NLTE Analysis of Neutral Magnesium in Cool Stars

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Abstract: The calculations of the statistical equilibrium of magnesium in the solar photosphere have shown that NLTE populations hardly affect Mg line formation in the Sun. However, in metal-poor stars and giants the influence of electron collisions is reduced, and a ultraviolet radiation field enhanced due to smaller background line opacity results in more pronounced NLTE effects. In the photosphere of a cool star excitation and ionization due to collisions with neutral hydrogen can outweigh electron collisions. Therefore the influence of different types of collisional interactions with electrons and neutral hydrogen atoms is examined. Thus analyses based on NLTE populations lead to significantly higher Mg abundances than those calculated from LTE. For stars of metallicity between $-2.0 <$ [Fe/H] < -1.0 abundance corrections $\Delta[Mg/H]_{NLTE-LTE} \sim$ 0.05-0.11 is found. We also found that $\Delta[Mg/H]_{NLTE-LTE}$ increase with the effective temperature increasing from 5000–6500 K. For extreme metal-poor stars the abundance corrections approaches $\Delta[Mg/H]_{NLTE-LTE} \sim 0.19$ at [Fe/H] ~ -3.0.

1 Introduction

The determination of the abundances of the light elements in stars of differing metallicities is important for understanding the chemical evolution of the Milky Way. The first stellar generations are supposed to produce mostly α-elements during massive supernova events of type II. This is observed as a super-solar Mg/Fe abundance ratio in very metal-poor stars, [Mg/Fe] $= +0.3 \ldots 0.4$ and has been reported by a number of researchers. Studies of α-element synthesis in SNe II have recently been undertaken by Thielemann et al. (1996), Arnett (1991), and Woosley & Weaver (1995). Due to small differences in the way stellar winds and semi-convection are treated and in the specification of the *mass cut* and explosion mechanism their predictions differ, mainly because of differences in the respective Fe yields but also due to non-negligible differences in the pre-explosion yields of Mg. There is no question that Mg, in principle, is less affected by the fine-tuning of SN II explosions. Therefore, inasmuch as the products of SN II nucleosynthesis are mixed into interstellar space ^{24}Mg should constitute a reliable reference of the early evolutionary time scale of the Galaxy.

Due to the number of strong absorption lines found in the visible spectra of even the more metal-poor stars, neutral magnesium is easier to observe than e.g. O I. However, it shares the disadvantage of most neutral metals in the atmospheres of moderately cool stars, with Mg II being the dominant ionization stage above ≈ 5000 K. Consequently, neutral Mg I is sensitive to deviations from *local thermodynamic equilibrium*, particularly as its ionization balance is dominated by photoionization from the 3p ^{3}P$^\circ$ state. In metal-poor cool stars most of the free electrons have vanished and the collision rates are correspondingly smaller. Together with an increased UV radiation field that leads to large photoionization rates this makes Mg I even more sensitive to non-LTE and affects any careful abundance analysis of Mg in these objects. It is interesting to estimate the changes expected with reduced metallicity. With the density of free electrons decreasing in proportion to the star's metal abundance we expect considerably reduced collisional interaction. This could lead to substantially stronger deviations from LTE at optical depths $\log \tau_{\rm c}$ between -3 and 0, if the reduced electronic interaction is not compensated by hydrogen collisions (Baumüller & Gehren 1996, 1997). The question then is: when do such deviations from LTE become important? An analysis of the stars with differing metallicities will enable us to answer this question.

In our present study, we use the various Mg I lines chosen from solar spectrum which were carefully checked in previous work (Zhao et al. 1998, hereafter Paper I) to fit the calculated NLTE equivalent widths from the models of differing stellar parameters and determine the Mg abundance corrections of the deviations from LTE analysis. All Mg I lines considered here are reproduced using standard NLTE line formation techniques with the radiative transfer solved in the Auer-Heasley scheme, taking the population processes between all levels of the Mg model atom into account.

2 Atomic Model

The standard atomic model is basically the same as that used for the solar calculation (Paper I). The Mg I model we constructed includes all levels nℓ up to $\rm n = 9$ and $\ell \leq \rm n - 1$ which results in a total of 83 Mg I terms. The model is completed by the doublet ground state of Mg II. All energies were taken from the compilation of Martin & Zalubas (1980) except for those terms with $\ell > 5$ which were obtained using the polarisation formula of Chang & Noyes (1983). Fine structure splitting has been neglected. The terms are coupled by radiative and collisional interactions as described in details in Paper I.

As we have shown in Paper I, the collisional interactions with neutral hydrogen atoms will not affect the results obtained for most of the solar Mg I lines except those in the infrared wavelength. However, since collisional interactions with neutral hydrogen are not varying with metal abundance, they can maintain an important influence in metal-poor stellar atmospheres and raise the total collision rates to high enough efficiency at which they can even compensate the strongly increased photoionization. As outlined in Paper I the hydrogen collisions are based on the formula of Drawin's (1969). It is most often used in a form due to Steenbock & Holweger (1984) although the validity of this latter formula cannot be judged. We carefully investigated the influence of hydrogen collisions in our atomic model by fitting all available Mg I lines. We had to modify Drawin's formula by a scaling factor. However, for Mg I the factor varies *exponentially* with upper level excitation energy $E_{\rm n}$ (in eV),

$$S_{\rm H} = 1000 \times e^{-{\rm n}E_{\rm n}/2} \quad .$$

This was determined in a fully empirical manner, recomputing the complete non-LTE line formation with statistical equilibrium equations including the differing hydrogen collision rates, and it enabled us to fit lines of different excitation energies. The notion of hydrogen collision cross-sections decreasing systematically with excitation energy is also in rough agreement with Kaulakys' (1985, 1986) prediction for Rydberg transitions.

