

# *Spherically symmetric model atmospheres for low mass pre-Main Sequence stars with effective temperatures between 2000 and 6800 K*

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## **1. Introduction**

In a recent paper (Hauschildt et al. 1999, hereafter: NG-giant) we have presented a grid of spherically symmetric model atmospheres for stars with  $\log(g) \leq 3.5$  and in the temperature range  $3000 \leq T_{\text{eff}} \leq 6800$  K. In this paper, we present an update of the NG-giant grid tuned for young pre-MS (PMS) stars. This PMS grid spans the parameter range  $2000 \text{ K} \leq T_{\text{eff}} \leq 6800 \text{ K}$  and  $2.0 \leq \log(g) \leq 3.5$  for solar abundances. The models were calculated for very low mass stars with  $M = 0.1 M_{\odot}$  but in the parameter range considered the mass of the star changes the synthetic spectra and the atmospheric structure only marginally. A major difference from our NextGen grids of model atmospheres (Hauschildt, Allard, & Baron 1999; Hauschildt et al. 1999) is the replacement of TiO and H<sub>2</sub>O line lists with the newer line list calculated by the NASA-AMES group, Schwenke (1998) for TiO (about 175 million lines of 5 isotopes) and Partridge & Schwenke (1997) for H<sub>2</sub>O (about 350 million lines in 2 isotopes).

In the next section we give a brief overview over the model construction and the differences from the NextGen grids. Then we discuss some results, in particular the effects of the new line lists and we end with a summary of the paper.

## 2. Model calculations

We have calculated the models presented in this paper using our multipurpose model atmosphere code PHOENIX, version 10.7. Details of the code and the general input physics setup are discussed in Hauschildt, Allard, & Baron (1999); Hauschildt et al. (1999) and Hauschildt & Baron (1999) and references therein. The model atmospheres presented here were calculated with the same general input physics as in NG-giant. However, the change of the line lists has some impact on the model structure and synthetic spectra (see below). Our combined molecular line list includes about 550 million molecular lines. These lines are treated with a direct opacity sampling technique where each line has its individual Voigt (for strong lines) or Gauss (weak lines) line profile (see Hauschildt, Allard, & Baron 1999, and references therein for details). The number of lines selected by this procedure depends on the the model parameters. Typically, the smallest amounts of molecular lines are selected at the cool and hot ends of the grid, e.g., about 75 million for  $T_{\text{eff}} = 2000 \text{ K}$ ,  $\log(g) = 3.5$  and 80 million for  $T_{\text{eff}} = 4000 \text{ K}$ ,  $\log(g) = 2.0$ . The maximum number of selected molecular lines is about 215 million at  $T_{\text{eff}} = 3000 \text{ K}$ ,  $\log(g) = 2.0$  (all data are for solar abundances).

## 3. Results

We have calculated a grid of solar abundance (table 5 of Jaschek & Jaschek 1995) model atmospheres and grids with enhanced metallicities  $[M/H] = +0.3$  as well as reduced metallicities,  $[M/H] = -0.3$ . The models span a range of  $2000 \text{ K} \leq T_{\text{eff}} \leq 6800 \text{ K}$  and  $2.0 \leq \log(g) \leq 3.5$ . These models were originally intended to be used for low mass stellar evolution models (Baraffe et al, in preparation) and thus assume a mass of  $0.1 M_{\odot}$  for the stars. In the parameter range (mainly  $\log(g)$ ) considered here, the synthetic spectra can also be applied to other masses. Most of the basic results have been described in Hauschildt et al. (1999), so we are concentrating here on comparison with the NG-giant models.

### 3.1. Comparison with NG-giant models

The largest change from the input physics of the NG-giant models is due to the different and larger line lists for TiO and water vapor. In Figures 1 and 2 we compare NG-giant models (dotted lines) to the PMS grid. The main difference between these models is the selection of the input line lists, we used the same version of PHOENIX and the same thermo-

