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NLTE analysis of Mn and Co in metal-poor stars

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Abstract
We analyse the statistical equilibrium of Mn and Co in the atmospheres of subdwarfs and subgiants of different metallicities. Significant departures from local thermodynamic equilibrium (LTE) level populations are found for the neutral ions. They are related to overionization in Co I; deviations from LTE in Mn I are due to the strong radiative processes in discrete transitions as long as the solar metallicities and temperatures are considered.
In environments where the radiation field is amplified, such as metal-poor stars with solar or supersolar effective temperatures, overionization in Mn I is the dominant process.
The ground states of the singly ionized species are almost unaffected by non-local thermodynamic equilibrium (NLTE). Differential analyses of Mn and Co is carried out for 18 stars in the metallicity range $-2.5 < [\mathrm{Fe/H}] < 0$. The abundances are derived by the method of spectrum synthesis. The NLTE abundances of Mn and Co in metal-poor stars are higher than the LTE abundances. The difference $[\mathrm{El/Fe}]_{\mathrm{NLTE}} - [\mathrm{El/Fe}]_{\mathrm{LTE}}$ increases with decreasing [Fe/H] and reaches 0.4 dex for Mn and 0.6 dex for Co in the most metal-poor stars. [Mn/Fe] is slightly subsolar all over the metallicity range studied here; [Co/Fe] ratios steadily increase with decreasing Fe abundances in halo and thick-disc stars.

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(Some figures in this article are in colour only in the electronic version.)

1. Introduction

The chemical composition of low-mass metal-poor stars in the Milky Way is a subject of increased interest. This interest is mainly stipulated by the correlation of surface element abundances with the age of such stars. This correlation is not a coincidence: old low-mass stars were born soon after the initial formation of the Galaxy, which was at that times poor in chemical elements heavier than He, the so-called metals. As time passed, more and more massive stars exploded as supernovae (SNe) and enriched the interstellar medium in the Galaxy with elements from C to U. The star formation in the Galaxy went on, and next generations of stars of different masses have been born in the continually changing interstellar medium (ISM). The low-mass stars are evolving very slowly, and even after several gigayears their atmospheres are still untouched by the processes of nuclear fusion that takes place in the stellar cores. Thus, such stars carry the same chemical composition as the ISM at that epoch of their formation. Knowing the mechanisms, which produce the chemical elements in the Milky Way, carry them to the ISM and recycle them, one can reconstruct galactic chemical evolution.

The abundances of elements in stellar photospheres can be derived only by means of high-resolution spectroscopy. However, it is not only the spectral resolution of an instrument that determines the accuracy of the abundances. By definition, any parameter determined from stellar spectra is strongly model-dependent because it implies fitting the available physical models to the observations. One of the most important issues in the modelling is the description of an excitation–ionization equilibrium of elements in a stellar

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atmosphere. The choice of local thermodynamic equilibrium (LTE) or non-local thermodynamic equilibrium (NLTE) depends on the aims of the research. However, when one studies the formation of spectral lines and wants to derive a photospheric abundance of an element, more physically accurate assumption of NLTE is absolutely necessary.

The majority of heavy elements, mainly due to their complex atomic structure, have not been studied in NLTE. Among others, these are the iron 'relatives'—Mn, Co, Cr. Nissen *et al* (2000) proposed that Mn abundances might be subject to NLTE effects due to overionization by a strong radiation field. Other researchers encountered problems with excitation and ionization equilibria of Mn and Co in metal-poor stars. The discrepancy of ∼0.4 dex between Mn abundances in metal-poor stars derived from strong and weak lines are reported by Cayrel *et al* (2004). Later, Lai *et al* (2008) confirmed it but did not specify the magnitude of the discrepancy. According to Johnson (2002), manganese abundances derived from Mn II lines are systematically higher than abundances derived from Mn I lines. The failure to satisfy excitation and ionization equilibria of the elements is the most common problem of LTE.

