Analysis of Keck High Resolution Spectra of VB10*

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ABSTRACT

We use a preliminary version of our “NextGen” grid of cool star model atmospheres to compute synthetic line profiles which fit high resolution Keck spectra of the cool M dwarf VB10 satisfactorily well. We show that the parameters derived from the Keck data are consistent with the parameters derived from lower resolution spectra with larger wavelength coverage. We discuss the treatment of van der Waals broadening in cool, molecular (mostly H$_2$) dominated stellar atmospheres. The line profiles are dominated by van der Waals pressure broadening and are a sensitive indicator for the gravity and metallicity. Therefore, the high-resolution Keck spectra are useful for determining the parameters of M dwarfs. There is some ambiguity between the metallicity and gravity. For VB10, we find from the high-resolution spectra that 5.0 < log($g$) < 5.5 and 0 < [M/H] < +0.5 for an adopted fixed effective temperature of 2700 K (Schweitzer, 1995), which is consistent with recent interior calculations (e.g. Baraffe et al., 1995).

Key words: line: profiles – stars: individual: VB10 – stars: low mass, brown dwarfs – stars: fundamental parameters – stars: atmospheres – atomic processes

1 INTRODUCTION

M dwarfs are among the faintest and coolest stellar objects. Their spectra are dominated by molecular band absorption. In the optical region the major opacity sources are the TiO bands, which produce a pseudo continuum with the atomic lines superposed. These atomic lines show very broad wings due to van der Waals broadening, whereas the molecular lines show only relatively small damping wings. We have recently obtained a high resolution optical spectrum of the dM8e star VB10 (Gl 752B) with the HIRES echelle on the Keck telescope. The collection and reduction of the data are as in Basri & Marcy (1995). In this paper, we use this spectrum to assert our treatment of the van der Waals line broadening in M dwarf atmospheres and to estimate the gravity and the chemical composition of VB10. VB10 is known to be a chromospherically active flare star. However, in this paper we will neglect the chromosphere and do not attempt to model chromospheric spectral features, such as core emission observed in resonance lines.

Our calculations are based on a preliminary version of our latest grid of model atmospheres (the “NextGen” or “version 5” grid) for cool dwarf stars and version 6.2 of the generalized stellar atmosphere code PHOENIX. An important improvement over the previous generation of this grid (Allard & Hauschildt, 1995, hereafter, AH95) are larger and more reliable molecular line lists which allow us to compute detailed molecular line profiles. A complete description of all changes and improvements over the AH95 version of the models will be given in a subsequent paper (Allard, Hauschildt, & Schweitzer, 1995, hereafter, AHS96). Note that we use metallicities scaled from the solar values of Anders & Grevesse (1989) and we use the notation

\[
[M/H] := \log \left( \frac{M/	ext{H}}{\text{M}_\odot/	ext{H}_\odot} \right)
\]

to specify abundances.

* Based on observations obtained at the W.M. Keck Observatory, which is operated jointly by the University of California and the California Institute of Technology
A previous analysis based on low resolution spectra by Brett (1995) yielded only rough values for $T_{\text{eff}} = \pm 2400-2600 \, \text{K}$, $\log(g) \approx 5.0$ and $[M/H] \approx 0.0$. Interior calculations (e.g. Burrows et al., 1993) require for solar M dwarfs in the effective temperature range of $\approx 2700 \, \text{K}$ gravities of $\log(g) \approx 5.3$.

In the next section we will describe our theoretical approach to the problem. We will discuss the basic approximations we use as well as their numerical realization. In section 3 we present the results of our modeling. We discuss the sensitivities of the profiles and try to establish error limits. In section 4 we compare the observed high resolution spectra of VB10 to our model spectra.

2 THE TREATMENT OF LINE BROADENING

2.1 The line profiles

We include all common line broadening mechanisms, i.e., thermal broadening, micro-turbulence, natural broadening and pressure broadening, both in the model calculations and synthetic spectra. The resulting Voigt profiles $V(u, \alpha)$, where $u = \Delta \lambda / \Delta \lambda_D$ and $\alpha = (X^2 / 4 \pi c) / \Delta \lambda_D$ ($\Delta \lambda_D$ is the Doppler width, $\gamma$ the Lorentz width, $\Delta \lambda$ the distance from the line center and $\lambda$ the wavelength), are calculated as a convolution of a Gauss and a Lorentz profile using standard approximations (e.g. Baschek & Scholz, 1982). The gas temperatures in M dwarf atmospheres are not high enough to sustain a significant amount of ionization in the atmosphere. The electron and proton densities are, therefore, much smaller than the densities of the most important neutral and molecular species. Consequently, the contribution of Stark broadening to the total damping constant is very small, even in stars with very low metallicities. We include a correction factor for $C_6$ of the van der Waals damping constant:

