | −0.02                            | 0.10                             | Ed93         |
| HD 12042      | −0.22                            | −0.25                            | −0.26                            | Ed93         |
| HD 13555      | −0.19                            | −0.21                            | −0.08                            | Ed93         |
| HD 14214      | 0.15                             | 0.07                             | ...                              | Ed93         |
| HD 15335      | −0.08                            | −0.13                            | −0.14                            | Ed93         |
| HD 15798      | −0.10                            | −0.15                            | −0.11                            | Ed93         |
| HD 16673      | 0.10                             | 0.05                             | 0.19                             | Ed93         |
| HD 16895      | 0.08                             | −0.04                            | 0.01                             | Ed93         |
| HD 17548      | −0.43                            | −0.46                            | −0.42                            | Ed93         |
| HD 19994      | 0.18                             | 0.13                             | 0.18                             | Ed93         |
| HD 20807      | −0.05                            | −0.16                            | −0.08                            | Ed93         |
| HD 22001      | −0.01                            | −0.08                            | −0.19                            | Ed93         |
| HD 22484      | 0.00                             | −0.07                            | −0.01                            | Ed93         |
| HD 23754      | 0.16                             | 0.04                             | 0.11                             | Ed93         |
| HD 25621      | 0.16                             | 0.00                             | 0.15                             | Ed93         |
| HD 26491      | −0.08                            | −0.08                            | −0.05                            | Ed93         |
| HD 29645      | 0.16                             | −0.01                            | ...                              | Ed93         |
| HD 30562      | 0.22                             | 0.22                             | 0.27                             | Ed93         |
| HD 30649      | −0.40                            | −0.36                            | −0.13                            | Ed93         |
| HD 30743      | −0.21                            | −0.31                            | 0.02                             | Ed93         |
| HD 33256      | −0.14                            | −0.31                            | ...                              | Ed93         |
| HD 33608      | 0.37                             | 0.28                             | 0.26                             | Ed93         |
| HD 34411      | 0.09                             | −0.06                            | 0.11                             | Ed93         |
| HD 35296      | 0.10                             | 8.88                             | 0.18                             | Ed93         |
| HD 38393      | 0.00                             | −0.02                            | 0.06                             | Ed93         |
| HD 41330      | −0.07                            | −0.18                            | −0.09                            | Ed93         |
| HD 43042      | 0.12                             | −0.06                            | −0.05                            | Ed93         |
| HD 43318      | −0.03                            | −0.17                            | −0.03                            | Ed93         |
| HD 43947      | −0.19                            | −0.22                            | −0.16                            | Ed93         |
| HD 45701      | 0.20                             | 0.13                             | 0.11                             | Ed93         |
| HD 48938      | −0.26                            | −0.26                            | −0.17                            | Ed93         |
| HD 49933      | −0.27                            | −0.36                            | ...                              | Ed93         |
| HD 50223      | −0.04                            | −0.09                            | −0.13                            | Ed93         |
| HD 51530      | −0.38                            | −0.53                            | −0.30                            | Ed93         |
| HD 55575      | −0.21                            | −0.25                            | −0.08                            | Ed93         |
| HD 58551      | −0.40                            | −0.43                            | −0.27                            | Ed93         |
| HD 60532      | −0.07                            | −0.13                            | −0.09                            | Ed93         |
| HD 61421      | 0.05                             | −0.16                            | 0.01                             | Ed93         |
| HD 67228      | 0.14                             | 0.02                             | 0.12                             | Ed93         |
| HD 68284      | −0.41                            | −0.45                            | −0.23                            | Ed93         |
| HD 68456      | −0.15                            | −0.20                            | −0.08                            | Ed93         |
| HD 69611      | −0.40                            | −0.33                            | −0.15                            | Ed93         |
| HD 69897      | −0.12                            | −0.22                            | ...                              | Ed93         |
| HD 70110      | 0.12                             | 0.1                              | 0.00                             | Ed93         |
| HD 74011      | −0.46                            | −0.37                            | −0.25                            | Ed93         |
TABLE 3—Continued

