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The effects of new Na I D line profiles in cool atmospheres *(Research Note)*

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ABSTRACT

Aims. New Na I D line profiles and their effects on synthetic spectra of cool dwarfs computed with PHOENIX are studied. Sodium is the most abundant alkali in cool dwarf atmospheres and mostly responsible for the shape of the optical spectrum.
Methods. In previous work we have pointed out the importance of atomic hydrogen as a perturber. Here, broadening due to collisions with atomic hydrogen as well as fully quantum mechanically calculated profiles for perturbations by helium are introduced for the Na I resonance line profiles. Furthermore, the effects of the new line profiles are compared to already existing line profile calculations.
Results. We have calculated a number of "GAIA-cond" class model atmospheres and synthetic spectra for effective temperatures from 1100 K to 3000 K considering a gravity of 4.5. The line formation process has been analyzed with the flux contribution function. Due to changes in atmospheric structure, the effects of the line profiles on the synthetic spectra become larger for smaller effective temperatures. The influence of hydrogen as perturber is visible at higher effective temperatures although at the same time the strength of molecular bands increases. Furthermore, the newly introduced fully quantum mechanically calculated He I broadened profiles change the synthetic spectra by reducing the flux and the depths of the sodium absorption lines.

Key words. stars: atmospheres – line: profiles – stars: low-mass, brown dwarfs

1. Introduction

In 1995, the first brown dwarf Gliese 229b was discovered (Nakajima et al. 1995). Since then there has been tremendous progress in the search for and identification of such cool objects. As a result of this work the spectral types L and T have been introduced by Kirkpatrick et al. (1999) and Burgasser et al. (2002) to classify the spectra of these substellar objects. Kirkpatrick et al. (1999) and Burrows et al. (2000) showed that in the spectra of brown dwarfs the wings of the alkali lines have widths of several 1000 Å.

The broadening of the alkali absorption lines in atmospheres of cool dwarfs is due to pressure broadening by the most important constituents of the atmospheres: molecular hydrogen, helium and (for M dwarfs) neutral hydrogen. Major improvements in the theoretical description of pressure broadening have been made compared to the commonly used van der Waals broadening in the impact approximation, see Allard et al. (2003) and Burrows & Volobuyev (2003). In this research note, we resume the discussion about the influence of different approximations for the line profiles in synthetic spectra for such cool stellar objects, as introduced in Johnas et al. (2006). One of the main conclusions of Johnas et al. (2006) was that further studies of atomic hydrogen as a perturber are necessary, in particular for M dwarfs for which it is the species with the highest concentration in the atmospheric layers where the line wings of the alkalis form. We have also included the perturbations by atomic hydrogen data by Leininger et al. (2000). In addition, the new profiles of Na I, K I and Li I perturbed by helium from Mullamphy et al. (2006) have been added. The new profile data are damping constants for a Lorentzian line profile shape. Hence they represent the physical conditions in the absorption near wing and core regions. The profiles have been incorporated into the general model atmosphere code PHOENIX, version 15 (Hauschildt & Baron 1999). The model atmospheres and synthetic spectra presented here have been generated for effective temperatures from $T_{\rm eff}$ = 1100 K to 3000 K with a step size of 500 K and a gravity of $\log(g)$ = 4.5. In the following, we concentrate on the neutral sodium resonance doublet since it is the most abundant alkali in such cool atmospheres.

2. Profiles

In addition to the van der Waals profiles in the impact approximation (hereafter, impact) (Schweitzer et al. 1996) and modern and detailed calculations (hereafter, modern1), described in (Johnas et al. 2006) and references therein, in which molecular hydrogen in the symmetries C_{2v} and C_{∞} as well as neutral helium have been considered as perturbers, we will discuss the following specific line profiles: line widths and shifts of a Lorentzian profile for atomic hydrogen perturbers of Na I in the impact approximation (Leininger et al. 2000) are added to modern1 resulting in the model type "modern2". In "modern3" we have substituted the helium broadened Na I, K I, and Li I line profile data of modern2 with the results of Mullamphy et al. (2006). These have been obtained by using the fully quantum mechanical theory of Baranger (1958). In this theory the perturbers are treated quantum mechanically. Thus inelastic collisions, degeneracy and overlapping lines are taken into account. Furthermore the impact approximation is used. Although concentrating on the sodium D