$$\gamma_{\text{vdW}} = \sum_p \gamma_{\text{vdW}}^p,$$

where we sum over all perturbers considered. Due to the lack of availability of any vdW broadening mechanisms for molecules in this temperature range, we also use this approximation for the molecular lines.

Earlier investigations (Weidemann, 1955) showed that the values as calculated by Eq. (3) are in good agreement with observed line widths for alkali metals but not for other elements, such as iron (Kusch, 1958). This has lead to the introduction of correction factors to the ‘classical’ formula. Therefore, we include a correction factor for $C_6$ of

$$C_6 = C_6^0 \times C_6^\text{corr} = 10^{1.8} \times C_6^0$$

as described in Wehrse & Liebert (1980) for non-alkali like species. For alkali-metals and ions with alkali-like electron structure we omit any correction factor. This will be discussed and investigated in greater detail in sections 4 and 5. However, as these results will show, the use of this correction factor remains unclear for the non-alkali like species.

2.2 The numerical treatment of vdW broadening

In order to calculate the emerging spectrum we have to calculate a Voigt profile at every wavelength point for every line at every depth point. To limit the computation time we make the following simplification.

Before calculating the absorption coefficient, a line selection procedure decides which lines are calculated with Voigt profiles. We follow the line selection procedure described by AH95. Only lines that are stronger than a certain threshold relative to the continuum are treated with Voigt profiles. This is decided by comparing the absorption coefficient at the line center $\kappa_\lambda$ with the corresponding continuous absorption coefficient $\kappa_c$. Only if the ratio $\Gamma = \kappa_\lambda / \kappa_c$ for at least one of three representative depth points is larger than a preset threshold value, a line is treated with a Voigt profile. Otherwise the line is considered so weak that to a good approximation it can be treated as a Gauss profile in order to save computation time. The number of considered atomic lines is much smaller than the number of molecular lines. This allows us to set $\Gamma$ for atomic lines very low in order to treat as many lines as possible with Voigt profiles. The number of molecular lines is about two orders of magnitude larger but since the atmosphere structure does not change significantly (as test calculations showed) with the inclusion of more Voigt profiles for molecular lines we set the
Table 1. The perturbers included in the calculations and their polarizabilities. The percentages are taken from models with log($g$) = 5.0, $[M/\odot] = 0.0$ and the respective $T_{\text{eff}}$. We chose the optical depth $\tau_{\text{std}} = 1$ ($d\tau_{\text{std}} = ks$ where $k$ is the absorption coefficient at a standard wavelength of 1.2$\mu$m (AH95) and $s$ the geometric depth) as an example for an average line forming depth. The percentages are rounded on the last figure.

| Perturber | $\alpha_p$ in 10$^{-24}$cm$^3$ | Fraction of $P_{\text{gas}}$ in per cent at $\tau_{\text{std}} = 1$ for $T_{\text{eff}} = 2000$ | $T_{\text{eff}} = 2700$ | $T_{\text{eff}} = 3500$ |
|-----------|-------------------------------|-----------------------------------------------|----------------|----------------|----------------|
| H         | 0.666793                      | 1.2                                           | 14.9           | 66.6           |               |
| He        | 0.204956                      | 16.2                                          | 15.1           | 10.7           |               |
| Ne        | 0.3956 ± 0.1%                 | 0.02                                          | 0.02           | 0.01           |               |
| Fe        | 8.4 ± 25%                     | 0.01                                          | 0.01           | $\approx$ 0.005 |               |
| H$_2$     | 0.806 ± 0.5%                  | 82.4                                          | 69.8           | 22.4           |               |
| CO        | 1.95 ± 0.5%                   | 0.06                                          | 0.06           | 0.04           |               |
| H$_2$O    | 1.45 ± 0.5%                   | 0.07                                          | 0.06           | 0.01           |               |
| N$_2$     | 1.7403 ± 0.5%                 | 0.01                                          | 0.01           | $\approx$ 0.004 |               |

Figure 1. The calculated NaI λ8183,8195 doublet in vacuum with different broadening methods (log($g$) = 5.0, $T_{\text{eff}} = 2700K$, $[M/\odot] = 0.0$). From top to bottom : Gauss profile, only H and He as perturbers, H, He and H$_2$ as perturbers, perturbers of Tab. 1 without the correction factor (this plot is lying exactly on the previous one), perturbers of Tab. 1 and the correction factor of 10$^{1.8}$ artificially applied.