| Star     | [Fe/H]_{NLTE} | [Ca/H]_{NLTE} | [Mg/H]_{NLTE} | EW Reference |
|----------|---------------|---------------|---------------|--------------|
| HD 76151 | 0.10          | -0.12         | 0.04          | Ed93         |
| HD 79028 | 0.00          | -0.20         | 0.05          | Ed93         |
| HD 82328 | -0.05         | -0.10         | -0.13         | Ed93         |
| HD 84737 | 0.15          | 0.08          | 0.11          | Ed93         |
| HD 86728 | 0.20          | 0.15          | 0.21          | Ed93         |
| HD 87141 | 0.15          | -0.04         | 0.06          | Ed93         |
| HD 88737 | 0.26          | 0.11          | 0.20          | Ed93         |
| HD 88986 | 0.04          | 0.01          | 0.08          | Ed93         |
| HD 89125 | -0.24         | -0.34         | ...           | Ed93         |
| HD 89744 | 0.28          | 0.14          | 0.20          | Ed93         |
| HD 91752 | -0.13         | -0.23         | ...           | Ed93         |
| HD 91889 | -0.11         | -0.17         | -0.13         | Ed93         |
| HD 95128 | 0.04          | 0.00          | 0.03          | Ed93         |
| HD 95241 | -0.16         | -0.21         | -0.16         | Ed93         |
| HD 98553 | -0.28         | -0.30         | -0.31         | Ed93         |
| HD 98991 | 0.00          | -0.14         | ...           | Ed93         |
| HD 99747 | -0.36         | -0.42         | ...           | Ed93         |
| HD 102574 | 0.22         | 0.13          | 0.19          | Ed93         |
| HD 102634 | 0.30         | 0.14          | 0.20          | Ed93         |
| HD 102870 | 0.22         | 0.10          | 0.08          | Ed93         |
| HD 107113 | -0.52        | -0.53         | -0.32         | Ed93         |
| HD 107213 | 0.36         | 0.18          | 0.35          | Ed93         |
| HD 108309 | 0.15         | 0.12          | 0.08          | Ed93         |
| HD 108954 | 0.00         | -0.09         | ...           | Ed93         |
| HD 110897 | -0.05        | -0.20         | -0.12         | Ed93         |
| HD 112164 | 0.32         | 0.18          | 0.26          | Ed93         |
| HD 121370 | 0.05         | -0.24         | -0.07         | Ed93         |
| HD 124570 | 0.35         | 0.26          | 0.37          | Ed93         |
| HD 125184 | 0.17         | 0.00          | 0.11          | Ed93         |
| HD 128167 | 0.29         | -0.16         | 0.02          | Ed93         |
| HD 128620 | 0.23         | 0.14          | 0.10          | Ed93         |
| HD 127334 | 0.16         | 0.14          | 0.18          | Ed93         |
| HD 130551 | 0.27         | -0.43         | -0.38         | Ed93         |
| HD 130551 | 0.20         | 0.14          | 0.22          | Ed93         |
| HD 131117 | 0.22         | 0.18          | 0.20          | Ed93         |
| HD 134169 | 0.05         | -0.16         | 0.02          | Ed93         |
| HD 136064 | 0.23         | 0.14          | 0.10          | Ed93         |
| HD 141004 | 0.16         | 0.14          | 0.18          | Ed93         |
| HD 142860 | 0.05         | -0.24         | -0.07         | Ed93         |
| HD 142860 | 0.20         | 0.14          | 0.22          | Ed93         |
| HD 142860 | 0.05         | -0.50         | -0.41         | Ed93         |
| HD 143761 | 0.22         | 0.18          | 0.20          | Ed93         |
| HD 144172 | 0.05         | -0.16         | 0.02          | Ed93         |
| HD 144585 | 0.23         | 0.14          | 0.10          | Ed93         |
| HD 148211 | 0.29         | 0.26          | 0.23          | Ed93         |
| HD 148816 | 0.47         | 8.88          | -0.29         | Ed93         |
| HD 150177 | 0.51         | 0.47          | -0.36         | Ed93         |
| HD 150453 | 0.40         | 0.51          | -0.40         | Ed93         |
| HD 151769 | 0.23         | 0.27          | -0.29         | Ed93         |
| HD 153597 | 0.15         | -0.01         | ...           | Ed93         |
| HD 155358 | 0.04         | -0.19         | -0.06         | Ed93         |
| HD 156098 | 0.39         | -0.33         | -0.26         | Ed93         |
| HD 157089 | 0.32         | -0.19         | -0.05         | Ed93         |
| HD 159307 | 0.54         | 0.56          | -0.44         | Ed93         |
| HD 160032 | 0.16         | -0.27         | -0.10         | Ed93         |
| Star        | [Fe/H]$_{\text{NLTE}}$ | [Ca/H]$_{\text{NLTE}}$ | [Mg/H]$_{\text{NLTE}}$ | EW Reference |
|------------|------------------------|------------------------|------------------------|--------------|
| HD 160933  | −0.20                  | −0.23                  | −0.18                  | Ed93         |
| HD 162396  | −0.24                  | −0.31                  | •                      | Ed93         |
| HD 163989  | −0.05                  | −0.13                  | −0.03                  | Ed93         |
| HD 165908  | −0.40                  | −0.53                  | −0.34                  | Ed93         |
| HD 168151  | −0.19                  | −0.31                  | −0.20                  | Ed93         |
| HD 169830  | 0.20                   | 0.07                   | 0.18                   | Ed93         |
| HD 173667  | −0.06                  | −0.06                  | •                      | Ed93         |
| HD 174913  | −0.42                  | −0.39                  | −0.28                  | Ed93         |
| HD 175317  | 0.25                   | 0.15                   | 0.09                   | Ed93         |
| HD 177565  | 0.07                   | 0.07                   | 0.11                   | Ed93         |
| HD 181096  | −0.13                  | −0.24                  | −0.10                  | Ed93         |
| HD 184499  | −0.59                  | −0.34                  | −0.19                  | Ed93         |