An additional complication arises for odd-*Z* Fe-peak elements Mn and Co. The unpaired nucleon in the nucleus results in a net spin, which interacts with the angular momentum of the electrons that leads to splitting of fine structure lines into hyperfine structure (HFS) components. The importance of HFS on profile shapes was recognized long ago. Abt (1952) noted that if the solar Mn I line at 5420 Å was modelled without HFS, one would need a temperature of 96 000 K or a turbulent velocity of 5.5 $\mathrm{km\,s^{-1}}$ to fit it. Only few authors take into account HFS of Fe-peak in the analyses (del Peloso *et al* 2005, McWilliam *et al* 2003); others neglect it and provide numerous reasons to justify their choice.

However, the importance of these studies must not be underestimated. All authors produced a very interesting result: Mn is strongly depleted relative to Fe in metal-poor stars (Gratton 1989, Nissen *et al* 2000, Sobeck *et al* 2006), whereas Co is nearly solar (Gratton and Sneden 1991) and even supersolar (Cayrel *et al* 2004) in the most metal-poor stars. Present theories of element production in massive and intermediate-mass stars do not provide a simultaneous explanation to both trends (François *et al* 2004, Timmes *et al* 1995). The interpretation of the abundances in metal-poor stars in terms of element nucleosynthetic origin is still rather controversial.

In the current paper, we investigate the statistical equilibrium of Co in the Sun and metal-poor stars and compare it with that of Mn. The NLTE abundances are derived for a sample of 18 stars. For Mn, we extend the list of stars from paper I with three stars of the thick disc. The resulting trends of [Mn/Fe] and [Co/Fe] as a function of [Fe/H] are analysed.

2. Spectra, models of atmospheres and stellar parameters

Our stellar sample includes the Sun, 1 star of the thin disc (Procyon), 4 thick-disc stars and 12 stars of the Galactic halo. The population membership is taken from Gehren *et al* (2006). The solar abundance analysis is carried out with the Kitt Peak Solar Flux Atlas (Kurucz *et al* 1984). For the other stars, spectra obtained with the ESO Ultraviolet and Visual Echelle Spectrograph (VLT UT2, Chile) and with the FOCES echelle spectrograph (2.2 m telescope, Calar-Alto Observatory) are used. The spectra for Procyon, HD 84937, and HD 122563 were taken from the UVESPOP survey (Bagnulo *et al* 2003). The resolution of UVES spectra is ∼80 000 and $S/N \sim 300$ at 5000 Å. The FOCES spectra have $R \sim 60\,000$ and $S/N \sim 200$ at 5000 Å.

Table 1. Parameters for the selected sample of stars.

Object	HIP	$T_{\rm eff}$ (K)	$\log g$	ξ_t ($\mathrm{km\,s^{-1}}$)	[Fe/H]
HD 19445	14594	5985	4.39	1.5	−1.96
HD 25329	18915	4800	4.66	0.6	−1.84
HD 29907	21609	5573	4.59	0.9	−1.60
HD 34328	24316	5955	4.47	1.3	−1.66
HD 61421	37279	6510	3.96	1.8	−0.03
HD 84937	48152	6346	4.00	1.8	−2.16
HD 102200	57360	6120	4.17	1.4	−1.28
HD 103095	57939	5110	4.69	1.0	−1.35
BD−4°3208	59109	6310	3.98	1.5	−2.23
HD 122196	68464	5957	3.84	1.7	−1.78
HD 122563	68594	4600	1.50	1.9	−2.51
HD 134169	74079	5930	3.98	1.8	−0.86
HD 148816	80837	5880	4.07	1.2	−0.78
HD 184448	96077	5765	4.16	1.2	−0.43
HD 140283	76976	5773	3.66	1.5	−2.38
G20-8	86443	6115	4.20	1.5	−2.19
HD 200580	103987	5940	3.96	1.4	−0.82

The same atmospheric models are used to calculate statistical equilibria of the elements and perform spectrum synthesis. These models are computed with the MAFAGS code (Fuhrmann *et al* 1997). The line blanketing is treated with opacity distribution functions from Kurucz (1992). However, the overall metal abundance in these opacity distribution functions is reduced by $[\mathrm{Fe/H}] = -0.16$. In addition, the models of halo and thick-disc stars have the α-element abundances enhanced by 0.4 dex. The stellar parameters for these models are taken from the analyses of Gehren *et al* (2004, 2006) and Fuhrmann (2004). In short, the effective temperatures for stars are determined from fitting H_α and H_β profiles. The surface gravities are calculated from HIPPARCHOS (ESA 1997) parallaxes and masses determined from the tracks of VandenBerg *et al* (2000). The iron abundances and microturbulent velocities were obtained from Fe II line profile fitting requiring that the derived Fe abundances are independent of the line strength. The average errors of [Fe/H], and ξ_t, are 0.05 dex and 0.2 $\mathrm{km\,s^{-1}}$, respectively. The basic stellar parameters for our stars are listed in table 1.