Figure 4. The calculated NaI λ8183,8195 doublet in vacuum with different broadening methods (log($g$) = 5.0, $T_{\text{eff}} = 2700K$, $[M/\odot] = 0.0$). From top to bottom : our method without the correction factor, using Kurucz’s damping constant per Hydrogen atom at 10000 K, our method and the correction factor of 10$^{1.8}$ artificially applied, the old method. See Sec. 3.2 for details.
used by Allard (1990) and AH95, and (2) using the precalculated damping constants per hydrogen atom at 10,000 K provided on CD-ROM No.1 by Kurucz (1994).

The method (1) used an average broadening mechanism by taking the total particle density instead of the density calculated damping constants per hydrogen atom at 10,000 K used by Allard (1990) and AH95, and (2) using the precalculated perturbers, i.e., not taking into account the different polarizabilities and reduced masses, latter influencing the relative velocity in Eq. (2). In addition, it used the correction factor for all lines.

In Fig. 4 we compared now the same Na i \( \lambda 8183, 8195 \) profiles as above calculated with the old method with one calculated with the new method but the correction factor artificially applied for comparison. As can be seen there are clear differences between the two methods. The new method results in narrower line since it accounts for the different polarizabilities and reduced masses which decrease \( C_6 \) in Eq. (3) or \( \gamma_{vdW} \) in Eq. (2) compared to a \( C_6 \) and \( \gamma_{vdW} \) calculated as described above and, therefore, also decreases the damping constants of Eq. (4).

In Fig. 4 we also plot the profiles using the damping constants provided by Kurucz. We find only small differences between Kurucz’s \( \gamma_{vdW} \) damping constant and ours, if we omit the correction factor. In test calculations we also compared the use of natural damping constants provided by Kurucz with those calculated with the classical approximation. Since the total line width in M dwarfs is dominated by \( \gamma_{vdW} \) broadening, it makes little observable difference which treatment of natural damping is employed to model their spectra. We adopt our own methods in the following discussion.

We furthermore compared directly the damping constants obtained with our approximation with the corresponding values from Kurucz’s list and found only small differences for the vast majority of the lines above 6000 Å. The largest differences arise from the correction factor we included for non-alkali species. For the UV region the differences are larger. Here the hydrogenic approximation for the absorber we used differs substantially from the method Kurucz used. This does not affect the spectra we present here. In general, the photospheric UV flux from M dwarfs is negligible. However, a more thorough investigation must be performed for stars that are significantly hotter than M stars.

### 3.3 Uncertainties in the broadening mechanism of molecular lines

As can be seen from Figs. 5 and 11 the molecular lines are much narrower than the atomic lines, both in the observations (cf. Sec. 4.6) as well as in our models. This is due to the fact that each molecular line is very weak compared to the strong atomic lines. Therefore only the Gauss cores remain visible in the spectra and the line width is only the line width of the Gauss core. Nevertheless, the Voigt profiles need to be included since they lift the Gauss cores significantly without changing the line width as corresponding comparisons showed. In addition, the molecular lines lie so densely together that only their cores can remain visible; any wing contribution will effectively be blocked by the core of neighboring molecular lines. This means that the total width of molecular features is not as much dominated by the wings of the \( \gamma_{vdW} \) broadening as for the atomic lines.

In order to estimate the error resulting from our approximations, we performed test calculations in which we omitted the correction factor from Eq. (5) for molecules which results in a change in the interaction constant by nearly 2 orders of magnitude. In contrast to the atomic lines (cf. Sec. 3.1 and Fig. 1), we found only small differences in the overall appearance of molecular lines in the optical (see Fig. 5), since only the line wings change and they are completely blended in the spectrum.

