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Letter to the Editor

Pa-beta as a chromospheric diagnostic in M dwarfs

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Abstract. We have obtained, for the first time, a high resolution near-infrared spectrum in the region of Paβ of a chromospherically active M dwarf (AU Mic). We demonstrate that both Paβ and Hα can be fit with a model of large chromospheric pressure, but that the two lines indicate clearly different values of the exact pressure. There are several important types of missing physics that need to be included in the calculations before the importance of this apparent discrepancy can be assessed. Nevertheless, the approximate agreement of the two lines lends support to an earlier theoretical result that the Paschen series is a useful chromospheric diagnostic in M dwarfs.

Key words: stars: late-type – stars: activity – stars: chromospheres – line: formation

1. Introduction

The H I spectrum has long been one of the main diagnostics of chromospheric structure in late-type stars. However, the Lyman series suffers from the same problem that plagues many other traditional spectral diagnostics of chromospheric heating: it falls in the UV spectral region, which is relatively inaccessible. The lower members of the Balmer series, especially Hα, have proven to be of great diagnostic value. However, in general, the varying details of formation of different lines causes them to be sensitive to atmospheric structure in different ways. Therefore, each new line that can be added to the arsenal of understood chromospheric indicators adds complementary diagnostic power to the study of chromospheric structure.

Both Andretta et al. (1997) and Short & Doyle (1997) have presented studies of non-LTE H I line formation in a grid of chromospheric models that corresponds to a dM0 star of activity level varying from low to high. One of the results of both studies was that the low members of the Paschen series respond sensitively to the chromospheric pressure and temperature structure in the highest activity models that correspond to dMe stars. The Paα line at λ18750 is obscured by heavy telluric contamination, whereas the Paβ line is in a relatively clear part of the spectrum. However, Paβ, at λ12818, falls in the near infrared, a spectral region that until recently has not been readily accessible to high quality spectroscopy.

We have obtained a high resolution spectrum of the Paβ line in the dMe star AU Mic (Gl 803). AU Mic is a rapidly rotating, chromospherically active M dwarf, and provides an ideal laboratory for the study of active chromospheres. To our knowledge, this is the first time a high resolution spectrum of a near-IR H I line has been used as a chromospheric diagnostic in stars other than the Sun.

2. Observations and reductions

Paβ. A series of fourteen spectra of exposure time ten seconds was obtained on 30 June, 1997 between UT 13:59:41 and 14:37:44 as part of a service observing run with the Cooled Grating Spectrometer (CGS4) at the United Kingdom Infrared Telescope (UKIRT). We obtained echellograms centered at 1.2822 μm with a spectral resolution, R, of 20 500. The reductions were carried out by the UKIRT staff and the spectrum presented here is the final sky-subtracted, co-added signal. A portion of the spectrum in the region of Paβ is shown in Fig. 1. The line identifications were made by comparison with the solar infrared spectral atlases of Hall (1973) and of Livingston & Wallace (1991). The blue wing of Paβ is contaminated by a strong, narrow, non-stellar absorption feature that we have been unable to identify. Because the feature is not present in the telluric spectrum shown in the atlas of Livingston & Wallace (1991), we surmise that it is interstellar. The strong feature at λ12821 is not present at any level in the solar spectrum. However, it does correspond closely in position to a strong telluric feature shown in the atlas of Livingston & Wallace (1991).

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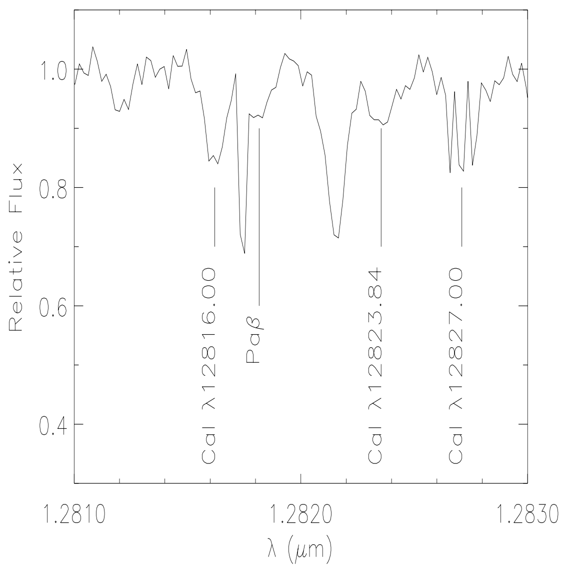

Fig. 1. Portion of observed spectrum in the region of Paβ.

