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The Effects of Chromospheric and Shock Photons on Molecular and Atomic Opacities in Late–type Giants

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Abstract. We show that UV and violet resonance lines for neutral metals in the photospheres of late–type giant stars (M, S, and C types) are greatly influenced by the radiation field of chromospheres (or calorispheres) and/or shocks. These resonance lines, which dictate the number densities of excited and ionized states, are very far out of LTE. This has a significant impact on the opacities of higher level transitions and molecular equilibrium calculations, which are based on the number densities of neutral atoms. This in turn can lead to spurious results in classical abundance analyses of these stars.

1 Introduction

Late–type giant stars all show evidence of atmospheric regions with enhanced temperature ($T_{eff} < T < 10,000$ K). These stars are all variable with visual magnitude variations of a few tenths of a magnitude (*i.e.*, irregular and semi–regular variables) to greater than 2 magnitudes (*i.e.*, Mira variables). The enhanced temperature regions in these stars give rise to emission lines in the violet and UV, typically of singly ionized metals (*i.e.*, Mg II k and h). This region probably results from acoustic wave heating, which form chromospheres, and/or shocks that are produced by long period pulsational waves.

Classical techniques used to study the atmospheric structure and the chemical abundance of these stars have mainly invoked the assumption of local thermodynamic equilibrium (LTE), by either model atmosphere calculations or the crude curve–of–growth analysis (*e.g.*, Dominy & Wallerstein 1986). Such analyses may be suspect due to NLTE effects in the transfer of radiation in these atmospheres. We will show how NLTE affects the bound and ion level densities of neutral atoms in both *pure* photospheric and chromospheric models representative of g Her (M6 III, SRb) and TX Psc (N0 II); and of a Bowen (1988) hydrodynamic model representative of the Mira variable S Car (K5-M3 IIIe). We will then show how the atomic ionization equilibrium affects the molecular equilibrium.

2 Calculations

The radiative transfer code PANDORA has been used to compute emergent spectra for a variety of different stellar environments including the Sun (Ver-

nazza, Avrett, & Loeser 1981), the M–type supergiant α Orionis (Hartmann & Avrett 1984), the cool M giant g Her (Luttermoser, Johnson, & Eaton 1994), and the N–type carbon star TX Psc (Luttermoser *et al.*, 1989) to name a few. PANDORA solves the equations of radiative transfer and statistical equilibrium in either plane parallel or spherical geometry in a self–consistent manner. Macroscopic velocity fields can be included in the calculation of the line profiles, source functions, and rate equations. Only electronic collisions are included *for the metals*; inelastic collisions by neutral atoms are not yet considered. However, neutral hydrogen atom collisions are included in the hydrogen (and all Rydberg–type ions) collisional rates as described by Kaulakys (1985). For the modeling done here, the neutral hydrogen collisional rates are still small with respect to the electron collisional rates. Should this also hold true for neutral metals, neutral hydrogen collision will not force the net bound–bound and bound–free rates back to LTE. In these atmospheric models, collisional ionizations and recombinations are negligible with respect to photoionizations and photorecombinations due to the low electron and atomic densities.

We have made modifications to the Indiana version of the LTE stellar atmosphere's code ATLAS (Kurucz 1970) to incorporate the atomic NLTE departure coefficients from PANDORA into the molecular equilibrium calculations. We follow the atomic/molecular equilibrium calculations as described by Kurucz (1970) using the equilibrium and partition function coefficients of Irwin (1981). Prior to converging the solution of the atomic, ionic, and molecular densities, ATLAS internally determines the ionization fractions, f, of each atomic species. At this point, the NLTE departure coefficients of the neutral and singly–ionized species from the PANDORA calculations (*i.e.*, H, He, C, Na, Mg, Al, and Ca) are multiplied by f and the total species number density to determine the ionic number densities. The iterative procedure described by Kurucz (1970) is then used to determine, self–consistently, the molecular densities.

3 Results and Conclusions

This proceedings paper is far too limited to describe and display all the results found in this study. Such a detailed description can be found in Luttermoser (1994). Instead, we mention a few specific examples. Comparisons between the atomic bound and ion level calculations of the *pure* photospheric models and the chromospheric models show 2 main effects:

(1) The photospheric radiation field alone produces substantial (sometimes enormous!) departures from LTE in the bound and ionized states of neutral metals and hydrogen. For the cases of hydrogen and carbon however, the reservoir of the neutrals (and H_2 and CO) are so large, that these NLTE effects have little impact on the number density of the ground state. As such, the molecular equilibrium calculations for molecules containing H or C result in no changes between the LTE and NLTE cases. *Note however that excited states are very far from LTE in much of these atmospheres and any abundance analysis calculation based upon lines out of these levels will not be accurate!*

