THE SOLAR HYDROGEN SPECTRUM IN NON-LTE

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ABSTRACT

We investigate the synthesis of the Balmer and Paschen lines of the quiet Sun, using both classical semi-empirical and theoretical model atmospheres, modern line broadening theory and non-LTE line-formation. The computations alleviate long-standing discrepancies between LTE predictions and the observed lines. Theoretical and semi-empirical model atmospheres without a chromosphere on the one hand and semi-empirical models with a chromosphere on the other produce two physically disjoint solutions for the run of non-LTE level populations, including H II, throughout the model stratification. The resulting synthetic non-LTE line profiles are practically identical and reproduce the observation in either case, despite large differences in the line-formation depths, e.g., a chromospheric origin of the Hα core (in concordance with observation) versus a photospheric origin. The findings are of much broader interest, assuming the Sun to be a prototype cool dwarf star. A consistent account for chromospheres in cool star analyses is required, due to their potential to change atmospheric structure via non-LTE effects on the ionization balance of hydrogen and thus the free electron pool. The latter in turn affects the main opacity source H - . This will in particular affect the atmospheres of metal-poor and evolved stars, in which the contribution of hydrogen to the electron pool becomes dominant.

Subject headings: line: formation – line: profiles – Sun: chromosphere – Sun: photosphere – stars: fundamental parameters – stars: late-type

1. INTRODUCTION

Understanding the Sun is of fundamental importance to stellar astronomy and astrophysics. Naturally, the hydrogen lines are an important aspect, in particular the first members of the Balmer line series. The Balmer lines are vital for tests of the internal consistency of model atmospheres as they sample the physical conditions throughout the stellar atmosphere. Modelling of the hydrogen line wings allows for an accurate temperature determination in cool stars, superior to that achievable using broad- or intermediate-band photometric indicators (Fuhrmann, Axer & Gehren 1993, 1994).

Traditionally, either semi-empirical atmospheres (e.g. Maltby et al. 1986, MACKKL; Holweger & Müller 1974, HM) – with or without chromosphere – or models computed from basic physical principles including local thermodynamic equilibrium and energy flux conservation (e.g. Kurucz 1994, SUNK94) are used for analyses. In combination with the most recent data on line-broadening, in particular the Stark broadening tables of Stehlé & Hutcheon (1999, SH) and the self-broadening formalism of Barklem, Piskunov & O’Mará (2000, BPO), good fits to the wings of the normalised Balmer lines are obtained (BPO; Cowley & Castelli 2002). However, the models fail to reproduce the cores of the lines, most notably the Doppler core of Hα , which are of chromospheric origin, and the far line wing–continuum transition of Hβ and the higher Balmer lines, see e.g. BPO.

Recently, the first sophisticated time-dependent ab-initio 3D radiative-hydrodynamical models of the solar atmosphere became available (Asplund et al. 2000), together with its temporally and spatially averaged 1D representation (Asplund et al. 2004, A-1D). It has been suggested that these solve many long-standing issues of the quantitative interpretation of the solar spectrum, and of cool stars (Asplund et al. 2004, and references therein). On the other hand, in a more conventional approach, Grupp (2004, MAFAGS-OS) shows that important improvements can be made when handling atomic data more realistically, reducing the missing opacity problem in the Sun and thus improving the modelling of the solar flux distribution.

Here, we investigate the relevance of non-LTE computations for the interpretation of the solar Balmer and Paschen lines as a test case for solar-type stars in general. The study is motivated by our findings on the impact of improved collision data on the modelling of the hydrogen lines in early-type stars (Przybilla & Butler 2004, PB), but it will be shown to be more far-reaching than that. In the following sections we provide details of our model calculations, compare with observation and discuss the implications.

