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V sin i-s for late-type stars from spectral synthesis in K-band region.

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ABSTRACT

We analyse medium-resolution spectra (R∼18000) of 19 late type dwarfs in order to determine v sin i -s using synthetic rather than observational template spectra. For this purpose observational data around 2.2 μm of stars with spectral classes from G8V to M9.5V were modelled.

We find that the Na I (2.2062 and 2.2090 μm) and ^{12}CO 2-0 band features are modelled well enough to use for v sin i determination *without* the need for a suitable observational template spectra. Within the limit of the resolution of our spectra, we use synthetic spectra templates to derive v sin i values consistent with those derived in the optical regime using observed templates.We quantify the errors in our v sin i determination due to incorrect choice of model parameters T_{eff} , log g, v_{micro}, [Fe/H] or FWHM and show that they are typically less than 10 per cent. We note that the spectral resolution of our data (∼16 km s^{-1}) limited this study to relatively fast rotators and that resolutions of 60000 will required to access most late-type dwarfs.

Key words: atomic lines – molecular lines – late-type stars

1 INTRODUCTION

The rotational velocity of a star is one of the basic parameters which can be obtained from its spectrum. Much efforts has been devoted to the determination of surface rotation of objects like protostars (Doppman et al., 2005) and main sequence stars with spectral types from mid-F (Charbonneau et al., 1997) through mid-M (Delfosse et al., 1998) until mid-L (Mohanty & Basri, 2003) dwarfs.

Precise determination of stellar rotational velocities are useful for many different analyses. Investigations have been devoted to the study of connection between v sin i and stellar activity (e.g., Noyes et al. 1984, Patten & Simon 1996, Reiners & Basri 2008). Stellar activity (chromospheric and coronal) increases with increasing of v sin i for mid-F to mid-M dwarfs. However the rotational velocities distribution for stars later than M7V differs from the one for early types (e.g., Jenkins et al. 2009), which is likely caused by the onset of fully convective interiors for spectral types ∼ M3V and later (see e.g., Reiners & Basri 2008). Moreover correlations of rotational velocity with spectral type and age were investigated both for stars of open clusters (Prosser et al., 1996; Stauffer et al., 1994, 1997) and for field stars (Delfosse et al., 1998).

Most studies devoted to determination of rotational velocities used optical spectra and known velocity templates (Jenkins et al. 2009, West & Basri 2009, Bailer-Jones 2004). Recent progress in observational equipment provides spectra of relatively faint dwarfs in the infrared at high resolution and make it possible to use them in v sin i determinations (e.g., del Burgo et al. 2009, Reiners 2007, Lyubchik et al. 2007). Such studies should help provide a better description of stellar parameters such as T_{eff} , log g, atmospheric element abundances for late type dwarfs where they are rather uncertain (e.g. Jones et al. 2005, Johnson & Apps 2009). In this paper we focus on the derivation of rotational velocities in the infrared K band where there is a good match between observational and theoretical spectra. This match allows rotational velocities to be derived using theoretical spectra and to quantify the errors on derived stellar properties in a manner not feasible when using template velocities.

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2 PROCEDURE

2.1 Observational spectra

For our derivation of rotational velocities, we used the spectra of late-type dwarfs presented in Doppmann et al. (2005). These near infrared spectra were obtained with the 10m Keck II telescope on Mauna Kea, Hawaii using the NIRSPEC spectrograph during several observing runs. The details of the observations and reduction procedures are described in Doppmann et al. 2005. The resolution of the observed spectra is ∼18000 (Doppman et al. 2005), which corresponds to a rotational velocity of ∼16 km s^{-1} for the spectral regions of our interest. These stars are used as standards in several studies of the properties of embedded young stars, including their evolutionary states (Doppmann et al. 2005), rotational and radial velocities (Covey et al. 2005, 2006), and magnetic field strengths (Johns-Krull et al. 2009).

2.2 Synthetic spectra

Synthetic spectra were computed using the WITA6 programme (Pavlenko, 2000). Calculations were carried out under the assumption of the local thermodynamic equilibrium, hydrostatic equilibrium and in the absence of sources and sinks of energy. The atomic line list used for our spectral modelling and line identification is taken from the VALD (Kupka et al. 1999). The solar abundances reported by Anders & Grevesse (1989) were used in calculations. All details of other input parameters are described by Pavlenko, Zapatero Osorio, Rebolo (2000).

