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The impact of M-dwarf atmosphere modelling on planet detection

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Abstract. M dwarfs are discussed as targets for planet detection as these stars are less massive, less luminous and have smaller radii, making it possible to detect smaller and lighter planets. Therefore M-dwarfs could prove to be a valuable source for examining the lower mass end of planet distribution, In order to do that, the characteristics of the host stars must be well studied. We study the ATLAS9, MARCS and DRIFT-PHOENIX stellar atmosphere model families in the M-dwarf parameter space. We examine the differences in the ($T_{\rm gas}$, $p_{\rm gas}$) structures, synthetic photometric fluxes and related colour indices. We find discrepancies in the hotter regions of the stellar atmosphere between the ATLAS and MARCS models. The MARCS and DRIFT-PHOENIX models agree to a better extend with variances of less than 300 K. We compile and compare the broad-band synthetic photometric fluxes of all models for the Johnson $UBVRI$ and 2MASS $JHK_{\rm s}$ filter systems.

Key words. Stars: atmosphere models – Stars: synthetic photometry– Stars: colour indices

1. Introduction

Up to date, there are 872 confirmed planets discovered in 683 planetary systems (http://exoplanet.eu). With various surveys, involving high-precision instruments, it is no surprise that, in the last two years, astronomers have detected more and more planets within the so-called Super-Earth group. However, our knowledge of a given planetary system depends on the knowledge of its host star. This study is dedicated to the modeling of M-dwarf atmospheres and the implications these models could pose in relation to exoplanets.

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2. Models used

The choice of models for this work consists of the ATLAS9 models (Kurucz 1970; Castelli & Kurucz 2003), the MARCS models (Gustafsson et al. 2008), and the DRIFT-PHOENIX models (Helling et al. 2008; Witte et al. 2009). All of these models obey LTE, hydrostatic and chemical equilibrium and energy flux conservation; they are homogeneous, 1D codes that assume plane-parallel symmetry.

The ATLAS models used here span the range for $\log g = 3.0 \ldots 5.0$, [Fe/H] = +0.5 to −2.5 and effective temperature $T_{\rm eff}$ = 3500 to 4000 K. A mixing length height $l/H_{\rm p}$ = 1.25 and $v_{\rm turb} = 2.0\,{\rm km\,s^{-1}}$ is adopted for all models. These values are chosen to maximise the size of the subset of ATLAS models used for this study. The MARCS models used span $\log g = 3.0 \ldots 5.0$, [Fe/H] $= +0.5 \ldots -2.5$, and $T_{\rm eff} = 3500$ and 4000 K in order to allow a comparison with the ATLAS models. Other MARCS models used are $T_{\rm eff} = 2500 \ldots 3000$ K, $\log g = 3.0 \ldots 5.5$, and [Fe/H]=0.0 for comparison with the Drift-Phoenix models. For all models, $v_{\rm turb} = 2\,{\rm km\,s^{-1}}$ and solar element abundances (Grevesse et al. 2007) were chosen. The Drift-Phoenix models are aimed at late-type stars and giant planet atmospheres as they include a model of dust cloud formation. The subset of models used is for the solar metallicity models with $2500 < T_{\rm eff} < 3000$ K and $3.0 < \log g < 5.5$.

The different model families have a different coverage of the M-dwarf regime. Therefore we analyse pairs of models, in particular the ATLAS+MARCS models for $T_{\rm eff} = 3500$ K and 4000 K, and varying $\log g$ and [Fe/H] values, as well as the MARCS+Phoenix models for solar metallicity and varying $T_{\rm eff}$ and $\log g$ values. A total of 105 models were considered.

3. Atmospheric structure comparison

A comparison of the atmospheric structures of the different models includes the ($T_{\rm gas}$, $p_{\rm gas}$) structures of model atmospheres with matching $T_{\rm eff}$, $\log g$ and [Fe/H] values, and the differences in the opacity structures.

We look at the residuals in local temperature versus local pressure between the ATLAS and MARCS models for $T_{\rm eff} = 3500$ K and $T_{\rm eff} = 4000$ K. We note that while the 3500 K models match better in the metalicity range -1.5 < [Fe/H] < -2.5, the 4000 K models display better agreement for [Fe/H]=+0.5 and [Fe/H]=0.0. For both $T_{\rm eff}$, the biggest discrepancies lie within the [Fe/H]=-1.0 models, with differences reaching over 1500 K in the $T_{\rm eff} = 3500$ K and over 1200 K for the $T_{\rm eff} = 4000$ K. We create residual plots for each pair of matching models by subtracting local temperature values at matching local pressure values by interpolating models where neccessary. In all cases, the models diverge as the pressure increases, i.e. as going deeper into the atmosphere, regardless of particular values for $T_{\rm eff}$, $\log g$ or [Fe/H]. These trends are also reflected in the Rosseland mean opacities, where higher divergence in opacity residuals is observed for the same model parameter values described in this paragraph.