The most important result, however, was the influence of rotational broadening on the appearance of the molecular lines which can be seen in Fig. 5 as well. As we applied rotational broadening on our test spectra we found that even a small rotational velocity will broaden the lines so much that the uncertainties in the \( \gamma_{vdW} \) broadening become unimportant. Only the cores of the stronger molecular lines remain visible. Also the influence of the gravity and metallicity become less important. We furthermore found that the effect of rotational broadening rises continuously with increasing rotational velocity. As a consequence, the molecular line ‘haze’ reveals a possibility to accurately measure the rotational velocity as it is very sensitive to it (see Sec. 4.6).

### 4 COMPARISON OF VB10 HIGH-RESOLUTION KECK SPECTRA WITH SYNTHETIC SPECTRA

Our observation of VB10 was obtained with the HIRES echelle on the Keck telescope during a run on 1995 March 12 under clear conditions. Our exposure time was 30 minutes with 0.8 arcsec seeing. The instrumental setup and data reduction were very similar to those described by Basri & Marcy (1995). The wavelength setting was slightly modified to include the subordinate Na i \( \lambda 8183, 8195 \) doublet, the K i \( \lambda 7665, 7699 \) resonance doublet, the Ca i \( \lambda 6573 \) resonance line, the Ba i \( \lambda 7911 \) resonance line and the Fe i \( \lambda 7913, \lambda 8662 \) and Fe i \( \lambda 8689 \) subordinate lines. Inclusion of Na i meant that we could not also observe the Rb i line discussed by Basri & Marcy (1995).

We consider models with any combination of \( \log(g) = 4.0, 4.5, 5.0, 5.5 \) and scaled solar metallicities \( \left[ \frac{M}{H} \right] = -0.5, 0.0, +0.5 \). For the purpose of this paper, we adopt a fixed effective temperature of 2700 K for VB10, derived from...
failing low-resolution spectra obtained by Kirkpatrick et al. (1993) and Jones et al. (1994) to low-resolution models (see Schweitzer, 1995). It is not the purpose of this paper to investigate the influence of the effective temperature on the line profile. This will be done in subsequent work where the parameters will be verified or revised, if necessary. A rotational velocity of 8 km s$^{-1}$ was adopted, using the method of Basri & Marcy (1995). We reconsider this in section 4.6. Due to the complexity of the spectra we performed the fits and decided on their quality by eye.

4.1 The sodium doublet

The Na$^i$ $\lambda\lambda$8183,8195 doublet lines are subordinate transitions and, therefore, form mainly in the photosphere and should not be significantly affected by the chromosphere of VB10. Our best fits are the two models with log($g$) = 5.0 and [M/H] = 0.0 and with log($g$) = 5.5 and [M/H] = +0.5 shown in Fig. 6. There are no significant differences in the appearance of the two model spectra, although the parameters differ substantially. This demonstrates the effect mentioned above, namely that an increase in metallicity decreases the number density of the major perturbers, H$^i$, He$^i$ and H$_2$, and thus partly cancels the effect of increasing the gravity, in particular for strong lines. This shows that one has to be very careful when analyzing M dwarf spectra in detail. In our case here, we found good agreement between observation and models for parameters within the intervals 5.0 < log($g$) < 5.5 and 0.0 < [M/H] < +0.5. We therefore use this as an error limit on our analyses. For any parameter combination beyond these intervals we find no reasonable agreement.

The synthetic line profiles show a deeper core than the observed lines. We calculated several models with a different microturbulence in order to “fill in” the core but we found no significant improvement to the fit. The remaining difference is most likely due to NLTE effects which might make line cores less deep. This will be investigated in detail in future work (see e.g., Hauschildt et al. (1996)). NLTE effects will have to be considered as they are highly non-linear and are very likely to affect the cores of strong lines.

We also like to point out the numerous weak lines in the wings of the atomic lines. These are mostly TiO lines which are also visible in the observed spectrum and are not to be considered as noise (see also below, Sec. 4.6).

4.2 The potassium doublet

The K$^i$ $\lambda\lambda$7665,7699 lines show a clear core reversal (see Fig. 7). This is due to the chromospheric activity of VB10. The doublet is a resonance transition and thus will be strongly influenced by chromospheric activity. Since we are not treating the chromospheric effects here, our models can only reproduce the line wings which are formed deeper in the photosphere.