For the computation of the synthetic spectra we used molecular line lists from different sources:

•Water vapour is the main contributor to the line opacity across most of the infrared for late type M dwarfs and brown dwarfs. There are several H_2O line lists which are used at present time in computations of synthetic spectra of dwarfs (see for details and comparisons of H_2O line lists Pavlenko 2002, Jones et al. 2002, 2003, 2005). In our computations we used the BT2 line list (Barber et al. 2006)

• To model CO band at ∼2.3 μm we used line list by Goorvitch (1994).

The relative contributions of these molecules to the formation of the spectra around 2.2 μm are shown in Fig. 1. This figure shows synthetic spectra with effective temperatures 2800 K, 3500 K, 4200 K, log g=5.0, microturbulent velocity $v_{\rm micro}$=2km s^{-1} , [Fe/H]=0.0.

The grid of synthetic spectra was computed from model structures of NextGen (Hauschildt et al. 1999) for the following range of parameters: temperatures from 2500 to 5000 K, log g from 4.5 to 5.5, microturbulent velocities from 1 to 3 km s^{-1} and metallicities from -0.5 to 0.0.

Theoretical spectra were computed with a wavelength step of 10^{-5} μm and convolved with Gaussians to match the instrumental broadening (R∼18000). The rotational broadening of spectral lines is implemented following Gray (1976).

2.3 Testing of model atmospheres parameters and synthetic spectra.

In most papers the determinations of v sin i are made with reference to template spectra (e.g., Mohanty & Basri 2003, Reiners & Basri 2008). Such determinations are based on the assumption that the choice of rotational velocity standard is appropriate. However, in practice rotational velocity standards may have quite different physical properties though share similar spectra. The primary goal of our paper is to obtain the rotational velocities using synthetic spectra. For these purposes we investigate the affect of small changes in temperature, metallicity, gravity, microturbulent velocity and FWHM on v sin i determination in the spectral region of our interest 2.2670–2.3050 μm .

Our tests are based on the automatic minimization procedure of Pavlenko & Jones (2002).

Table 1 presents the results of analysis for synthetic spectra with effective temperatures 2800 K, 3500 K and 4200 K and v sin i -s 10, 20 and 35 km s^{-1} . Other model atmosphere parameters were fixed: log g = 5.0, $v_{\rm micro}$ = 2km s^{-1} and [Fe/H] = 0.0. Hereafter all these parameters are called reference ones.

First, we analysed how our determination of v sin i value reacts to increasing and decreasing of the FWHM parameter. Synthetic spectra were computed with reference model atmosphere parameters and then convolved with fixed FWHM which correspond to the R = 18000 (16.65 km s^{-1}) in 2.2670–2.3050 μm wavelength region. Then we changed the instrumental profile width within the limits of 10 per cent. Deviations of the determined v sin i values from the reference v sin i -s are presented in column 3 of the Table 1. Once the resolution limit is exceeded, the errors in rotational velocities determination depending on instrumental profile decrease to a few per cent. Using synthetic spectra at v sin i = 10 km s^{-1} , the errors are higher, but remain less than 20 per cent, which is equal to 2 km s^{-1} , the average accuracy for v sin i determination with template spectra.

Other columns of the Table 1 present the percentage deviations of v sin i -s determination for model atmospheres Δ-s of $T_{\rm eff}$, log$g$, $v_{\rm micro}$ and [Fe/H] from the reference v sin i -s. Macroturbulent velocity is masked by using a Gaussian profile for the FWHM, so we didn't analyse this parameter. Errors in v sin i -s determination related to the deviations of model atmosphere parameters are larger than in the case of FWHM. Partially it is caused by the relatively large step of parameters in available model atmospheres. Even so the errors are at the ∼10 per cent level with the only exception being the gravity parameter at 4200 K where the errors increase to 11-23 per cent.

Our investigations indicate that the errors for the reference value v sin i =10 km s^{-1} arise from minimization procedure errors while computing v sin i values less than instrumental resolution, so in the Table 1 the model differences are denoted in italic font. Thus for the precise determination of rotational velocities we should use the spectra with a resolution comparable or higher than the v sin i .