3. Statistical equilibrium of Mn and Co

3.1. NLTE calculations

The atomic model and NLTE calculations for Mn were presented in paper I (Bergemann and Gehren 2007), paper II (Blackwell-Whitehead and Bergemann 2007) and paper III (Bergemann and Gehren 2008). The papers discuss the mechanisms of departures from LTE and their effect on line

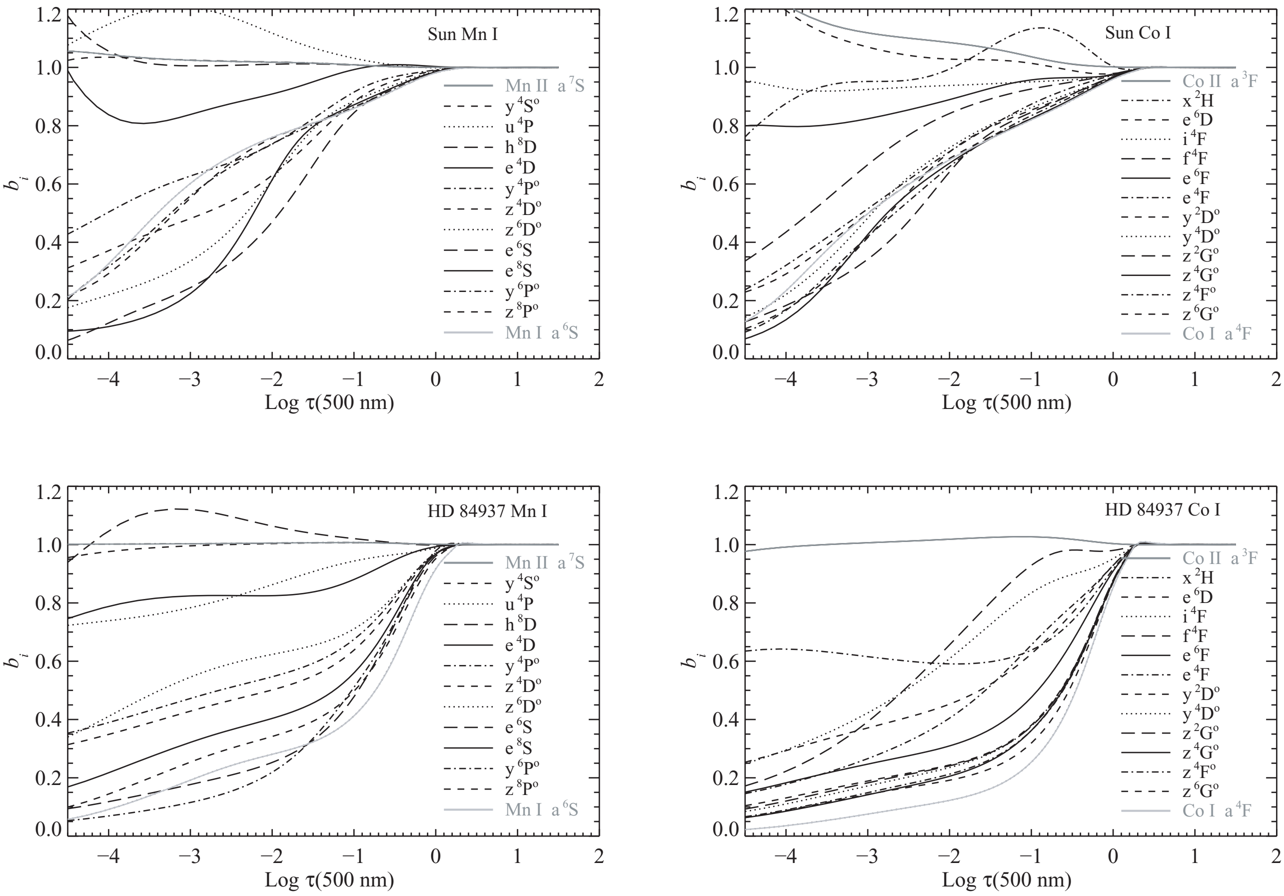

Figure 1. The departure coefficients b_i for selected levels of Mn I and Co I as a function of the optical depth log τ_{5000}: the solar model atmosphere (upper panels), the model of a metal-poor subdwarf HD 84937 (lower panel). The b-factors for the ground states of ionized species Mn II ($a\,^7$S) and Co II (a^3F) are also shown.

