A Grid of Model Atmospheres for Cool Stars

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Abstract. A new and extensive grid of model atmospheres is under construction with the MARCS computer program. The models are spherically symmetric, in LTE and with mixing-length convection. They include a detailed treatment of opacities with opacity sampling. The grid covers the range from $T_{\text{eff}} = 2500$ to $8000$ K, log $g = -1.0$ to 5.0 (cgs), masses from 0.5 to $30M_\odot$, and metallicities [A/H] from $-6.0$ to $+1.0$.

1. Introduction: Why Classical Models?

As demonstrated by the present volume, recent progress in the consistent modelling of statistical equilibrium and 3D convection in stellar atmospheres is impressive, and will undoubtedly find future application in standard analyses of cool-star spectra. Presently, however, such spectra are difficult to analyze due to the heavy blanketing, and to the lack of any relevant model atmospheres and detailed model spectra. Thus, not even 1D LTE modelling, with a realistic representation of the line absorption, has been pursued systematically for cool stars. Therefore, we contribute a basis of detailed, 1D LTE models with synthetic spectra, also as a reference for more advanced modelling attempts that are to come.1

2. MARCS Model Grid

We use an updated version of the MARCS program (cf. Gustafsson et al. 1975, Plez et al. 1992, Jørgensen et al. 1992, Asplund et al. 1997) to calculate over 5000 plane-parallel and spherically symmetric models in a grid extending from $T_{\text{eff}} = 2500$ K to $8000$ K, with logarithmic surface gravities from log $g = -1.0$ to

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1 Among recent developments are models of Miras (Hoefner et al. 2002) and convective supergiants (Freytag 2001) which consider the interaction between hydrodynamics and radiative processes in detail. Also note recent full non-LTE models of cool stars (Hauschildt et al. 1999).
Figure 1. Net heating/cooling by radiation, \( Q = (\kappa_\lambda + \ell_\lambda) \cdot (J_\lambda - B_\lambda) \) vs. wavelength and depth for M-giant (left, \( T_{\text{eff}} = 3000 \, \text{K}, \) solar composition) and C-star (right, \( T_{\text{eff}} = 2800 \, \text{K}, \) C/O = 1.1) models for \( 1 \, M_\odot, \log g = 0. \) Note the effects of polyatomics at the surface, diatomics and metals in deeper layers.

Figure 2. Flux vs. wavelength and depth (models as in Fig. 1). Left: TiO absorption redirects visual flux to longer \( \lambda. \) Right: HCN, C\(_2\)H\(_2\) absorption at 3 \( \mu\)m.

Figure 3. Contributions from single opacity sources to surface fluxes (same models as Fig. 1). Grey curves: continuous flux (top) and full spectrum (bottom).
Figure 4. Model structures (left) and spectra (right), for $1M_\odot$, $T_{\text{eff}} = 3000$ K, $\log g = 0$, and different C/O ratios. Note the changes around C/O $\approx 1$.

Figure 5. Observed spectra (solid lines) of HD 141477 (M0 III) and HD 123857 (M5 III). Model spectra (dotted lines) for solar composition, $T_{\text{eff}} = 3800$ and 3500 K, and $\log g = 1.5$ and 0.9, respectively; cf. Alvarez & Plez 1998.
5.0 (cgs units), masses ranging from $0.5M_\odot$ to $30M_\odot$, and overall metallicities [A/H] from $-6.0$ to $1.0$. In addition, certain abundances are varied individually, in particular those of C and N (with C/O between 0.5 and 3.0); also O, Ne, Mg, Si, Ca and Ti are varied in unison with respect to Fe, in accordance with observations for stars in the Galactic Disk.

One emphasis of the grid lies in M and C stars, whose spectra are dominated by absorption from CH, C$_2$, CN, CO, NH, OH, MgH, SiO, CaH, TiO, YO, VO, FeH and ZrO, as well as C$_2$H$_2$, C$_3$, HCN and H$_2$O—all of which have been included in the models via data that are primarily from calculations but supported by laboratory data when available (see Jørgensen 1997, Jørgensen et al. 2001, Plez 1998). Atomic and ionic lines are based on VALD data (Kupka et al. 1999). For a few thousand stronger lines whose calculated strengths depart considerably from those of observed solar spectra, the $g_f$ values have been adjusted to provide a good fit. Damping by hydrogen collisions, of great significance for dwarfs, is done following Anstee, Barklem & O'Mara (see Barklem et al. 2000). Hydrogen lines are calculated following Barklem et al. (2002).

Figure 1 shows the effects of the opacity on the cooling/heating in model atmospheres for a solar-composition M giant and for a carbon star as a function of wavelength and depth, while Figure 2 shows the corresponding model fluxes. Figure 3 illustrates the contribution of individual opacity sources to the model surface fluxes.

Rather small changes in the C/O ratio lead to drastic changes in the model structure. Figure 4 shows a series of models with varying carbon-to-oxygen ratios, corresponding to the spectral sequence M $\rightarrow$ MS $\rightarrow$ S $\rightarrow$ SC $\rightarrow$ C.

Figure 5 shows the good agreement between observed and model spectra for two M giants (Alvarez & Plez 1998). This and other comparisons suggest that the present models will be applicable and useful in analyses of cool-star spectra, although more realistic models are eagerly awaited.

References