3 RESULTS OF v sin i DETERMINATIONS.

Using our grid of synthetic spectra we investigate the best fits to the observed spectra from Doppmann et al. (2005)

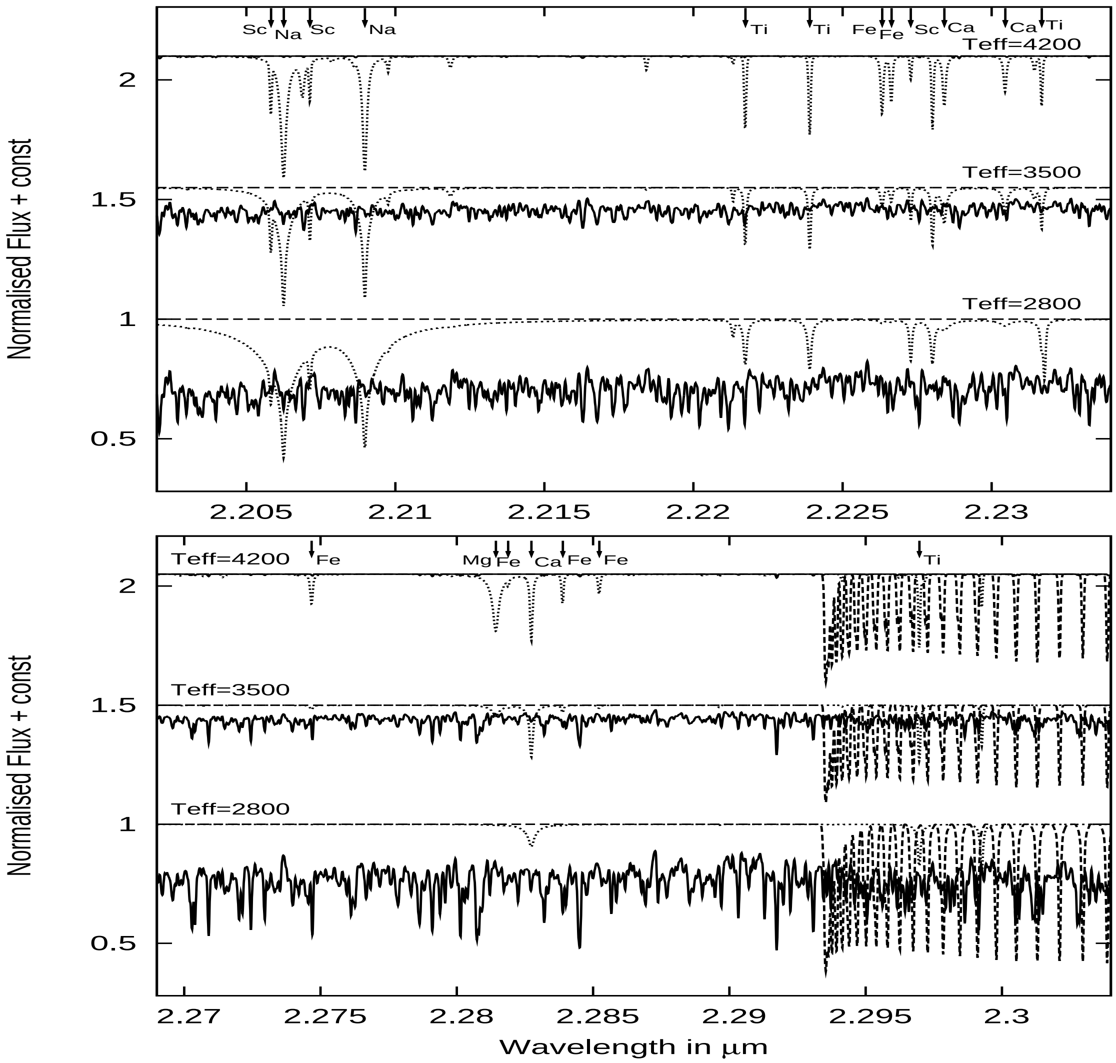

Figure 1. The relative contribution of different opacity sources to the stellar spectra is shown (atomic spectra are in dotted lines, molecular spectra of CO and H_2O in dashed and solid lines, respectively).