profiles and Mn abundances in the Sun and metal-poor stars. In short, the model of Mn atom includes two ionization stages with 245 levels of Mn I and the ground state of Mn II. That is, we neglect all excited states of Mn II (for the explanation, see papers II and III). Photoionization is treated in hydrogenic approximation. However, we use the effective principal quantum numbers to avoid the problem of extremely large photoionization rates from doubly excited configurations. The cross sections for inelastic collisions with hydrogen atoms are calculated with Drawin's formula in the version of Steenbock and Holweger (1984) and are by 'default' scaled with $S_{\rm H} = 0.05$.

The model of Co atom is constructed with energy levels and transition probabilities from Pickering and Thorne (1996) and Pickering *et al* (1998). The model is complete up to the ground state of Co III. The number of levels and transitions is 246 and 6027 for Co I and 165 and 2539 for Co II. The fine structure levels with $E < 6.80$ eV in Co I and $E < 6$ eV in Co II are treated explicitly in spectral energy (SE) calculations. At higher excitation energies, fine structure levels are combined into a single superlevel with the weighted mean of their excitation energies and statistical weights. The transitions between two combined superlevels are also grouped, and the oscillator strength of a superline is the average of $\log gf$'s weighted according to the appropriate lower-level statistical weights. We made sure that none of the lines used in the abundance analysis has either of its levels grouped.

The treatment of photoionization and inelastic collisions with hydrogen for Co atom is analogous to Mn (see above). The rates of discrete and ionization transitions due to collisions with electrons are calculated with the formulae of van Regemorter (1962), Allen (1973) and Seaton (1962). All NLTE computations are carried out with the revised version of DETAIL code (Butler and Giddings 1985), which is based on the method of accelerated lambda iteration (Rybicki and Hummer 1992).

3.2. Departure coefficients and NLTE mechanisms

Departure coefficients are defined here as $b_i = n_i^{\rm NLTE}/n_i^{\rm LTE}$. They provide all information required to understand the mechanisms, which lead to deviations from LTE in distibution of atomic level populations. The b-factors for Mn and Co levels calculated for the solar model are presented in figure 1 (upper panel). Only the levels typical for their depth dependence are shown. For comparison, the departure coefficients calculated with the model atmosphere corresponding to the metal-poor subdwarf HD 84937 are shown in figure 1 (lower panel). Both neutral ions are characterized by the underpopulation of all levels relative to the LTE ($b_i = 1$). NLTE mechanisms in Mn and Co reflect the known atomic properties of the elements, such as number and strength of transitions and energy separation of levels.

The basic NLTE processes for Mn were discussed in detail in papers I and III. Mn I is a mixed-domination

ion, where photoionization is not dominant, as long as solar metallicities and temperatures are considered. Line pumping (due to $J_\nu > B_\nu$) combined with very efficient collisional coupling to the Mn II ground state maintains the underpopulation of the levels. In the environment, where the radiation field is amplified, the photoionization dominates the distribution of Mn I level populations. The latter is the basic NLTE phenomenon in metal-poor stars (figure 1, (lower left)). The ground state of Mn II remains in LTE even in the solar photosphere. Although some excited states become overpopulated in the metal-poor atmospheres, the ionized lines form too deep to be affected by these deviations. We do not investigate the SE of Mn II here because it is not possible to analyze any of its lines in the solar spectrum.