dynamical and opacity data (other than TiO and water vapor) for the calculations. Both sets of models were iterated to convergence with their respective setups, so the differences in the spectra are the results of both direct opacity changes and changes in the structure of the model atmospheres due to the different opacities. In the optical spectrum, the result is generally *weaker* TiO bands for the PMS models compared to the NG-giant models at  $T_{\text{eff}} = 3000$  K but slightly *stronger* TiO bands at  $T_{\text{eff}} = 4000$  K. The situation is slightly different for the water bands shown in Figure 2. The NextGen-type models show stronger H<sub>2</sub>O bands with less inter-band opacity than the PMS models. More importantly, the shape of some water bands are noticeably different between the two setups. The reason for this behavior is the changes in the structure of the atmosphere caused by the different degree of completeness of the water vapor line lists used (see Allard, Hauschildt & Schwenke, submitted). For low  $T_{\text{eff}}$ , the strengthening of the overall water opacity going from the NG-giant models to the PMS models produces weaker TiO bands due to changes in the structure of the atmospheres. However, in hotter models the water bands are not as important as the TiO bands and the net effect of the overall slightly stronger TiO lines produces stronger TiO bands in the optical. These effects are more pronounced for higher gravities (water opacity is relatively more important for larger gravities at the same effective temperature).

In general, the PMS setup applied to M dwarfs produces somewhat better fits to field stars (Leggett et al. 1999; Leinert et al. 1999), although the water bands are still not perfectly reproduced by the models (Allard, Hauschildt, & Schwenke 1999). One reason for this are problems with the water line lists, but other opacity sources (such as dust formation in very cool models) as well as the treatment of convection in optically thin layers are additional sources of uncertainty.

### 3.2. Effects of metallicity changes

The effects of metallicity changes on low resolution synthetic spectra are shown in Figs. 5–8 for models with  $T_{\text{eff}} = 3400$  K and  $T_{\text{eff}} = 2400$  K for the extreme values of the gravity in our grid. For the higher effective temperature, Figs. 5 and 6, the effects of metallicity are most pronounced in the optical (reduced metallicity causes increased flux due to decreased TiO opacity) and in region from 1 to 1.5  $\mu\text{m}$  (the reaction of the atmosphere causes reduced flux in this region to compensate for the larger flux in the optical). The water band get stronger with reduced metallicity due to these redistribution effects. For lower effective temperatures, Figs. 7 and 8, the effects of metallicity of the spectra are significantly smaller, in particular for the lower gravity shown in Fig. 7. Here the tem-

peratures are so low that the bands are saturated and thus will not change much within the range of metallicities considered here (larger changes will eventually affect the spectra). Significant changes occur only in localized bands, e.g., the metal hydrides and other non-saturated bands such as VO.

### 3.3. Formation of radiative and convective zones

Typically, a cool stellar atmosphere has only one convective zone at the bottom of the atmosphere whereas the top of the atmosphere is (and has to be) in radiative equilibrium. The convective zone at the bottom of the atmosphere connects to the convective envelope of the interior of the star. However, our calculations indicate that the convective region at the bottom of the atmosphere can be disrupted by the onset of an isolated radiative zone within specific parameter ranges. These ranges are illustrated in Fig. 3. Each symbol represents a model with multiple convective and radiative zones. The plot shows that a continuous and not an arbitrary parameter range exhibits this behavior.

We investigated the cause of this effect and found it to be due to the relative strengths of  $H^-$  absorption and  $H_2O$  absorption.  $H^-$  absorption is strongest in the inner part of the atmosphere whereas  $H_2O$  absorption is strongest in the outer part. The maximum of the  $H_2O$  absorption is in layers of the atmosphere with electron temperatures of roughly 2500 to 3500 K. If in this region the  $H^-$  absorption is weak enough so that the slope with depth of the overall absorption coefficient is significantly affected by  $H_2O$  absorption, an inner radiative zone forms. In that case the total absorption coefficient drops fast enough toward the outer boundary to make the atmosphere transparent enough to form a radiative zone. As soon as water forms and the  $H_2O$  absorption becomes strong enough, the energy is more efficiently carried by convection until the final radiative zone forms at the very outside of the atmosphere.

For the hottest models with the lowest  $\log(g)$  (i.e. the models left and below the “multiple zone strip” in Fig. 3) the single convective zone at the bottom of the atmosphere is substantially different from that of the models right above the “multiple zone strip”. For the hot models with low  $\log(g)$ , the water absorption will never become strong enough to change the slope of the total absorption and the intermediate radiative zone becomes large enough to remove the intermediate convective zone. In the cool models with high  $\log(g)$ , the water absorption is strong already deep inside the atmosphere and dominates the slope of the total absorption coefficient.