| HD 187013  | −0.06                  | −0.07                  | 0.03                   | Ed93         |
| HD 187691  | 0.18                   | 0.07                   | 0.12                   | Ed93         |
| HD 193307  | −0.22                  | −0.25                  | −0.25                  | Ed93         |
| HD 196378  | −0.30                  | −0.32                  | −0.27                  | Ed93         |
| HD 198084  | 0.18                   | 0.02                   | 0.20                   | Ed93         |
| HD 199289  | −0.86                  | −0.76                  | −0.55                  | Ed93         |
| HD 199623  | −0.21                  | −0.31                  | −0.35                  | Ed93         |
| HD 200790  | 0.03                   | −0.14                  | −0.01                  | Ed93         |
| HD 201099  | −0.39                  | −0.38                  | −0.27                  | Ed93         |
| HD 201877  | −0.87                  | −0.77                  | −0.59                  | Ed93         |
| HD 205294  | −0.21                  | −0.30                  | −0.26                  | Ed93         |
| HD 207978  | −0.45                  | −0.50                  | −0.38                  | Ed93         |
| HD 208906  | −0.58                  | −0.59                  | −0.53                  | Ed93         |
| HD 210752  | −0.47                  | −0.51                  | −0.44                  | Ed93         |
| HD 210855  | 0.18                   | 0.04                   | 0.23                   | Ed93         |
| HD 215257  | −0.44                  | −0.54                  | −0.51                  | Ed93         |
| HD 215648  | −0.21                  | −0.29                  | −0.06                  | Ed93         |
| HD 216385  | −0.18                  | −0.35                  | −0.12                  | Ed93         |
| HD 217014  | 0.16                   | 0.05                   | 0.24                   | Ed93         |
| HD 218470  | −0.04                  | −0.11                  | −0.01                  | Ed93         |
| HD 218504  | −0.46                  | −0.42                  | −0.24                  | Ed93         |
| HD 222368  | −0.10                  | −0.20                  | −0.01                  | Ed93         |
| HD 59984   | −0.62                  | −0.69                  | −0.37                  | J99          |
| HD 61902   | −0.59                  | −0.54                  | −0.47                  | J99          |
| HD 63077   | −0.66                  | −0.59                  | −0.40                  | J99          |
| HD 63598   | −0.73                  | −0.57                  | −0.45                  | J99          |
| HD 78747   | −0.61                  | −0.44                  | −0.25                  | J99          |
| HD 79601   | −0.53                  | −0.38                  | •                      | J99          |
| HD 97320   | −1.02                  | −0.96                  | −0.76                  | J99          |
| HD 111971  | −0.58                  | −0.58                  | −0.50                  | J99          |
| HD 126793  | −0.63                  | −0.49                  | −0.28                  | J99          |
| HD 152924  | −0.57                  | −0.44                  | −0.39                  | J99          |
| HD 189558  | −0.94                  | −0.74                  | −0.59                  | J99          |
| HD 193901  | −0.90                  | −0.86                  | −0.85                  | J99          |
| HD 194598  | −0.96                  | −0.91                  | −0.85                  | J99          |
| HD 196892  | −0.85                  | −0.72                  | −0.58                  | J99          |
| HD 203608  | −0.52                  | −0.60                  | −0.39                  | J99          |
| M92-18     | −2.45                  | −2.23                  | −2.46                  | B98          |
| M92-21     | −2.38                  | −2.14                  | −2.57                  | B98          |
| M92-34     | −2.43                  | −2.33                  | −2.33                  | B98          |
| M92-46     | −2.41                  | −2.15                  | −2.84                  | B98          |
| M92-60     | −2.40                  | −1.98                  | −2.53                  | B98          |
| M92-350    | −2.38                  | −1.94                  | −2.24                  | B98          |
| BD +2 3375 | −2.29                  | −1.91                  | −1.77                  | ZM90         |
| BD +3 740  | −2.50                  | −2.11                  | −2.34                  | ZM90         |
| BD +17 4708 | −1.54               | −1.32                  | −1.31                  | ZM90         |
| HD 16031   | −1.56                  | −1.36                  | −1.33                  | ZM90         |
| HD 19445   | −1.88                  | −1.79                  | −1.47                  | ZM90         |
| HD 34328   | −1.42                  | −1.25                  | −0.95                  | ZM90         |
| HD 59392   | −1.44                  | −1.25                  | −1.20                  | ZM90         |
| HD 74000   | −1.83                  | −1.44                  | −1.60                  | ZM90         |
| HD 84937   | −1.86                  | −1.79                  | −1.79                  | ZM90         |
| HD 116064  | −1.87                  | −1.50                  | −1.51                  | ZM90         |
| HD 140283  | −2.21                  | −2.14                  | −2.17                  | ZM90         |
| HD 160617  | −1.48                  | −1.42                  | −1.39                  | ZM90         |