The atomic level populations of Co I are also affected by NLTE, although in a less complex way than levels of Mn I. The main difference between ions is that the total number of transitions in Co I is by a factor of four larger than that in Mn I that maintains efficient radiative and collisional coupling between levels of different excitation energies. This coupling between majority of low- and intermediate-excitation levels is seen on the distribution of b-factors in figure 1 (upper right). The lines used in the abundance analysis are formed by transitions between the levels of 1–2 and 4–5 eV excitation; hence their source functions S_ν are close to the thermal values B_ν. The main effect of NLTE is a change of the line opacity, $\kappa_\nu \sim b_i$. For the majority of Co I levels, $b_i < 1$, so the lines under NLTE are weaker than those under LTE. The overall underpopulation of the levels is due to overionization. In the metal-poor stars, the effect of overionization is amplified (figure 1, (lower right)). The ground state of Co II a^3F is also affected by NLTE, although departures in the line formation region are not large.

4. Spectral lines and abundances

The abundances of Mn and Co are derived by means of spectrum synthesis using the SIU code. The solar profiles are broadened by the rotation velocity of 1.8 km s^{-1} and by the macroturbulence velocity, which is allowed to vary from 2.5 to 4 km s^{-1}. Depth-independent microturbulence velocities are assumed for the Sun and metal-poor stars. A solar ξ_t of 0.9 km s^{-1} is adopted. Van der Waals damping constants $\log C_6$ are calculated using the Anstee and O'Mara (1995) line broadening tables. A correction to these $\log C_6$'s was introduced for some multiplets of Mn I. HFS is accurately included in the spectrum synthesis of all lines of investigated elements. For the levels of Co I, we use the A and B magnetic dipole and electric quadrupole splitting constants measured by Pickering (1996). These data, together with the detailed list of parameters used for synthesis of Co lines, will be presented in a separate series of papers. All data necessary to synthesize Mn lines including HFS were presented in papers I, II and III.

To calculate the stellar element ratios, we use our solar $\log gf\varepsilon$ values. The abundances from Co I lines in metal-poor stars are calculated strictly relative to the Sun, i.e. $[\mathrm{El/H}] = \log(gf\varepsilon)^* - \log(gf\varepsilon)\odot$. The methods of differential analysis of stars relative to the Sun for Mn were described in detail in paper III. It is important to note that the near-UV triplet

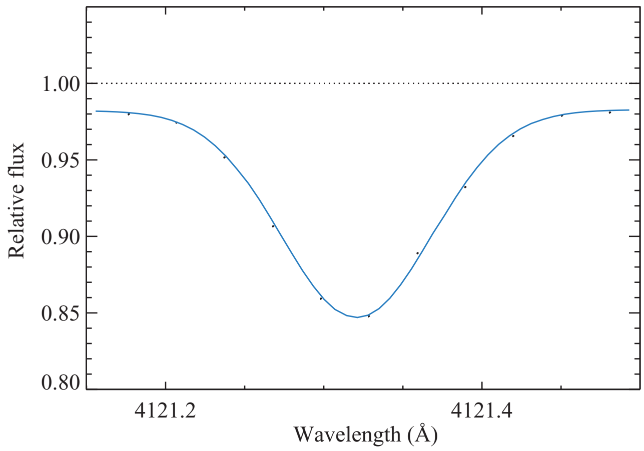

Figure 2. Synthetic NLTE profile (blue solid line) of the Co I line at 4121 Å, calculated with the model atmosphere of a metal-poor star HD 84937 with [Fe/H] = −2.16. The observed spectrum is shown with dots.

at 403 nm is not used for abundance analysis in the *solar spectrum* due to severe blending.

The Co abundances of stars with $-2 < [\mathrm{Fe/H}] < -1$ are based on three lines at 4020, 4110 and 4121 Å. In stars with $[\mathrm{Fe/H}] < -2$, only 4121 is analysed. This line is sufficiently strong even in the most metal-poor stars (see figure 2) so that uncertainty due to continuum placement is small. It is valuable to derive the abundances from the lines of Co II and Mn II; however, the differential analysis will not produce reliable abundances because in the solar spectrum the lines of both ionized species are located in the UV region, where the line opacity is at the maximum. At present, we will restrict the analysis to [Mn/Fe] and [Co/Fe] stellar ratios derived from the lines of neutral ions. The abundances derived from ionized species will be presented in future papers.