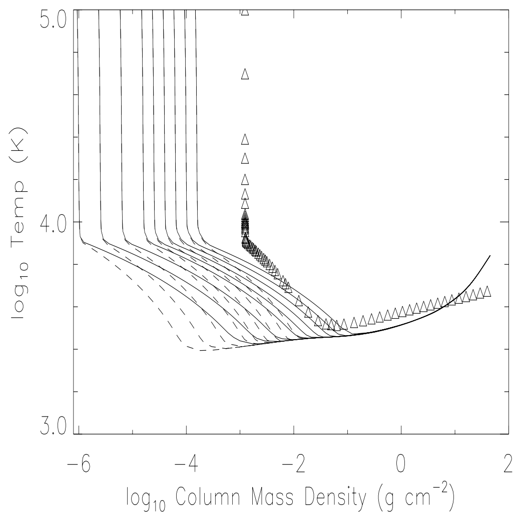

Fig. 2. Temperature structure of models. $1A$ series: solid line, $2A$ series: dashed line. Model of Houdebine & Doyle (1994): triangles.

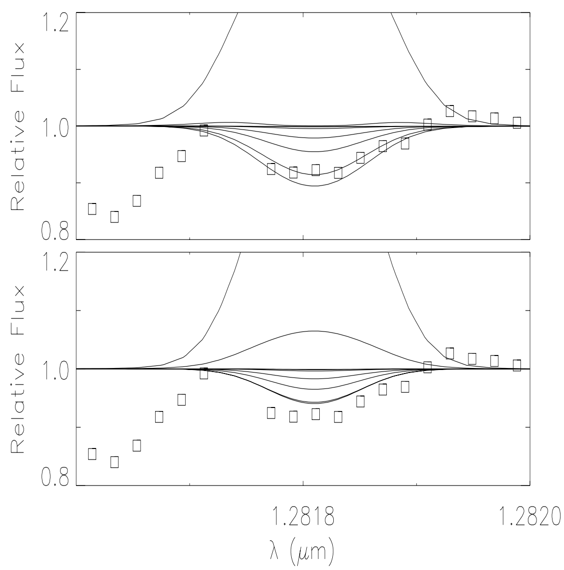

Fig. 3. Gl 803, Paβ. Upper panel: models of $1A$ series, lower panel: models of $2A$ series. Squares: observed spectrum. Models shown span the range in $m_{\rm TR}$ from -6.0 tp -3.8. As $m_{\rm TR}$ increases the line first becomes more strongly absorbent, then more weakly absorbent, then finally goes into emission.

Hα. An echellogram containing the Hα region was obtained by P.B. Byrne with the University College London Echelle Spectrograph (UCLES) at the Anglo-Australian Telescope (AAT) on 24 August 1991. The exposure time was 500 sec and R = 50 000. Reductions were carried out at Armagh Observatory by M.T. Eibe. The extracted spectrum is shown in Fig. 4.

3. Modelling

Andretta et al. (1997) have presented a grid of 72 chromospheric and transition region (TR) models in which the photospheric base was computed with PHOENIX (Allard & Hauschildt 1995) and is representative of a dM0 star ($T_{\rm eff}$ = 3700K, $\log g$ = 4.7, $[\frac{A}{H}]$ = 0.0). The grid explores a wide range in chromospheric pressure from low to high, which corresponds to the range in observed chromospheric activity level from low (dM stars) to high (dMe stars). The grid also explores two values of the chromospheric thickness (or, equivalently, the mean chromospheric temperature gradient), two different functional forms of the chromospheric temperature variation with column mass density, and two different values of the TR thickness. The models of their Series $1A$ and $2A$ (chromospheric $dT/d\log m$ = constant) are shown in Fig. 2.