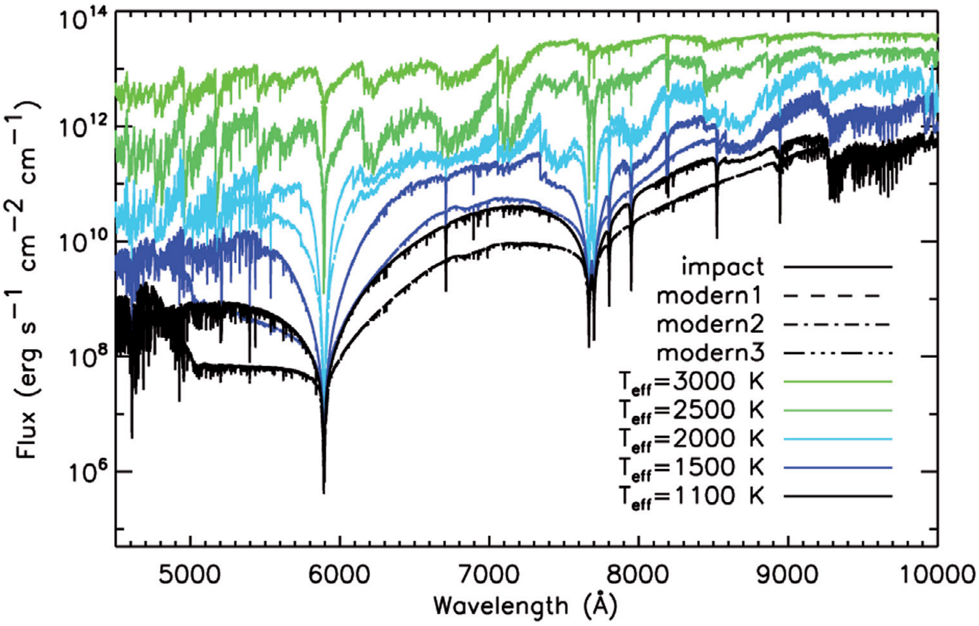

Fig. 1. Smoothed synthetic spectra with a resolution of 10 000 for models with $T_{\rm eff}$ = 1100 K to 3000 K displaying the differences between the four different line profile setups.

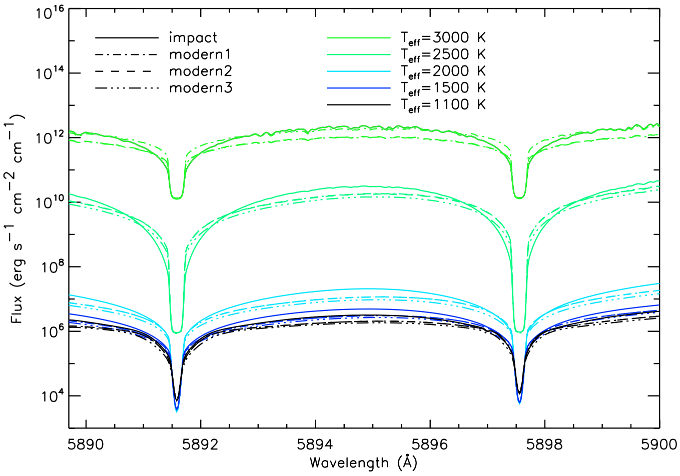

Fig. 2. Zoom in of Fig. 1 showing the Na I doublet at a resolution of 3×10^5.

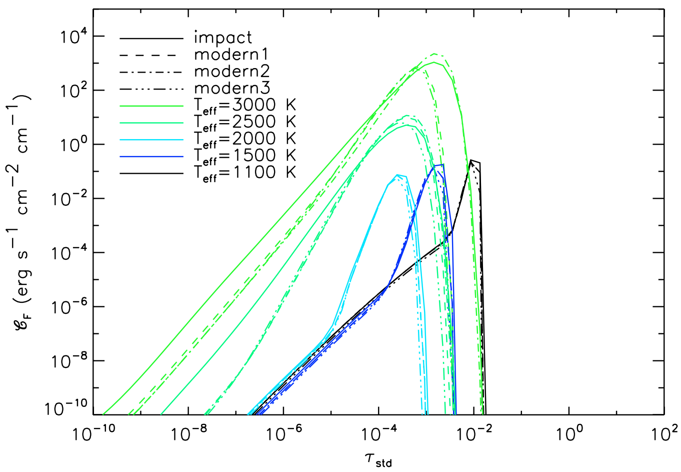

Fig. 3. Contribution function at 5891 Å for effective temperatures from 3000 K to 1100 K for the four line profile setups.

doublet, the inclusion of the potassium modern3 line profile is important for this work since sodium and potassium resonance lines form the pseudo continuum in the optical range. We present only synthetic spectra calculated using the "GAIA-cond" model setup (Allard et al. 2001) in order to demonstrate the influence of the line profiles in the synthetic spectra. The "GAIA-cond" approximations consider fully "rained-out" condensed dust in chemical equilibrium, see Allard et al. (2001) for details. For each line profile setup, a model atmosphere has been calculated and converged before generating the synthetic spectrum.