The results of calculations are presented in figure 3, where [Mn/Fe] and [Co/Fe] ratios calculated under NLTE and LTE are plotted as a function of a stellar iron abundance. The standard deviations σ of the Mn abundances are in the range 0.03 to 0.07 dex. For thick-disc stars, we get σ for [Co/Fe] of <0.04 dex in NLTE and up to 0.15 dex in LTE. For the halo stars, there is an unresolved discrepancy between NLTE abundances derived from two Co I lines, located in the near and far red wing of H_δ. This discrepancy amounts to ∼0.1 dex for the Sun, and increases to ∼0.2 dex in the metal-poor stars. After unsuccessfull attempts to ascertain the reason for the discrepancy, we decided to use both lines. No indications of this problem are found in the literature, mainly because there are very few *accurate* studies of Co abundances in metal-poor stars, and neither of those includes the discrepant line at 4110 Å. Two stars with very low [Co/Fe] ratios are HD 25329 and HD 103095 (Gmb 1830).

However, NLTE offers a solution to a long-standing discrepancy between the abundances derived from the Mn I resonance triplet at 403 nm and excited lines found in many LTE analyses of Mn in metal-poor stars (Cayrel *et al*, Johnson 2002, Lai *et al* 2008). Test calculations in the wide range of stellar parameteres show that the NLTE corrections for the triplet at 403 nm are especially high for models with $[\mathrm{Fe/H}] \leqslant -2.5$ and supersolar effective temperatures (up to 0.8 dex), whereas NLTE abundance corrections for other lines

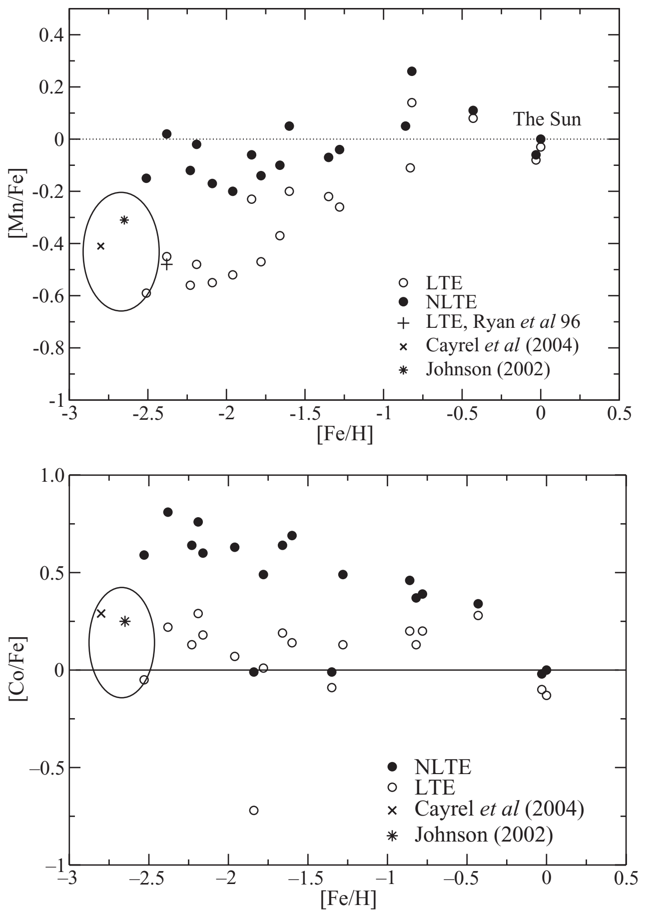

Figure 3. [Mn/Fe] and [Co/Fe] ratios as a function of [Fe/H]. NLTE and LTE abundances are marked with filled and empty circles, respectively. The large circles mark the abundances for the metal-poor giant HD 122563 derived by two other research groups Johnson (2002) and Cayrel *et al* (2004).

do not exceed 0.3–0.5 dex. Also, there is ∼0.2 dex difference in NLTE abundance corrections between the resonance and excited lines for the models with subsolar temperatures ($T_{\rm eff} \sim 5500$) and $[{\rm Fe/H}] \leqslant -3$. Thus, NLTE can solve the discrepancy in the analysis of metal-poor subdwarfs and subgiants. But we did not carry out test NLTE calculations for the extreme cases, such as giants, except for HD 122563. At present, it is unclear whether the large discrepancies between two line sets found by Johnson (2002) and Cayrel *et al* (2004) in their studies of giant stars are due to NLTE. More calculations will be performed to check this.