Table 1. v sin i deviations based on an automatic minimization procedure for different model atmosphere parameters.

Reference model $T_{\rm eff}$ (K), v sin i (km s^{-1})		+/-0.1 of FWHM	$\Delta T_{\rm eff}$, +/-100K	$\Delta \log g$, +/-0.5dex	$v_{\rm micro}$ +/-1km s^{-1}	Δ[Fe/H] -0.5dex
		per cent	per cent	per cent	per cent	per cent
2800	10	*18.0 / 10.0*	*20.0 / 25.0*	*15.0 / 5.0*	*20.0 / 20.0*	*10.0*
	20	2.0 / 3.0	7.5 / 12.5	10.0 / 2.5	9.8 / 9.8	2.5
	35	<1.0 /<1.0	5.7 / 8.6	5.7 / 2.9	4.2 / 7.0	2.9
3500	10	*14.6 / 12.5*	*5.0 / 5.0*	*35.0 / 45.0*	*20.0 / 25.0*	*45.0*
	20	2.0 / 2.0	2.5 / <1.0	10.0 / 20.0	10.0 / 10.0	15.0
	35	<1.0 /<1.0	1.4 / 1.4	7.1 / 11.4	5.7 / 5.7	8.6
4200	10	*16.3 / 12.2*	*5.0 /10.0*	*70.0 / 40.0*	*20.0 / 20.0*	(*)
	20	2.0 / 2.0	2.5 / 5.0	22.5 / 17.5	10.0 / 10.0	(*)
	35	<1.0 /<1.0	1.4 / 2.9	14.3 / 11.4	5.7 / 5.7	(*)

(*) – we had no low metallicity model atmosphere for this temperature.

which provide partial coverage from 2.0814 to 2.3040 μm (2.0800–2.1150 μm - Mg 2.1066 μm and Al 2.1099 μm strong lines; 2.1380–2.1750 μm - region containing of H I Brγ 2.1661 μm line; 2.2000–2.2390 μm - strong Na 2.2062 and 2.2090 μm lines; 2.2670–2.3050 μm region with CO 2-0 band head at 2.2935 μm). We show the fits of synthetic spectra to the observed VB 10 (M5 V) in all spectral regions of interest as example on Fig.2. The positions of atomic lines according to the VALD are labeled by arrows on the top of each panel.

We found that our automatic procedure works better for hotter stars, where the contribution of strong molecular water lines is lower or has almost disappeared. However, for the cooler stars we found that the v sin i values derived from the Na lines (2.2062 and 2.2090 μm) and the CO band lines were usually considerably lower than those derived from other features. Rather than attribute such differences to astrophysical causes we believe this arises because the Na and CO features are intrinsically stronger than other spectral features and thus suffer less from blending with weak worse modelled lines, mostly H_2O. We focus on two particular regions of interest: 2.2000–2.2390 μm (specifically around the strong Na doublet), hereafter "Na-region" and 2.2670–2.3050 μm (specifically around the region with CO band lines), "CO-region" hereafter in the text. Figure 1 shows these spectral ranges and the identification of other atomic lines in these regions: Fe, Sc, Ti, Mg, Ca and Cr. Fig. 3 along with panels c and d of Fig.2 show the examples of best fit synthetic spectra for Na- and CO-regions for stars of different spectral types.

Tables 2 and 3 present the effective temperature and v sin i determinations for the whole sample of stars from M9.5 to G8 spectral types for the different spectral regions. The optical spectral and luminosity classes taken from Simbad database (*http://simbad.u-strasbg.fr/simbad/*) are also shown. In this work, initial effective temperature estimates were assigned on the based of spectral class using Tsuji et al. (1996) for M dwarfs, Allen (1973) for K dwarfs, and Doppmann & Jaffe (2003) for G subdwarfs. Log g is defined by fitting to the wings of Na lines in observed spectrum.

The best fit synthetic spectra are uncertain to within the range of $\pm\Delta$-s of model atmosphere parameters. The standard NextGen (Hauschildt et al. 1999) model atmospheres grid steps $\Delta T_{\rm eff}$ = 100 K for the temperatures below 4000 K and 200 K above, Δlog g = 0.5 and Δv sin i = 2km s^{-1} for determinations of upper limit values of v sin i are used. We used Solar metallicities for all stellar atmospheres calculations.