**TABLE 3—Continued**
| Star      | [Fe/H]_{NLTE} | [Ca/H]_{NLTE} | [Mg/H]_{NLTE} | EW Reference |
|-----------|---------------|---------------|---------------|--------------|
| HD 166913 | −1.46         | −1.25         | −1.25         | ZM90         |
| HD 181743 | −1.71         | −1.63         | −1.19         | ZM90         |
| HD 213657 | −1.75         | −1.55         | −1.68         | ZM90         |
| BD −21 3420 | −0.88        | −0.77         | −0.76         | NS97         |
| CD −33 3337 | −1.16        | −1.2          | −1.06         | NS97         |
| CD −45 3283 | −0.72        | −0.71         | −0.80         | NS97         |
| CD −47 1087 | −0.64        | −0.51         | −0.28         | NS97         |
| CD −57 1633 | −0.73        | −0.78         | −0.90         | NS97         |
| CD −61 0282 | −0.97        | −0.92         | −1.06         | NS97         |
| G 005-040 | −0.68         | −0.54         | −0.38         | NS97         |
| G 046-031 | −0.61         | −0.68         | −0.66         | NS97         |
| G 088-040 | −0.64         | −0.64         | −0.42         | NS97         |
| G 102-020 | −0.93         | −0.78         | −0.81         | NS97         |
| HD 3567  | −1.05         | −1.01         | −1.15         | NS97         |
| HD 17288  | −0.75         | −0.6          | −0.51         | NS97         |
| HD 17820  | −0.54         | −0.42         | −0.11         | NS97         |
| HD 22879  | −0.67         | −0.54         | −0.33         | NS97         |
| HD 24339  | −0.48         | −0.52         | −0.17         | NS97         |
| HD 25704  | −0.68         | −0.60         | −0.51         | NS97         |
| HD 76932  | −0.73         | −0.58         | −0.29         | NS97         |
| HD 83220  | −0.40         | −0.46         | −0.39         | NS97         |
| HD 103723 | −0.61         | −0.62         | −0.77         | NS97         |
| HD 105004 | −0.64         | −0.71         | −0.60         | NS97         |
| HD 106038 | −1.07         | −1.02         | −0.96         | NS97         |
| HD 113083a | −0.78        | −0.68         | −0.77         | NS97         |
| HD 113083b | −0.76        | −0.66         | −0.68         | NS97         |
| HD 113679 | −0.45         | −0.29         | −0.037        | NS97         |
| HD 120559 | −0.78         | −0.61         | −0.43         | NS97         |
| HD 121004 | −0.57         | −0.40         | −0.17         | NS97         |
| HD 126681 | −0.96         | −0.81         | −0.79         | NS97         |
| HD 241253 | −0.87         | −0.83         | −0.77         | NS97         |
| W7547     | −0.30         | −0.35         | −0.20         | NS97         |
| HD 45865  | −0.54         | −0.64         | ...           | North        |
| HD 147609 | −0.36         | −0.29         | ...           | North        |
| HD 99383  | −1.36         | −1.60         | ...           | Pet86        |
| BD +26 3578 | −2.02        | −1.78         | −1.36         | Pet76        |
| BD +34 2476 | −1.80        | −1.59         | −1.10         | Pet78        |
| HD 64090  | −1.52         | −1.47         | −1.32         | Pet78        |
| HD 94028  | −1.31         | −1.25         | −1.03         | Pet78        |
| HD 97916  | −0.86         | −0.75         | −1.06         | Pet78        |
| HD 108177 | −1.51         | −1.49         | −1.13         | Pet78        |
| HD 103095 | −1.19         | −1.01         | ...           | Pet79        |
| BD −33 1173 | −2.69        | −2.3          | −2.29         | R91          |
| BD −13 3442 | −2.72        | −2.24         | −2.34         | R91          |
| CD −71 1234 | −2.05        | −1.83         | −2.17         | R91          |
| L56-75    | −2.41         | −2.20         | −2.21         | R91          |
| L635-14   | −2.18         | −1.93         | −2.14         | R91          |
| L732-48   | −2.08         | −2.09         | ...           | R91          |
| L815-43   | −2.64         | −2.22         | ...           | R91          |
| L831-70   | −2.85         | −2.42         | −2.25         | R91          |
| LR 740    | −2.16         | −1.96         | −1.75         | R91          |
| HD 6582   | −0.56         | −0.55         | −0.52         | Tom85        |
| Sun       | 0             | 0             | 0             | ...          |