Short & Doyle (1997) recomputed the non-LTE H I spectrum for the Series $1A$ and $2A$ models as part of their investigation of the effect of background opacity treatment on the non-LTE H I equilibrium. Andretta et al. (1997) and Short & Doyle (1997) contain extensive detailed discussions of the effect of different line blanketing treatments on the calculated non-LTE H I spectrum. Here, for this preliminary study of Paβ, we will confine our discussion to the comparison of unblanketed synthetic profiles, which we take from Short & Doyle (1997), with the observed spectra.

4. Results and discussion

Houdebine & Doyle (1994) modelled the chromosphere and TR of AU Mic to fit simultaneously the Hα and Hβ line profiles and the Lyα/Hα flux ratio. Their best fit model is shown in Fig. 2. Houdebine & Doyle (1994) also contains a compilation of all the stellar measurements that are relevant to computing a model photosphere and synthetic spectrum, and all the stellar data used henceforth is from that source. They adopt as their photospheric base a radiative equilibrium model from Mould (1976) with $T_{\rm eff}$ = 3500K and $\log g$ = 4.75. To this they add

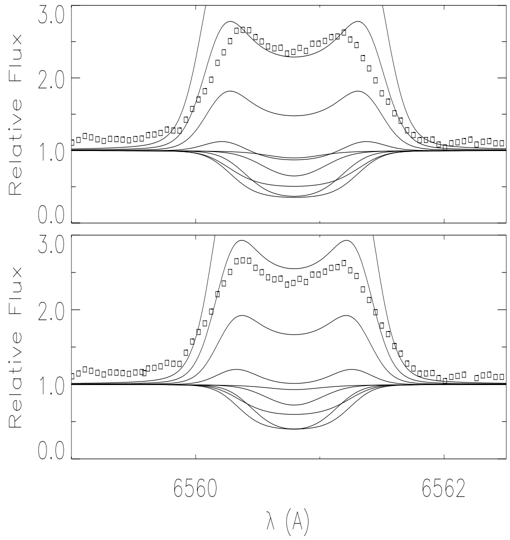

Fig. 4. Gl 803, Hα. See Fig. 3 for caption.

a chromospheric and TR temperature structure to produce the model denoted by squares in Fig. 2.

Paβ. The synthetic Paβ profiles shown in Fig. 3 have been rotationally broadened with a value of $v \sin i = 6.2$ km s^{-1}, which was found for this star (Pettersen 1983). The line responds to increasing chromospheric pressure in the same way that Hα does. In the basal model it is very weakly in absorption, with minimal W_λ. As the chromospheric pressure increases, the line becomes more strongly absorbent, with maximal W_λ occurring at $\log m_{\rm TR} = -4.2$. Then, as the chromospheric pressure increases further the line makes a rapid transition to emission. For the $\log m_{\rm TR} = -4.0$ model, the line is balanced between absorption and emission for the Series $1A$ models and is in emission for the Series $2A$ models. By analogy with the intermediate activity "zero Hα" stars with $\log m_{\rm TR} = -4.0$, in which Hα is balanced between emission and absorption, we can define "zero Paβ" stars which have $\log m_{\rm TR} = -4.0$. The column mass density at the transition region that is required to drive Paβ into emission is about 0.4 dex higher than that required for Hα. The closest fit in either series of models is provided by the models in which the line is close to maximal absorption: either the $\log m_{\rm TR} = -4.2$ or -4.4. The $\log m_{\rm TR} = -4.4$ model in Series $1A$ provides a particularly close fit throughout the line profile.

Carlsson & Rutten (1992) performed detailed modelling with a solar chromospheric model of the formation of IR H I lines arising from lower levels with $n = 4$ to 18. They found that Stark broadening due to protons was dominant in the deep photosphere, and that Stark broadening due to heavier ions dominated throughout the rest of the atmosphere. Currently, we have the ability only to include Stark broadening by electrons and our line profile calculation only includes natural and van der Waals damping. We found that natural broadening dominated throughout the TR and upper chromosphere in both models. In the models of high chromospheric pressure, van der Waals damping became dominant in the low chromosphere, whereas in the models of lower chromospheric pressure natural broadening remained dominant all the way down to the upper photosphere below $T_{\rm min}$. The effect of Stark broadening by protons and heavier ions should be investigated, and their neglect is a potentially serious limitation to the detailed accuracy of our calculated line profiles.