As in the case of the sodium lines, both models fit equally well and a distinction between the two parameter sets of log($g$) = 5.0 and [M/H] = 0.0 and of log($g$) = 5.5 and [M/H] = +0.5 is not readily possible (see Fig. 7). The fit itself is not as good as in the case of the sodium doublet as the models show many more molecular lines. This spectral region is partially contaminated by the telluric O$_2$ A bands present between 7595Å and 7680Å which we did not remove from the observed data. They are affecting the observations by decreasing the continuum flux to a not readily known extend. In addition, this part of the spectrum is dominated by the e-band of TiO for which the line data are of lower quality (AHFS96). Nevertheless, the lines are so broad, that we still can fit them as shown in Fig. 7.

4.3 The calcium line

The Ca$^i$ $\lambda\lambda$6573 resonance line shows also chromospheric features as can be seen in Fig. 8. The line is weak and very much filled up and the line is hardly detectable without a specific identification. Calcium, in contrast to the two elements discussed above, is not an alkali metal. This means that the vdW damping constant is calculated including the correction factor introduced in Eq. (5). Although it is hard to compare this weak line with models, we find that the correction factor is necessary in order to reproduce the observed line width with the same model parameters as used for the sodium and potassium lines. Without $C_6$ the theoretical line profile of the Ca$^i$ lines is not broad enough, however, we cannot say how accurate our value for $C_6$ is. In order to make a more accurate determination of this factor, we will have to investigate much stronger non-alkali lines with clearer and broader wings. This will be done in a subsequent analysis.

This line cannot be used to determine directly the parameters of VB10. But it can be used to confirm them. As in the case of Sodium and Potassium above, the two models with log($g$) = 5.0 and [M/H] = 0.0 and log($g$) = 5.5 and [M/H] = +0.5 produce equally good results.

4.4 The barium line and the iron line at 7913 Å

The fit to the Ba$^i$ $\lambda$7911 resonance line and the Fe$^i$ $\lambda$7913 line (which has 0.86 eV excitation energy) is shown in Fig. 9. Both lines are very weak but still visible and we find very good agreement between observations and our two models with log($g$) = 5.0 and [M/H] = 0.0 and log($g$) = 5.5 and [M/H] = +0.5. As in the case of calcium above, we only used these lines to confirm our range of fitting parameters, since the line widths are not dominated by the wings of the profiles. They are dominated by their Gauss cores but the Voigt profiles need to be included in order to lift the cores.

Both metals, barium and iron, are non-alkali metals as calcium above and, therefore, treated with $C_6^{corr}$ from Eq. (5). Although the lines are narrow, we find it also here necessary to include such a correction factor in order to fit
all lines consistently. However, we cannot make any accurate determinations of \( C_{\text{corr}}^g \), which still has to be done with stronger lines.

We also want to point out the very good fit of the surrounding molecular lines (see also Sec. (4.6)).

4.5 The iron lines at 8662 and 8689 Å

The two subordinate Fe I \( \lambda 8662 \) and Fe I \( \lambda 8689 \) lines visible in the observations are shown in Fig. 10. The lines are not very strong, yet they can be clearly identified. This spectral region is strongly contaminated by terrestrial absorption features which reduce the total flux and suppress the molecular pseudo continuum. Therefore, we did not try to fit the lines in detail. Instead we show them with an offset to demonstrate the resemblance of the line shapes of the two Fe I lines.

We cannot use these lines to determine the parameters of VB10. As in the cases above we used models with \( \log(g) = 5.0 \) and \( [\text{M/H}] = 0.0 \) and \( \log(g) = 5.5 \) and \( [\text{M/H}] = +0.5 \) and found consistency within the given constraints. Again, calculating the vdW damping constant including \( C_{\text{corr}}^g \) (see also Sec. (4.4)), results in consistent synthetic spectra. But due to the uncertainties in the observed spectrum we did not try to determine the accuracy of \( C_{\text{corr}}^g \) here either.

We want to point out the ‘edge’ at approximately 8671 Å in our models, which is due to an abrupt end of a VO band. In our models we can treat VO only with the JOLA method (AH95, AHS96) since no line list is yet available. Since the JOLA method will produce these edges, it is not suitable for computing high-resolution spectra. We point out that the Fe I \( \lambda 8662 \) line is slightly contaminated by a Ca II \( \lambda 8662 \) line.