This behavior is demonstrated in Fig. 4 where the most important continuous ab-

sorption coefficients have been plotted against optical depth. In the top graph the water absorption changes the steep slope of the total absorption already in the innermost part. In the middle two plots, water forms further out and leaves a steep enough slope in the absorption coefficient to produce an intermediate radiative zone. In the graph at the bottom, the water absorption can no longer change the slope imposed by the  $H^-$  absorption (they are almost parallel in the outer regions) and the energy is transported by radiation.

#### 4. Summary and Conclusions

In this paper we presented a grid of spherically symmetric model atmospheres for pre-MS stars. The main change with respect to the NG-giant grid is the use of new TiO and water vapor line lists. In the parameter range considered for the PMS models the changes in the structures of the atmospheres compared to similar models with the NextGen setup are relatively small but the differences of the optical and IR spectra are noticeable. We provide the model structures, spectra and broad-band colors in standard filters through the WWW and anonymous FTP for general use, see <http://dilbert.physast.uga.edu/~y...> or <ftp://calvin.physast.uga.edu/pub/PMS>. In a forthcoming paper we will discuss dust formation for cool dwarfs and giants that incorporate the opacities used in this paper, and will explore separately the effects of the present PMS models on evolution tracks for pre-main sequence stars.

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## 5. Figures

Fig. 1.— Comparison of the models presented in this paper (full line) to NG-giant models (dotted line) in the optical spectrum. The resolution has been reduced to  $5\text{\AA}$ . The top panel shows models with  $T_{\text{eff}} = 3000\text{ K}$ , the bottom panel for  $T_{\text{eff}} = 4000\text{ K}$ , both sets have  $\log(g) = 2.0$  and solar abundances.

Fig. 2.— Comparison of the models presented in this paper (full line) to NG-giant models (dotted line) in the near IR spectral range. The resolution has been reduced to  $15\text{\AA}$ . The top panel shows models with  $T_{\text{eff}} = 2000\text{ K}$ , the middle panel shows  $T_{\text{eff}} = 2000\text{ K}$ , and the bottom panel for  $T_{\text{eff}} = 4000\text{ K}$ , all three sets have  $\log(g) = 2.0$  and solar abundances.

Fig. 3.— Models with multiple radiative/convective zones. Each point marks a model that has multiple radiative/convective zones. To minimize the number of figures we plotted all metallicities in one graph and used different symbols for different metallicities as indicated in the figure. The  $\log(g)$  values for sub- and super-solar metallicities have been slightly shifted to keep the figure legible. Note the continuous distribution of models with multiple radiative/convective zones, which is also continuous in metallicity space.

Fig. 4.— Absorption coefficients versus optical depth at  $1.2\mu\text{m}$ . All models have  $z=-0.3$  and  $\log(g)=2.5$ . The effective temperature of the models are from top to bottom 2800 K, 3000 K, 3200 K and 3400 K. The cross hatched regions are the convective zones. For reference, we indicate the gas pressure and the gas temperature at the respective optical depth at the top of each figure. To the right we labeled the most important opacity sources.

Fig. 5.— Comparison of low-resolution (about  $50\text{\AA}$ ) synthetic spectra for models with  $T_{\text{eff}} = 3400\text{ K}$ ,  $\log(g) = 2.0$  and solar abundances (full line),  $[M/H] = -0.3$  (dotted line) and  $[M/H] = +0.3$  (dashed line).

Fig. 6.— Comparison of low-resolution (about  $50\text{\AA}$ ) synthetic spectra for models with  $T_{\text{eff}} = 3400\text{ K}$ ,  $\log(g) = 3.5$  and solar abundances (full line),  $[M/H] = -0.3$  (dotted line) and  $[M/H] = +0.3$  (dashed line).

Fig. 7.— Comparison of low-resolution (about  $50\text{\AA}$ ) synthetic spectra for models with  $T_{\text{eff}} = 2400\text{ K}$ ,  $\log(g) = 2.0$  and solar abundances (full line),  $[M/H] = -0.3$  (dotted line) and  $[M/H] = +0.3$  (dashed line).

Fig. 8.— Comparison of low-resolution (about  $50\text{\AA}$ ) synthetic spectra for models with  $T_{\text{eff}} = 2400\text{ K}$ ,  $\log(g) = 3.5$  and solar abundances (full line),  $[M/H] = -0.3$  (dotted line) and  $[M/H] = +0.3$  (dashed line).