**References.** (C97) Carney et al. 1997; (Ed93) Edvardsson et al. 1993; (J99) Jehin et al. 1999; (B90) Boesgaard et al. 1998; (ZM90) Zhao & Magain 1990; (NS97) Nissen & Schuster 1997; (North) North et al. 1994; (Pet86) Perrin 1986; (Pet76) Peterson 1976; (Pet78) Peterson 1978; (Pet79) Peterson & Carney 1979; (R91) Ryan et al. 1991; (Tom85) Tomkin et al. 1985.
The main goal of this procedure is to have a homogeneous table of derived non-LTE abundances. Results are presented in Table 3 for Ca and Mg. Figure 3 shows the abundance ratios [Ca/Fe] and [Mg/Fe] for halo and disk phases, presenting parallel structures in both evolutive diagrams.

Errors are hard to estimate because they involve many factors, as described previously. We estimated the uncertainties in our abundance determinations caused by the scatter on derived abundances when varying different parameters: stellar (log \( T_{\text{eff}} \), log \( g \), and [Fe/H]) and observational (EW). Figure 4 shows the percentage errors on log \( N_{\text{Ca}} \) and log \( N_{\text{Mg}} \) abundances, corresponding to an incertitude in a given atmospheric parameter. These error estimates are made for a star of log \( g \) = 4.2, and [Fe/H] = -2.0, for different abundance ratios [Ca/Fe] and [Mg/Fe], for the Ca I and Mg I lines of Table 2. We see that abundance variations are, on the average, more sensitive to uncertainties in \( T_{\text{eff}} \), reaching a maximum of 2.2% for some Ca I lines. We note that, in the case of log \( g \) and [Fe/H], the scatters adopted are the classical LTE errors, so the abundance errors can be overestimated.