2. MODEL CALCULATIONS

The non-LTE line-formation computations are carried out using a hybrid approach. Based on either the classical semi-empirical MACKKL and HM models or the theoretical SUNK94, A-1D and MAFAGS-OS models we perform 1D non-LTE computations using DETAIL and SURFACE (Giddings 1981; Butler & Giddings 1985). The coupled radiative transfer and statistical equilibrium equations are solved with DETAIL, using a 15-level+continuum version of the recommended model atom for hydrogen of PB, but it will be shown to be more far-reaching than that. In the following sections we provide details of our model calculations, compare with observation and discuss the implications.
which are from the Opacity Project (Seaton et al. 1992). Line-blocking is included by considering Kurucz’ (1993) Opacity Distribution Functions. The emergent flux is computed with SURFACE, either based on non-LTE populations or in LTE. Line-broadening by charged and neutral perturbers is accounted for by Stark profiles from SH and the self-broadening formalism of BPO.

Note that we cannot provide a fully consistent treatment of the problem with our restricted non-LTE approach, and we will miss the subtle effects introduced by a full 3D line-formation computation (e.g. Asplund et al. 2000). However, important conclusions can be drawn despite these restrictions, as will be shown next.

3. THE SOLAR BALMER AND PASCHEN LINES

The resulting best fits from our non-LTE and LTE computations are compared with the normalised NSO/Kitt Peak FTS data from the solar flux atlas of Kurucz et al. (1984) in Fig. 1. The overall improvement of the profile fits when accounting for non-LTE effects is evident. Large effects are found for the Hα line core, and a progressive decrease of the non-LTE strengthening towards the higher Balmer and Paschen lines. Only small discrepancies remain, notably at the very line centres and the well-known problems in the wings of Hβ and the higher Balmer lines. The former probably result from slight inaccuracies in the solar temperature structure, requiring a cooler outer photosphere, see also Fig. 1 of Asplund et al. (2004), or, alternatively, a modified photosphere-chromosphere transition as suggested by Avrett (2003). The synthetic non-LTE profiles from the other models vary only slightly from the best fits, most notably in the very line cores, as shown in Fig. 2 exemplarily for Hα and Pβ, with the exception of MAFAGS-OS which gives a slightly different solution. As shown for Hβ the line wings are significantly strengthened and the MAFAGS-OS model has the potential to resolve the long-standing discrepancy between observed and computed line wings of the blue Balmer lines. This is due to the higher continuum flux resulting from the opacity sampling approach in that case.

We thus show that accounting for non-LTE line formation practically removes the main discrepancies between theory and observation. We conclude, that non-LTE analysis of the hydrogen spectrum is mandatory to recover the physical structure of the solar atmosphere, and consequently the basic stellar parameters. This in turn makes non-LTE Balmer profile fitting attractive as a technique to determine the stellar parameters of cool stars in general, since it is a prototype of this class of stars. It is more powerful than the Balmer wing fitting technique (Fuhrmann et al. 1993, 1994), as it probes the atmosphere to a far greater extent. The method even gains in accuracy, if the Paschen lines can be also accounted for, since they originate from a level of different excitation energy. However, the problem is more complicated, as the quantitative interpretation of our findings will show.

We begin by discussing the departure coefficients \( b_i = n_i / n_i^* \) (the \( n_i \) and \( n_i^* \) being the non-LTE and LTE populations of level \( i \), respectively). These are displayed in the inset of Fig. 3 for the atmospheres without chromosphere. The ground state and the first excited level stay in detailed balance throughout
almost the entire Balmer line-forming depths in the solar atmosphere, due to the optical thickness of the Ly\alpha transition at those depths. The \( n = 3 \) and higher levels are in detailed balance deep in the photosphere, but develop a non-LTE underpopulation further out. However, the levels with higher \( n \)-values stay in detailed balance relative to each other at these atmospheric depths, and they also collisionally couple tightly to the continuum. Inspection of the non-LTE line core source functions \( S_b \) in the inset of Fig. 3 indicates a drop of \( S_b \) below the Planckian value and thus non-LTE strengthening of the lines.

The marked reduction of the line centre intensities in these cases is caused exclusively by photon escape (see e.g. Mihalas 1978, Ch. 11-2). In fact, it is photon escape from \( \text{H}_\alpha \) itself which controls the non-LTE departures of hydrogen: when setting \( \text{H}_\alpha \) into detailed balance, the non-LTE effects on all levels of hydrogen vanish, and the LTE line profiles are recovered in that case. The importance of this radiative transition for the non-LTE problem is due to the failure of collision processes to establish detailed equilibrium between the \( n = 2 \) and 3 levels, as the energy gap of 1.89 eV implies that only particles in the high-velocity tail of the Maxwell distribution will be relevant. For all other transitions between the energetically higher levels the gaps are 0.66 eV, or lower, thus they are easily coupled via collisions at the temperatures prevailing in the solar atmosphere.