As seen in figure 3, the effects of overionization on Mn I and Co I atoms are significant in metal-poor atmospheres and they cannot be ignored. The NLTE abundances of Mn and Co in the metal-poor stars are *higher* than the LTE abundances by 0.3–0.6 dex. As a result, a strong underabundance of Mn with decreasing metallicity, as found in majority of previous LTE analyses (Cohen *et al* 2004, Nissen *et al* 2000, Prochaska and McWilliam 2000), is not present in NLTE calculations. Instead, only a slightly subsolar trend is observed.

The overabundance of cobalt relative to Fe shows already in the thick-disc stars and becomes very strong in halo stars. A majority of recent LTE studies also indicate that Co is overabundant with decreasing [Fe/H]. The analysis of stars with $-4 < [{\rm Fe/H}] < -2$ carried out by Cayrel *et al* (2004) indicates supersolar [Co/Fe] ratios; however, their study covers only giant stars. Therefore, the abundances may be a result of internal mixing in giants, and they may have nothing to do with the nucleosynthesis in the early Galaxy. Analysing extremely metal-poor giants and dwarfs in the same metallicity range as Cayrel *et al*, Lai *et al* (2008) also find high Co abundances relative to Fe. But their [Co/Fe] ratios show very large scatter from 0.04 to 0.69 dex, which is actually the difference between our LTE and NLTE abundance trends. Cohen *et al* (2004) derive the mean $[{\rm Co/Fe}] \sim +0.42$ for dwarfs with metallicities $-3.5 < [{\rm Fe/H}] < -2$.

A direct comparison of our [Mn/Fe] and [Co/Fe] trends with the above-mentioned is a very complicated task, even when NLTE corrections for the selected elements are applied. The inhomogeneous stellar samples, differences in the procedure of stellar parameter and abundance calculations lead to systematic offsets of different trends. There is just one common star in our analysis and analyses of the other authors, a giant HD 122563, which we included just for the purposes of a comparative analysis. The [Mn/Fe] and [Co/Fe] ratios for this star derived by Johnson (2002) and Cayrel *et al* (2004) are also shown in figure 3. We note that stellar parameters are very different between three studies: Cayrel *et al* adopted $T_{\rm eff} = 4600$, $\log g = 1.1$, $[{\rm Fe/H}] = -2.8$, Johnson used $T_{\rm eff} = 4450$, $\log g = 0.5$, $[{\rm Fe/H}] = -2.65$ and our values are $T_{\rm eff} = 4600$, $\log g = 1.5$, $[{\rm Fe/H}] = -2.53$ (Mashonkina *et al* 2008). This is the reason for the large deviation of our LTE [Co/Fe] and [Mn/Fe] abundances from the others. Model parameters of other stars can be even more discrepant.

Unfortunately, the NLTE trends cannot be explained by the current theories of element production in massive and intermediate-mass stars. And this is also due to the controversy over the physical conditions in the sites where the elements are produced. One can tune the SNe models to produce different amount of Fe-peak elements without disturbing the underlying physical principles. For example, the production of Fe-peak elements in SNe II is sensitive to the mass cut, explosion energy and the amount of mixing, which are usually free parameters in the calculations. Kobayashi *et al* (2006) emphasized that it is possible to find a combination of these parameters that would explain the trends for Mn and Co with Fe. However, no one has succeeded yet.

5. Conclusions

The distribution of Mn and Co atoms over excitation energies and ionization stages in stellar atmospheres is far from what the local thermodynamic equilibrium prescribes. The underpopulation of Mn I levels is powered by radiative transitions with strong optical pumping effects. Photoionization in its hydrogenic approximation is inefficient at solar metallicities, but dominates in metal-poor atmospheres. Co I level populations are affected by overionization. This is the only process, which also takes place in the metal-poor stars. The NLTE effects on element abundances in the solar atmosphere are small for Mn (∼0.02 dex), for Co the difference between LTE and NLTE solar abundance is 0.13 dex. For the solar-metallicity stars, the incorrect treatment of HFS leads to large errors in abundances. For the lines with saturated cores, the neglect of

HFS leads to an abundance overestimate by 50%. Even the weak lines are not free from HFS effects.