For stars with available from literature rotational velocity values, column (7) in the Tables 2 and 3 gives the v sin i -s determined using templates. In Mohanty & Basri (2003) (hereafter MB03) this was Gl406 with v sin i less than 3 km s^{-1} , in Marcy & Chen (1992) (hereafter MCh92) Gl 411 and Gl 820B with rotational velocities less than 2 km s^{-1} were used, so two v sin i values are given. In Duquennoy & Mayor (1988) v sin i values were obtained using the widths of the cross-correlation dips based on calibration of Benz & Mayor (1981, 1984). The v sin i determination by using of cross-correlation function was studied by other authors. Hartmann et al. (1986) and Rhode et al. (2001) indicate that this technique allows v sin i determinations at the 90 per cent confidence level, so the errors are less than 10 per cent.

The differences in the derived model atmosphere parameters for some stars are at the same level as the model grid step. For $T_{\rm eff}$ and v sin i determinations of M dwarfs only strong atomic lines like Na I 2.2062 μm , 2.2090 μm , and lines of CO molecule can be used. For hotter stars: Mg I 2.2814 μm , Ti I 2.2217, 2.2239, 2.2316, 2.2969 μm can be used.

In Table 2 we present the v sin i determinations for three stars with rotational velocities greater than the instrumental resolution limit. For all stars we provide 2 values of $T_{\rm eff}$ and v sin i to show the impact of $T_{\rm eff}$ on v sin i determination. Features are shown in Fig.4. Looking at the sample as a whole in Table 2, it appears that Na and CO derivations of v sin i are consistent within the error bar with values of Mohanty & Basri (2003) derived using template spectra. We can note a bit systematically higher value of v sin i -s derived from the "CO-region" than from Na lines. In the "CO-region" water lines are slightly stronger (see Fig.1) and so can add some 'extra broadening' to the CO features.

We should note that GJ569B and GJ1245A are known to be close orbiting binary systems and this may affect the observations analysed here. Our GJ569B spectra are formed by a near equal mass and spectral type components: GJ569Ba M8.5V and GJ569Bb M9V (e.g., Lane et al. 2001). Our GJ1245A spectra consist of GJ1245A (M5.5V) and GJ1245C spectra. GJ1245C is 3.3 magnitudes fainter in the V band (Henry et al. 1999) and so can only make a minor contribution at K band.

Table 3 shows the v sin i upper limit determination for 16 stars in a wide range of spectral classes from M9 to G8. We don't show the v sin i errors in columns 4 and 6, but from the analysis in section 2 we adopt that accuracy is about $\pm$2–4 km s^{-1} . The usefulness of such upper limits values consists in v sin i determination through a wide range of spectral types using the synthetic spectrum method.

4 DISCUSSION

Due to ongoing improvements in input data and synthetic spectra, modelling is becoming a precise method for the determination of stellar atmosphere parameters including rotational velocities. Although there are many remaining uncertainties with abundance patterns (Gustafsson 2004), 3D modelling (Pereira 2009), NLTE (see Melendez et al. 2009), the synthetic spectra of solar type stars are relatively well determined. For the case of cool dwarf stars, the conditions of fully convective atmospheres and dust formation means that still there are some uncertainties with the model structures (e.g., Pavlenko et al. 2007). The presence of many H_2O, FeH and other molecular lines in the infrared region also makes spectral analysis and stellar parameter determination rather difficult (see e.g. del Burgo et al. 2009). For example, in the case of cool dwarf atmosphere conditions broad wings of resonance lines are overlapped by blends of numerous molecular lines. It is very challenging to analyse the pure shape of lines in such spectra and to separate the noise effects from the errors in molecular lines modelling.