The behaviour of the departure coefficients and line source functions for all the solar model stratifications without chromosphere is qualitatively similar, see the insets in Fig. 3 with only minor differences occur in the details.

The MACKKL model on the other hand shows a fundamentally different behaviour, our results agreeing closely with those of Avrett (priv. comm., 2004). Here an overpopulation of the \( n = 3 \) level occurs around the solar temperature minimum and a marked underpopulation in the chromosphere, where the cores of the \( \text{H}_\alpha \) and \( \text{H}_\beta \) are formed as seen in Fig. 3.

We attribute this to the irradiation of the photosphere by energetic photons from the high-temperature plasma of the chromosphere, a classical non-LTE situation which is accounted for in the construction of the MACKKL model (see Vernazza, Avrett & Loeser 1981). In order to test this, we artificially restrict the MACKKL model to depths below the temperature minimum, thus reproducing the non-LTE behaviour of the models without chromosphere in the same qualitative way. \( \text{H}_\alpha \) line-formation then takes place exclusively in the photosphere. However, the profiles with or without chromosphere are in all cases almost identical and show equally good agreement with the observed line profiles (core emission is characteristic for (unphysical) LTE calculations using MACKKL).

The differences in the model predictions produce more noticeable effects in \( \text{P}_\beta \), which probes the deeper solar photosphere. Distinguishing the different models is possible for the high quality spectrum available for the Sun – for stellar analyses, where compromises with regard to resolution and S/N have to be made in most instances, such efforts may be difficult.

4. IMPLICATIONS FOR QUANTITATIVE SPECTROSCOPY OF COOL STARS

Chromospheres are an integral part of the atmospheres of cool stars. Their impact on the hydrogen line-formation and atmospheric structure will gain in importance where chromospheres are more pronounced, e.g. young stars, or more generally, objects showing chromospheric activity, and in situations which facilitate departures from LTE, i.e. for metal-
poor or evolved objects. The mechanisms will be the same as for the Sun: irradiation by energetic photons from the chromospheres modifies the statistical equilibrium of hydrogen throughout the stellar photosphere, however leading to more pronounced deviations from LTE. More important than the changes of the level populations, which determine the line strengths, is the effect on the ionization balance and thus the pool of free electrons. This in turn controls the formation of $\mathrm{H}^+$, the main opacity source in cool stars, and consequently the stellar continuum. Metal-poor red giants will therefore show pronounced effects, as the role of hydrogen as electron source is strengthened with regard to the metals.

The primary target to verify this is the mildly metal-poor K-giant Arcturus, which can be studied in great detail due to its proximity, and allows for a model-independent determination of basic stellar parameters (Griffin & Lynam-Gray 1999). Synthetic $\mathrm{H}\alpha$ profiles from LTE and non-LTE line-formation calculations using a conventional model atmosphere without chromosphere (Peterson et al. 1993) with non-LTE (thin full line) and LTE (dotted) line formation: pointing towards an inadequacy of such models for quantitative spectroscopy.

Quantification of the systematic errors introduced by the use of conventional model atmospheres in present-day cool star analyses is a necessity, but will require the construction of semi-empirical non-LTE model atmospheres with chromospheres for stars other than the Sun in a first step and ultimately a theoretical understanding of chromospheres from first principles. If shown to be non-negligible, this will have far-reaching consequences since the properties of these stars (fundamental parameters, abundances) are the principal sources of our knowledge of galactic evolution (including the solar neighbourhood, globular clusters, galactic bulges, dwarf galaxies etc.), to the properties of giant ellipticals from their integrated light) and cosmology (the first step in the calibration of the galactic distance scale, which relies predominantly on late-type stars; visible baryonic matter content through modified $M/L$-ratios).

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