4.6 Molecular lines

As mentioned before, the high-resolution spectra are full with a large number of weak molecular lines. For TiO, we use the semi-empirical line list of Jørgensen (1994), which will not reproduce most of the TiO lines at their exact wavelength or their proper gf-value. But nevertheless many of the lines agree very well with observations. We found an excellent agreement with models of the two parameter sets of \( \log(g) = 5.0 \) and \( [\text{M/H}] = 0.0 \) and \( \log(g) = 5.5 \) and \( [\text{M/H}] = +0.5 \) as can be seen in Fig. 11. Because of the strong influence of rotational broadening, we only use the molecular lines to confirm the parameters and not to derive them directly. On the other hand, we can derive the rotational velocity a second time by using its strong influence on the profile of the molecular lines. We found that rotational velocities between 7 and 9 km s\(^{-1}\) produce very similar fits, whereas applying values beyond this interval result in worse fits. Therefore, we can confirm a rotational velocity of \( 8 \pm 1 \) km s\(^{-1}\).

5 SUMMARY AND CONCLUSIONS

We found that the line widths caused by pressure broadening due to van der Waals damping are very sensitive to both the gravity and the metallicity. Therefore fitting the lines of high resolution spectra provides a very important tool to determine these two parameters. Nevertheless, since both parameters influence the line widths in the similar ways, one has to be very careful with the analysis.

From the fits to the lines described above we estimate that VB10 has a gravity in the range \( 5.0 < \log(g) < 5.5 \) and a metallicity \( 0.0 < [\text{M/H}] < 0.5 \) based on line broadening considerations alone with an adopted effective temperature of \( T_{\text{eff}} = 2700 \) K (Schweitzer, 1995). We will investigate the influence of the effective temperature on the line profiles in subsequent work. However, \( \log(g) = 5.5 \) as well as \( [\text{M/H}] = +0.5 \) are rather high values and not expected for VB10 (cf. e.g. Henry & McCarthy Jr., 1993), so that the lower part of the interval is physically more likely.

Our calculations result in damping constants for alkali metals that agree satisfactorily well with the Keck observations. The damping constants for non-alkali metals include the correction factor of \( C_{\text{corr}}^g \) (see also Sec. (4.4)) and lead to line profiles which are consistent with the data. In order to obtain a better value for the correction factor, observations of strong non-alkali lines are required. We calculated synthetic spectra outside the observed spectral range available in this paper in order to find such strong lines, but the only line is a moderately strong Fe I \( \lambda 8829 \) line besides the Rb I \( \lambda 7948 \) line. The iron lines are stronger in hotter M dwarfs which would be more suitable for testing the vdW broadening of iron lines. We also find that our damping constants for atomic lines are in broad agreement with the values provided by Kurucz. No error should be expected from uncertainties in the oscillator strengths of the atomic lines since they are much smaller than any other uncertainties and are well known for the light element lines that we have mostly considered here.

Our analysis of the Keck spectra yields values for the gravity which are consistent with the results of interior calculations for VB10. The \( T_{\text{eff}} \), \( [\text{M/H}] \) and \( \log(g) \) combinations agree reasonably well with evolutionary models for M dwarfs (Burrows et al., 1993; Baraffe et al., 1995). Larger damping constants, e.g. as a result from a different treatment of line broadening, would immediately imply a too low \( \log(g) \).

There are still discrepancies between models and observations in some molecular line dominated regions of the spectrum. As mentioned we suspect this to be due to the
molecular line data. This will be improved in subsequent work. We also will investigate the influence of Non-LTE effects on M dwarf spectra as well as chromospheric features. In addition, observations of different strong atomic lines in spectral regions where molecular absorption is not dominating and blending is less severe (e.g. beyond 1.18μm, see also Jones et al., 1996), will clarify the calculations of the damping constants and the use of correction factors.

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Figure 10. The FeⅠλ8662 and FeⅠλ8689 lines. Solid: Observed. Dotted: $T_{\text{eff}} = 2700K$, log$(g) = 5.0$, $[\frac{M}{H}] = 0.0$ (left) and $T_{\text{eff}} = 2700K$, log$(g) = 5.5$, $[\frac{M}{H}] = +0.5$ (right). Both models with 8 km s$^{-1}$ rotationally broadened. There has been an offset applied to the observed spectrum. See text for details.

Figure 11. Molecular lines. Solid: Observed. Dotted: $T_{\text{eff}} = 2700K$, log$(g) = 5.0$, $[\frac{M}{H}] = 0.0$ (left) and $T_{\text{eff}} = 2700K$, log$(g) = 5.5$, $[\frac{M}{H}] = +0.5$ (right). Both models with 8 km s$^{-1}$ rotationally broadened.