The MARCS and Drift-Phoenix grids have common models for only one metalicity ([Fe/H]=0.0) but for various effective temperatures (2500-3000 K). We observe better agreement between MARCS and PHOENIX than the MARCS and ATLAS models with respect to residual values. Overall, this set of models do not vary by more than 300 K (with the exception of the case for $T_{\rm eff} = 3000$ K and $\log g = 3.0$ and 3.5).

In summary, we find that for the higher $T_{\rm eff}$ (3500 K, 4000 K) the ATLAS and MARCS temperature-pressure structures diverge from each other with an average of ~600 K in local temperature and extreme cases well over 1000 K. In contrast, the MARCS and Drift-Phoenix only differ by ~300 K for $2500\,{\rm K} < T_{\rm eff} < 3000$ K. A direct comparison between ATLAS and Drift-Phoenix is currently not possible as these models do not share any common $T_{\rm eff}$ values.

4. Synthetic photometry

The ($T_{\rm gas}$, $p_{\rm gas}$) structure determines the emergent spectral energy distribution for stars. To compare the SEDs of the different models, we perform synthetic photometry of all models considered. We convolve the model SEDs to the Johnson UBVRI and 2MASS $JHK_{\rm s}$ filters, using the HST spectrum of Vega (Bohlin & Gilliland 2004) for zero-point calibration.

We compare the ratios between the synthetic broad-band fluxes for all pairs of corresponding models in each filter. The broad-band fluxes of ATLAS and MARCS in the optical (Johnson $UBVR$) differ significantly more than those in the IR range. The flux ratios for $T_{\rm eff} = 3500$ K are deviating from 1.0 (perfect match) significantly more (as high as ~1.8) than those for $T_{\rm eff} = 4000$ K (less than ~ 1.3). The spread in ratios in the optical wavelength range is even bigger, with the highest values aproaching a factor of 2.0. Finally we compile a list of the synthetic colour indices for each model, using the calculated visual magnitudes

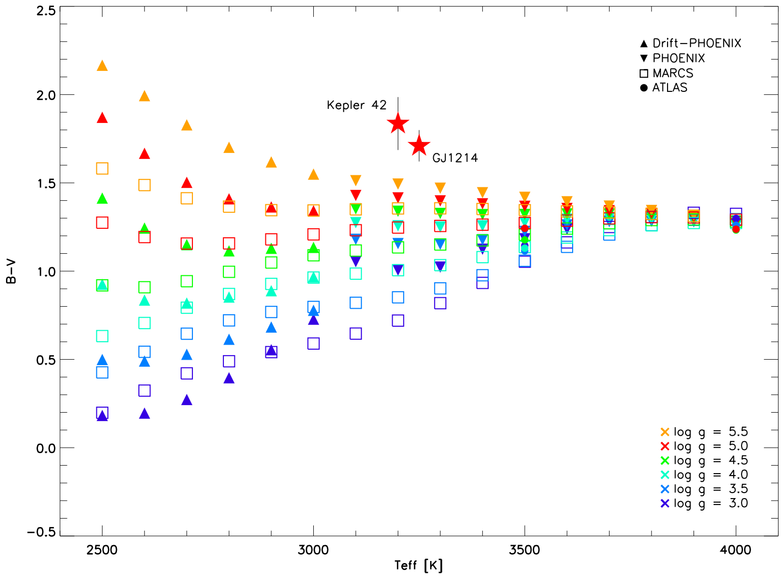

Fig. 1. $B-V$ versus effective temperature for all model families of solar metalicity. The two stars represent observed data for GJ 1214 and Kepler 42.

(Fig.1). The $B-V$ magnitudes differ by up to half a magnitude between the Drift-Phoenix and MARCS models in the low temperature half of the plot. The difference seems to diminish, when the models move to higher $T_{\rm eff}$ as the MARCS and ATLAS models diverge much less at $T_{\rm eff}$ = 4000 K. The two available data points from observations, Kepler 42 (Muirhead et al. 2012) and GJ1214 (Anglada-Escudé et al. 2013) do not lie on any of the theoretical curves compiled, which calls for an extension of the study presented here.

5. Conclusion

This study has compared the temperature-pressure and opacity structures of three model atmosphere families. The ATLAS and MARCS models have shown increasing discrepancies in both local temperature and opacity as one goes deeper into the stellar atmosphere. The MARCS and Drift-Phoenix models have shown better agreement with local temperature differences of no more than 300 K. The MARCS models display considerable deviations from both ATLAS and Drift-Phoenix in the optical regime in terms of sythetic photometric fluxes, which is further confirmed in the $B-V$ plots. Still, there are big gaps in the availability of models, which need to be filled in order to present a more comprehensive study.

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