In this paper we show the perspective of K band region, especially individual features like Na or CO lines, using for model atmosphere parameters determination. This region is suitable for such task because only H_2O molecules play a

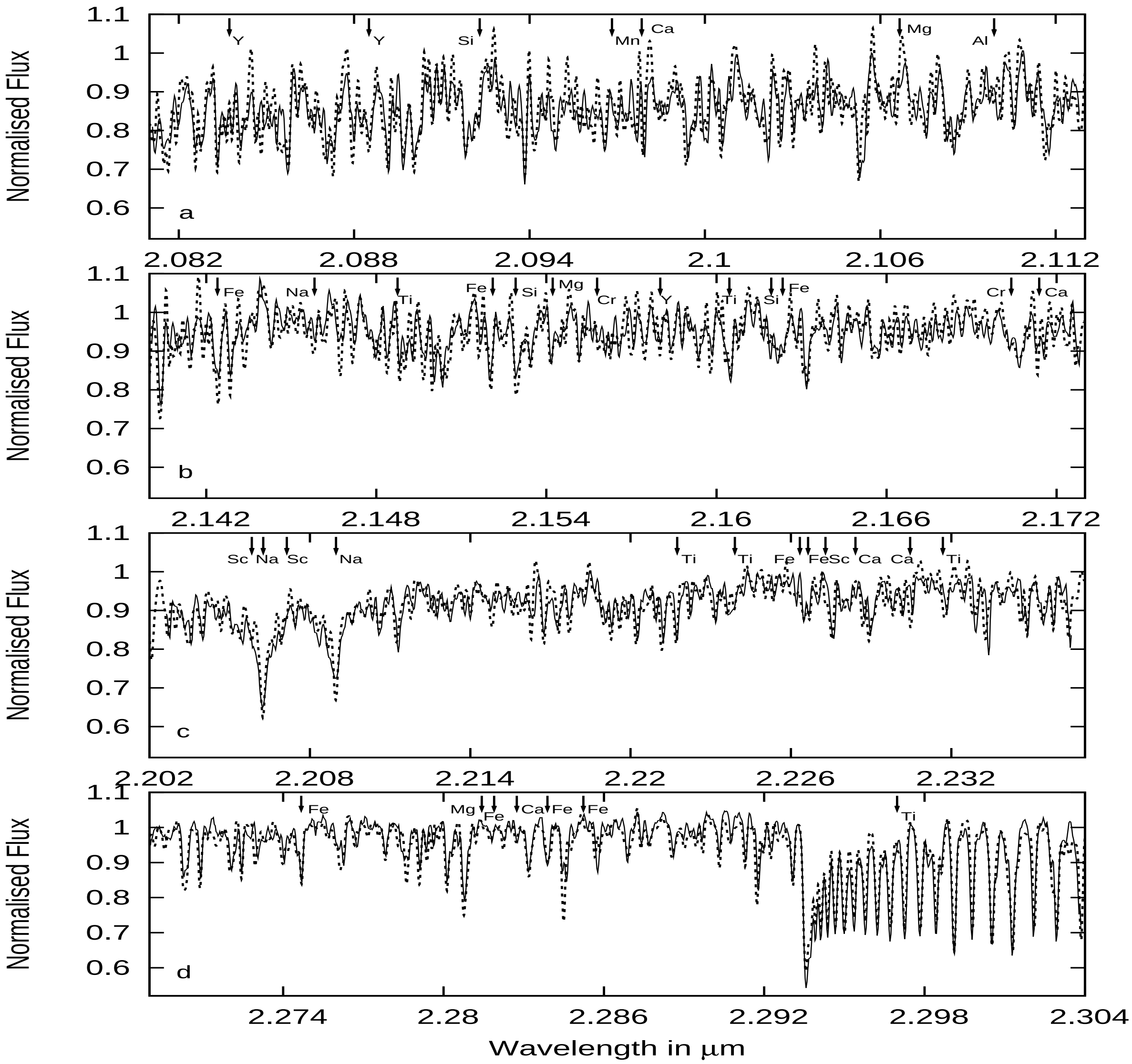

Figure 2. Synthetic spectra (dashed line) fitting to the observed spectra of VB 10 (solid line) in the regions of interest.

Table 2. v sin i determinations for the regions of the K band Na doublet and CO band.