Hα. For both series, models with $\log m_{\rm TR} = -4.0$ provide close fits to the flux level in the emission peaks and in the central reversal of the emission core. However, the Series $2A$ models with their narrower, steeper chromospheres give rise to narrower line profiles that better match the observed separation of the emission peaks.

While the value of $\log m_{\rm TR} = -4.0$ that best fits Hα only differs by 0.2 dex from the value that best fits Paβ, it is actually significantly discrepant because for Paβ, the difference between a model with $\log m_{\rm TR} = -4.0$ and -4.2 is the difference between a model with the line strongly in absorption and one with the line weakly in emission. On the other hand, for Hα, a value of $\log m_{\rm TR} = -4.4$ yields a line profile that is significantly weaker than the one observed. Therefore, because both lines respond very sensitively to small variations in chromospheric pressure in the emission line regime, it is not possible to find a single model in our grid that closely fits both lines.

Comparison to Houdebine & Doyle 1994. The models that we have fit here differ greatly from that fit by the previous H I modelling of AU Mic; that of Houdebine & Doyle (1994) (see Fig. 1). The values of $\log m_{\rm TR}$ that we infer from either line are 0.9 to 1.5 dex lower that the value of $\log m_{\rm TR}$ found in the latter study. In addition to having a greater value of $m_{\rm TR}$, their model has a chromospheric temperature rise that is similar to that of our Series $2A$ models, but which deviates from a log linear form, and is thinner, with a higher value of $T_{\rm min}$. Also, the values of $T_{\rm eff}$ and $\log g$ of our underlying photospheric model is 200 K larger and 0.05 dex smaller, respectively, than those of Houdebine & Doyle (1994). Generally, this difference may be expected to affect the non-LTE solution of H I, but it is difficult to specify the extent of the effect without a detailed study.

Houdebine & Doyle (1994) state that they are able to fit the Balmer lines, including Hα, with a number of different chromospheric models, including some that have $\log m_{\rm TR}$ as low as -4.0. However, they find that they require a large chromospheric pressure to simultaneously fit the observed value of 1.1 for the Lyα/Hα flux ratio. However, this observed value was not corrected for the interstellar attenuation of Lyα. A later study by Doyle et al. (1997) showed that the correct value of Lyα/Hα is about 3.3. Our Series $2A$ models with $\log m_{\rm TR} = -4.0$ and -4.2, which provide close fits to Hα and Paβ, respectively, yield computed Lyα/Hα flux ratios of 4.5 and 3.4, respectively. These values are in excellent agreement with the corrected observational value, and are much less discrepant than the value of 12.7

that Houdebine & Doyle (1994) derived for a log $m_{\rm TR}$ = -4.0 model.

5. Conclusions

We have presented the first exploitation of an observed Paβ spectrum as a chromospheric diagnostic. There is general agreement between this line and the traditional diagnostic, Hα, in the sense that both lines indicate a model a with relatively large chromospheric pressure. However, the lines disagree in detail in that each line indicates a chromospheric pressure that is significantly different.

We cannot draw strong conclusions about the disagreement at this point because of several limitations in the modelling: Andretta et al. (1997) and Short & Doyle (1997) have recently demonstrated the importance of complete line blanketing opacity for calculation of the non-LTE H I spectrum in chromospheric M dwarf models; the models in our grid all have log-linear chromospheric T structures whereas more complicated functional forms for $T(m)$ have been demonstrated to provide good multi-line fits to M dwarf chromospheres (Andretta et al. 1997); there has been growing evidence for thermal inhomogeneities (Ayres 1990) and dynamic effects (Carlsson & Stein 1995) in the outer layers of late-type stars (see, for example, Ayres (1990)) so that one cannot expect lines that are widely separated in wavelength to be fit by the same homogeneous model because of the non-linear averaging of the Planck function in temperature and wavelength. Computational limitations prevent us from exploring these possibilities immediately. However, it is worth noting now that because the absorption strength of the observed Paβ line is much stronger than that expected from a radiative equilibrium model, in agreement with the predictions made with chromospheric models, we *can* conclude that Paβ is a sensitive chromospheric diagnostic that can be added to multi-line semi-empirical chromospheric modelling efforts.

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