A similar analysis is made for EW uncertainties using the same Ca I and Mg I lines. Figure 5 shows the percentage errors in EW if we have errors in abundance ratios of the order of the structure separations (\( \pm 0.15, 0.2 \) dex in the halo phase) displayed in Figure 3. For example, the EWs of Ca I 4578.56 Å and Mg I 4571.1 Å lines from Zhao & Magain 1990 have, respectively, errors of 40% and 75% when [Ca/Fe] and [Mg/Fe] have variations between 0.15 and 0.2 dex. The magnitudes of these uncertainties are much greater than the observational errors estimated by EW sources, demonstrating that these structures can be real.

Figure 3 confirms that effects of data renormalization as sources of these structures can be discarded since the data of distinct sources are distributed in different parallel structures. As mentioned above, scattering in abundances is sensitive to temperature variations; however, this effect seems to be not strong enough to form these structures, as can be seen in Figure 6, which shows no correlation between abundance ratios and temperatures.

One should also keep in mind that such uncertainties in \( T_{\text{eff}} \) or log \( g \) result in variations in iron abundances of the same magnitude and sign as for Ca and Mg abundances, which minimizes uncertainties in the abundance ratios. Thus, one can say that the ratios [Ca/Fe] and [Mg/Fe] are less sensitive to these uncertainties on the stellar fundamental parameters.

4. DISCUSSION

The two non-LTE chemical diagrams in Figure 3 show that the chemical enrichment of the matter in our Galaxy may not be as simple as currently accepted. On the [Ca/Fe] diagram, parallel structures appear: (1) the halo phase shows three well-defined structures separated by \( \pm 0.15 \) dex and some very Ca-deficient stars, and (2) in the disk phase \( \pm 0.7 \) dex and no well-defined structures can be seen at least at four structures. This behavior is also present in the intermediate phase of the Galaxy \( \pm 1.2 \) dex and only on three incurved structures.

The [Mg/Fe] diagram shows the same structures but with a greater scatter. This scatter could be essentially the result of two facts: first, measured EWs for magnesium lines are more imprecise (there are fewer clean weak lines in observed spectra) than for calcium lines, and second, there are some differences between the mechanisms of Mg and Ca yield production by SNe II of distinct progenitor masses. Figure 7 shows a pronounced scatter in the [Mg/H] and [Ca/H] relation in the halo phase.