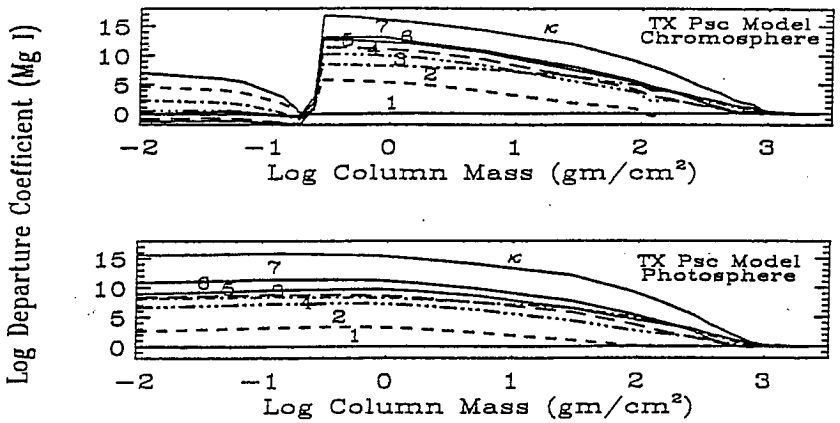

Fig. 1. A comparison between the LTE departure coefficients of Mg I for a *pure* photospheric and chromospheric (*i.e.*, photosphere plus chromosphere) model representative of the carbon star TX Psc. The chromosphere starts at $\log m = -0.7$. Note the impact *back–shining* chromospheric photons have on the excitation and ionization of the photosphere of this star (*i.e.*, enhancement of a factor 50–10^4 in the upper and middle photosphere for the ion and excited states).

(2) The chromospheric radiation field has a major impact (larger than the pure photospheric case) on excited and ionized states at photospheric depths from *chromospheric backwarming* (Luttermoser & Johnson 1992), especially for H, C, and Mg (see Figure 1). Na and Ca do not show the same severe NLTE effects from the chromospheric radiation field as the others. The main reason behind this has to do with the location of the strong resonance lines. H, C, and Mg all have strong resonance lines at UV wavelengths where the dominant continuous opacity sources are due to bound–free transitions from ground and metastable states of neutral metals. These bound–free opacities are typically at optical depth unity in the chromosphere. This produces a *pumping* effect on the excited levels through these resonance lines as described by Luttermoser & Johnson (1992) for hydrogen and the Lyα line. Once electrons get into the upper energy level, the larger number of photons in the visual and IR wavelength regimes, as compared to the UV, will produce overionizations as compared to LTE (and pure photospheric NLTE runs). Since Na and Ca have their strong resonance transitions at visual wavelengths, where *photospheric* H^- bf or H Rayleigh scattering dominates the continuous opacity, chromospheric photons produce little change.

These NLTE effects have a major impact on the formation of molecules with atomic constituents with ionization energies less than ~10 eV (otherwise the ionization energy is so high that the neutral reservoir of particles will be too big for NLTE processes to affect the ground state density). Figure 2 shows an example of the departures from LTE for Mg–bearing molecules in the g Her chromospheric model.

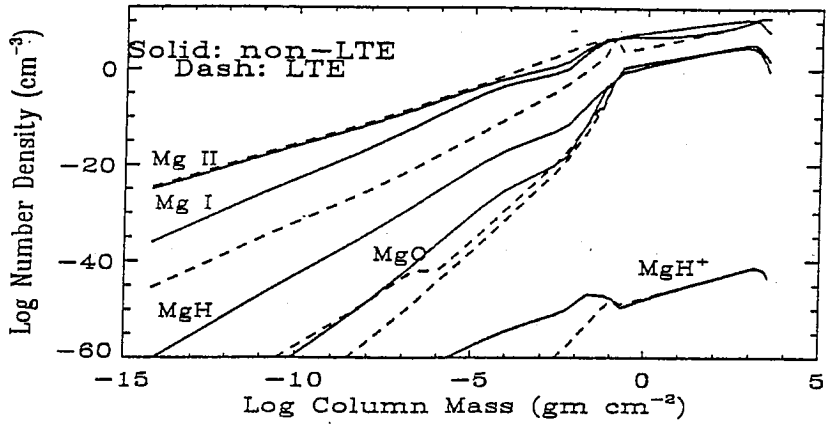

Fig. 2. Atomic, ionic, and molecular densities of Mg–bearing species for a chromospheric model of g Her. Solid lines represent NLTE results and dashed lines represent LTE results.

Finally, strong shocks which are known to exist in Mira stars have large and almost chaotic effects on the excitation and ionization equilibrium of the atoms and on the molecular equilibrium. Sharp changes in number densities over short distances make the chemical analyses of these stars virtually impossible with classical techniques. Curve–of–growth analyses, which assumes the source function of a given transition is slowly changing with respect to optical depth, will give results which are far from reality. Such studies should be met with much skepticism.

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