$T_{\rm eff}$ (K)	5200	5200	5200	5200	5780	5780	5780	5780
$\log g$	4.50	4.50	4.50	4.50	4.44	4.44	4.44	4.44
[Fe/H]	0.0	−1.0	−2.0	−3.0	0.0	−1.0	−2.0	−3.0
4571Å	0.022	0.060	0.091	0.113	0.047	0.087	0.128	0.182
4703Å	0.014	0.038	0.039	0.062	0.028	0.073	0.123	0.190
4730Å	0.021	0.051	0.058	0.068	0.042	0.088	0.111	0.172
5167Å	0.010	0.033	0.041	0.052	0.020	0.050	0.058	0.126
5173Å	0.010	0.033	0.041	0.048	0.020	0.051	0.059	0.089
5183Å	0.010	0.033	0.043	0.043	0.020	0.051	0.060	0.079
5528Å	0.010	0.022	0.028	0.058	0.023	0.060	0.099	0.180
5711Å	0.015	0.045	0.052	0.060	0.050	0.104	0.117	0.172
7657Å	0.035	0.065	0.055	0.050	0.060	0.130	0.120	0.200
8806Å	0.001	0.019	0.045	0.075	0.004	0.041	0.079	0.163
8213Å	0.042	0.115	0.098	0.095	0.076	0.202	0.234	0.430
11828Å	0.004	0.025	0.045	0.075	0.019	0.050	0.090	0.157
$\overline{\Delta \log \varepsilon}$	0.016	0.045	0.053	0.068	0.034	0.082	0.107	0.178
$\sigma_{(n)}(\log \varepsilon)$	0.011	0.025	0.020	0.021	0.020	0.044	0.046	0.084

$T_{\rm eff}$ (K)	5780	5780	5780	5780	6500	6500	6500	6500
$\log g$	3.50	3.50	3.50	3.50	4.50	4.50	4.50	4.50
[Fe/H]	0.0	−1.0	−2.0	−3.0	0.0	−1.0	−2.0	−3.0
4571Å	0.060	0.101	0.147	0.201	0.042	0.077	0.096	0.148
4703Å	0.033	0.081	0.157	0.224	0.041	0.102	0.142	0.178
4730Å	0.062	0.120	0.137	0.206	0.046	0.088	0.101	0.162
5167Å	0.031	0.059	0.025	0.130	0.026	0.036	0.006	0.122
5173Å	0.031	0.069	0.035	0.052	0.023	0.040	-0.011	0.077
5183Å	0.031	0.071	0.044	0.023	0.024	0.043	-0.005	0.038
5528Å	0.028	0.054	0.118	0.211	0.045	0.090	0.120	0.182
5711Å	0.090	0.151	0.136	0.207	0.083	0.123	0.105	0.179
7657Å	0.115	0.180	0.120	0.210	0.100	0.150	0.120	0.200
8806Å	0.016	0.018	0.045	0.212	0.042	0.051	0.075	0.178
8213Å	0.095	0.252	0.264	0.429	0.095	0.188	0.178	0.302
11828Å	0.026	0.053	0.085	0.210	0.047	0.072	0.094	0.175
$\overline{\Delta \log \varepsilon}$	0.052	0.101	0.109	0.193	0.051	0.088	0.085	0.162
$\sigma_{(n)}(\log \varepsilon)$	0.031	0.063	0.065	0.096	0.026	0.045	0.057	0.062

Table 1: Abundance differences between fitting calculated NLTE and LTE equivalent widths of Mg I lines using the same parameters in various stellar models. Results refer to $\Delta \log \varepsilon = [Mg/H]_{\rm NLTE} - [Mg/H]_{\rm LTE}$

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3 Statistical Equilibrium Calculations

The statistical equilibrium calculations are performed in horizontally homogeneous LTE model atmospheres in hydrostatic equilibrium. We account for metallic and molecular UV line absorption using Kurucz' (1992) opacity distribution functions interpolated for the proper solar mix of abundances. The model we used is flux-conserving, convection is taken into account parametrically with a mixing-length of 0.5 pressure scale heights (Fuhrmann et al. 1993) and line blanketing included with Kurucz' ODFs. The reason for adopting this model as a standard is that we can easily use the model as a differential *stellar* atmosphere with full physics included.

The statistical equilibrium is calculated using the DETAIL code (Giddings 1981; Butler & Giddings 1985) in a version based on the method of complete linearization as described by Auer & Heasley (1976). The calculation includes all radiative line transitions which are mostly represented by Doppler profiles; 99 lines were linearized. The Mg b lines are treated with full radiative and van der Waals damping. The linearized line transitions were selected from test calculations including different combinations with a preference for the stronger transitions including the $\ell = \mathrm{n} - 1$ levels. Adding more transitions did not change the results. The bound-free transitions of the lowest 22 levels were linearized, too.

4 Results

The results of the NLTE calculations with the different stellar models from various Mg I lines in the synthesis spectrum over a wavelength range extending from the blue to the infrared shown in Table 1 confirm that deviations from LTE of the level populations of neutral magnesium are increase with metallicity decreasing. The resulting effects on line formation are almost negligible in the solar metallicity stars. Generally, the NLTE effects are systematically stronger for the hotter models, which is in accordance with the statistical equilibrium of aluminium and sodium (Baumüller & Gehren 1996; Baumüller et al. 1998). The strongest departure from LTE are found for models with high temperature and low metallicities. The reduction of surface gravity results in a decreased efficiency of collisions by electron and hydrogen atoms which led the stronger NLTE effects trend.

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