Clearly, the structures pointed out by Nissen & Schuster (1997) and Jehin et al. (1999) are present in our calcium and magnesium diagrams and now extend to the disk and halo phases of our Galaxy. Flat structures of [\( \alpha / H \)] ratios versus [Fe/H] are consistent with the idea that both elements come from massive supernovae. The question is how field star formation can produce these structures if, at first, halo stars were formed independently throughout the entire protogalaxy.

Such structures and dichotomy also exist in globular clusters, as has been demonstrated more than 15 years ago. Calcium branch dichotomy in \( \omega \) Cen revealed possible self-enrichment due to SNe II, suggesting two epochs of star formation separated by a hiatus. Detailed discussion by Norris, Freeman, & Mighell (1996) rejects with convincing arguments a merger origin of the dichotomy of [Ca/H] abundances in globular clusters. Another intriguing coincidence is the bimodality of C and N abundances on the main sequence of 47 Tuc (Cannon et al. 1998). As suggested by the authors, a hybrid accretion-enrichment model could help to explain how globular clusters form and the role played by stellar winds and those of SNe II. Recently Boesgaard et al. (1998) have observed six turnoff stars in M92, an old very metal-poor cluster. Keeping in mind that the quality of the spectra is low, producing large uncertainties in possible derived chemical abundances from them, we derived non-LTE abundances for iron, calcium, and magnesium. As an exercise, we plotted the Ca and Mg ratios for these six stars on our diagram and discovered after renormalization that they lie at exactly the same places as for halo stars. To conclude that this is more than a coincidence is premature but raises an interesting possibility: a common origin for field and globular cluster stars. If such observations could be repeated in other globular clusters for main-sequence stars with better signal-to-noise ratios (S/Ns), then they would probably help greatly in the understanding of the formation of the Galaxy. Possible consequences could also be derived concerning the first stars in the protogalaxy as discussed by Cayrel (1986).

Another possible scenario of the formation of the Galaxy that can produce these structures in the halo phase is an incomplete mixing of SN II yields, as suggested by Karlsson & Gustafsson (2000). In an even more recent paper, Argast et al. (1999) have explored this scenario in more detail. Surprisingly, the model proposed by Argast et al. produces structures in the [Ca/Fe] and [Mg/Fe] diagrams ([Fe/H] < -1.5) similar to ours, as shown in Figure 3. Their theoretical [Mg/Fe] diagram also shows greater scatter than the [Ca/Fe] diagram, suggesting that the origin of this difference is mainly the yield production mechanism (see Argast et al. 1999 for more details), as mentioned in the second paragraph of this section.

For the disk phase, observed structures have a smaller separation and are more evident in the [Ca/Fe] diagram than in the [Mg/Fe] diagram. One interesting question is how can chemical evolution models reproduce this result for disk metal-rich stars? Is it that the mixing timescale of enriched gas was larger than the formation time of each generation of stars in the disk, as supposed for the halo
phase? Observations of open cluster stars could verify whether they have similar behavior to globular cluster stars.

5. CONCLUSIONS

We report here non-LTE differential abundances for 252 subdwarf to subgiant stars using published high-resolution equivalent widths. [Ca/Fe] and [Mg/Fe] diagrams show remarkable structures in both the halo and disk phases of the Galaxy, which are not related to observational or atmospheric parameter uncertainties. These results lead us to a possible evolutive galactic scenario of nonhomogeneity or incomplete mixing of synthesized SN II yields (Karlsson & Gustafsson 2000; Argast et al. 1999). A surprising result is the behavior of M92 stars, mainly in the Ca diagram, suggesting a common origin for field and cluster stars. Spectroscopic high resolution with good S/N of stars in clusters is needed to confirm or refute the sketch of a new chemical evolution model presented in this work. New non-LTE analysis for other α-elements is also necessary to verify whether this structural behavior applies to all α-capture SN II products.

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