In the metal-poor stars, the discrepancy between LTE and NLTE abundances of Mn and Co becomes enormous. The difference $[El/Fe]_{NLTE} - [El/Fe]_{LTE}$ increases with decreasing [Fe/H] and reaches 0.4 dex for Mn and 0.6 dex for Co in the most metal-poor samples. As a result, we find slightly subsolar [Mn/Fe] all over the metallicity range studied here, and [Co/Fe] ratios steadily increase with decreasing Fe abundances in the halo and thick-disc stars. The NLTE trends are inconsistent with predictions of Galactic chemical evolution models (Kobayashi *et al* 2006, Timmes *et al* 1995). If the new trends are confirmed on a larger sample of stars and are consistent with abundances derived from ionized species, we would need a new theory of odd-*Z* Fe-peak element production in SNe II and SNe Ia. A hint at faults in the current nucleosynthesis theory is that it predicts qualitatively similar trends for [Co/Fe] and [Mn/Fe] (Timmes *et al* 1995), where both Mn and Co are underproduced with respect to Fe by SNe II. However, neither in our NLTE nor in *all* LTE studies, the general trend of Mn with iron is present for Co.

One should keep in mind, however, that an NLTE analysis of the Fe-peak in its present state is not perfect. The cross sections of reactions, which enter the equations of statistical equilibrium, are poorly known. For manganese and cobalt, reliable cross sections for photoionization are absent. The only available hydrogenic formula is an oversimplification. Test calculations show that increasing the rates of photoionization leads to *larger* abundances of Mn and Co as derived from lines in their neutral species, i.e. Mn I and Co I. The proper photoionization data may also solve a long-standing discrepancy between the abundance of Mn in the Sun and in meteorites: Mn seems to be depleted by ~30% in the solar photosphere when compared with CI chondrites. As an explanation, one could assume possible mineralogical processes in the parent meteoritic body, or a first ionization potential effect. However, the ambiguity in photoionization cross sections has to be solved first of all.

Acknowledgments

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Appendix: Discussion

Q: (Hans Ludwig) (1) Are the iron abundances derived assuming LTE or NLTE? (2) Did you consider to use the center-to-limb variation of the Co and Mn lines in the Sun to constrain S_H?

A: (1) The iron abundances are derived from LTE fitting of Fe II lines. (2) I have not used the center-to-limb variation, but will do so in the future.

Q: (Regner Trampedach) Is the Hδ line wing included as part of the continuum for the Co I calculations?

A: Yes, it is included in the spectrum synthesis.

Q: (Bengt Edvardsson) You indicated problems to reconcile abundances between two lines of the same Co I multiplet in the wing of Hδ in the Sun. Did you check the absolute flux in the region from your MAFAGS-OFD solar model with the observed flux? Even if you have a perfect fit using normalized spectra, the abundances may be wrong (e.g. due to errors in the background continuum opacity).

A: There are discrepancies with the absolute observed solar fluxes at $\lambda < 4000$ Å (see Grupp 2004). However, the problems are not solved by using OS models with the new Fe bf opacities.

Q: (Bob Kurucz) Did you determine abundances from Co II lines for your low-abundance stars?

A: I have not calculated them yet. Small NLTE abundance corrections for intermediate-excitation lines can be expected.

Q: (Jeff Linsky) You have done important work showing that NLTE abundances can be very different from LTE abundances. My concern is that the many LTE abundances published in the literature that include only random errors (due to uncertain oscillator strengths, the temperature structure etc.) are deceptive because the systematic errors due to not including NLTE effects can be much larger, with different trends with metallicity as your calculations for Co and Mn show. Any comments on this?

A: NLTE calculations are not perfect, but they give the true estimate of abundance errors, compared to the LTE approach. The latter cannot give any guarantee about its reliability and accuracy: very seldom we see that LTE produces problems in excitation/ionization equilibria of elements (in most cases this is rather a problem of 'proper' line selection). But when we perform NLTE calculations, we see how large NLTE corrections are. This is the case with Mn, and I expect large NLTE corrections for Cr and Ti. At least, for the latter two elements we know for sure that there are some discrepancies between abundances derived from neutral and ionized lines when assuming LTE.

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