3. Analysis of the different line profiles in the synthetic spectrum

Figure 1 displays synthetic spectra for $T_{\rm eff}$ = 1100–3000 K and $\log(g)$ = 4.5 at a reduced resolution of 10 000 around the sodium resonance doublet. The original calculated resolution of the synthetic spectra is 3×10^5. All wavelengths are given in vacuo. In Fig. 1, for effective temperatures of 1100 K, 1500 K, and 2000 K, large differences between the different model types are obvious, especially "impact" versus "modern1-3". At $T_{\rm eff}$ = 2500 K and 3000 K, molecular bands, such as TiO, VO, CaH, and FeH, become predominant and overwhelm the effect of the different line profiles on the emitted spectrum. A close up of the sodium doublet in Fig. 1 is shown in Fig. 2. It shows the differences in more detail at the full computed resolution. The contribution of sodium broadened by neutral hydrogen (modern2) is most visible in the near wings at $T_{\rm eff}$ = 3000 K, as predicted by Johnas et al. (2006) and depicted in Fig. 2. Under these atmospheric conditions, atomic hydrogen is the most prominent species at the optical depths where the line wing forms. At this effective temperature, there are differences[1] of up to 50%

[1] If not otherwise mentioned, the comparison refers to a wavelength range between 5850 Å and 5950 Å.

between the modern1 and modern2 spectra for the sodium D lines. The differences between modern1 and modern2 spectra decrease rapidly with decreasing effective temperature, so that at $T_{\rm eff}$ = 2500 K, the difference is at the most about 10%. At even lower effective temperatures, the differences are only in the range of one-tenth of a percent due to decreasing concentration of atomic hydrogen in the atmosphere.

When comparing the impact spectra with modern2 spectra, the differences in the near wing and core regions are already 60% at $T_{\rm eff}$ = 3000 K. For lower effective temperatures starting at $T_{\rm eff}$ = 2000 K, the influence in the line wings (at 5800 Å) is even greater, decreasing from 90% to 75% at $T_{\rm eff}$ = 1500 K and 60% at $T_{\rm eff}$ = 1100 K. The wing–core regions are affected by 70%, 50% and 45% respectively for these effective temperatures. The changes at the core wavelengths of the two sodium D absorption lines reach up to 400%. This is expected, however, as there are substantial differences between the impact and modern1–3 line profiles.

Due to the similar characteristics of the modern3 and modern2 spectra at $T_{\rm eff}$ = 3000 K, the difference between the two is at the most 4%. The comparison between the modern1 and modern3 spectra gives similar results. In contrast, at $T_{\rm eff}$ = 2500 K the difference between modern2 and modern3 spectra reaches up to 35%, as between modern1 and modern3. As mentioned before, because of the evanescent differences between the spectra calculated with the modern1 and modern2 profiles at effective temperatures ≤ 2000 K, the differences between the modern1 and modern3 spectra are similar, namely 25% at $T_{\rm eff}$ = 2000 K, 20% at $T_{\rm eff}$ = 1500 K, and 29% at $T_{\rm eff}$ = 1100 K. Following the discussion above, comparing with the spectra of the impact setup, the differences between the impact and modern3 spectra are again of the same order of magnitude and the changes increase in the wings towards lower effective temperatures as can be seen in Fig. 1.

With the flux contribution function $\mathscr{C}_F$ as introduced in Magain (1986) and Fuhrmeister et al. (2006) and applied in Johnas et al. (2006), the differences around 5891 Å seen in Figs. 1 and 2 between the different model types can be interpreted. The maximum of $\mathscr{C}_F$ indicates the layers where the line forms in the atmosphere at a specific wavelength. The wavelength 5891 Å has been chosen to represent the near wing region in which the changes in the setups are significant. For each effective temperature slightly different locations of the line forming region in the atmosphere for each model type are found, as shown in Fig. 3. This causes the differences in the emergent flux of the synthetic spectra. Further analyses of the flux contribution function and the gas pressure of each model type for each effective temperature have shown that the locations of the maxima of the flux contribution functions are consistent with the theoretical predictions. Moving closer to the line core, the maxima are positioned at higher and hence cooler regions of the atmosphere. On the other hand, moving further into the line wings of the Na I D_2 absorption line, the flux contribution originates in deeper and hotter layers of the atmosphere.

4. Conclusions

We have demonstrated the effect of different line profiles of the Na I D lines on the emitted spectra. Although only small changes in the intrinsic line profiles were applied when introducing modern2 and modern3, concerning the data of the near wings, the synthetic spectra show visible changes. Despite of the presence of strong molecular bands at higher effective temperatures, the inclusion of neutral hydrogen perturbers for the sodium D line profile data is significant for computing synthetic spectra.

There is an obvious need for extending the modern2 profiles especially to potassium and lithium lines, due to their prominence in brown dwarf spectra. It is crucial to improve the Na I and K I line profiles as they are also essential for the modeling of the other strong alkali doublets, i.e. Li I, Rb I, and Cs I. Furthermore, far wing calculations for both modern2 and modern3 should be done in order to produce complete sets of line profiles, from the line core to the farthest wing. In a subsequent paper the dependence of the equivalent widths on the different models will be discussed. Finally, it is very important to compare the results for the different profile types with low and high resolution observations of L and T dwarfs for conclusions of the quality of each profile type.

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