		"Na-region" T_{eff} / logg	v sin i	"CO-region" T_{eff} / logg	v sin i	v sin i lit.	Ref.
GJ569B	M8.5 V	2400 / 5.0	19.0±6.5	2400 /5.0	32.0±6.5	—	
		2500 / 5.0	27.0±1.0	2500 /5.0	28.0±1.0		
GJ1245A	M5.5 V	3000 / 5.5	27.0±1.0	3000 / 5.5	27.0±1.0	22.5±2.0	MB03
		3100 / 5.5	23.0±1.0	3100 / 5.5	24.5±1.0		
GJ791.2	M4.5 V	3200 / 5.5	31.5±3.0	3200 / 5.5	37.5±3.0	32±2.0	MB03
		3300 / 5.5	34.0±1.0	3300 / 5.5	35.5±1.0		

MB03 - Mohanty & Basri 2003

significant role in formation of late type stars spectra here (see Fig.1 and Pavlenko et al. 2006). Around 2.2 μm there is a good match between observational and synthetic spectra. This circumstance makes the K band region preferable to the optical region where there is strong TiO and VO absorption and the J band (around 1.1 μm), where FeH and CrH along with H_2O make spectral analysis much more difficult.

Although there are no established standards for rotational velocity determinations for late type stars, usually these values are determined using the spectrum of a slowly rotating star with a close spectral type as a template star.

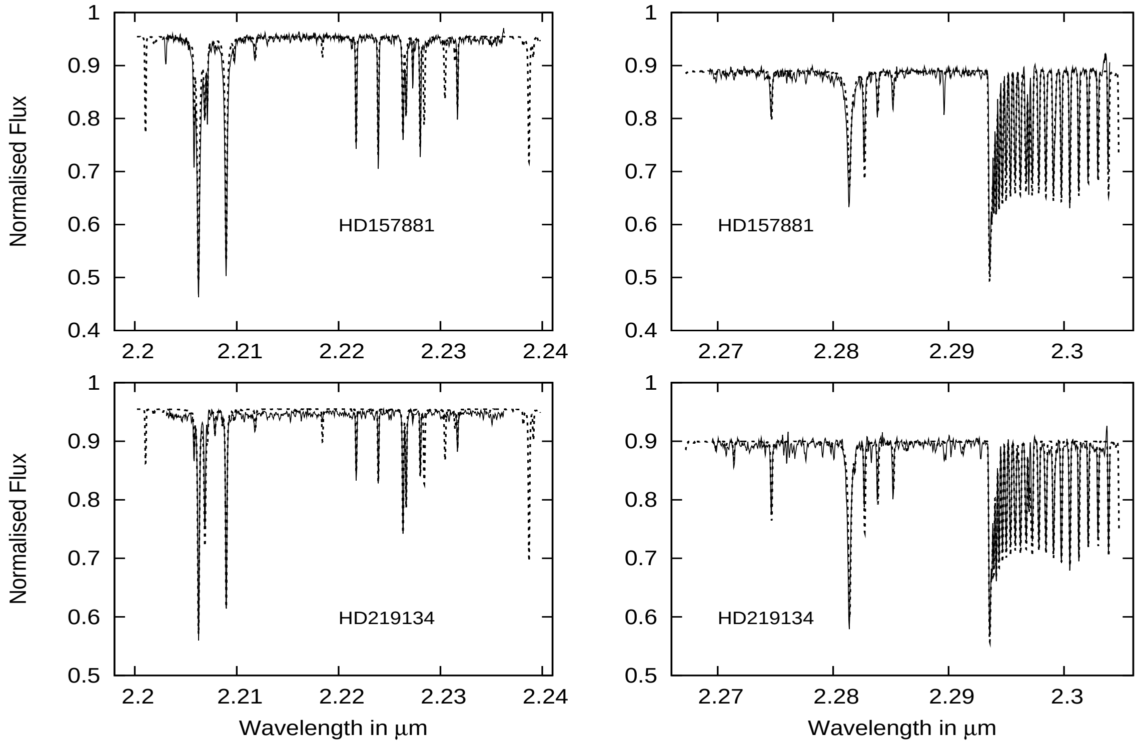

Figure 3. Synthetic spectra (dashed line) fitting to the observations (solid line) for the "Na" (left panels) and "CO" (right panels) regions for stellar spectra of K type stars .

Table 3. v sin i upper limit determinations for the regions of Na doublet and CO band. Spectral types for observed stars were taken from the Simbad database (http://simbad.u-strasbg.fr/simbad).

		"Na-region" T_{eff} / log$g$	v sin i	"CO-region" T_{eff} / log$g$	v sin i	v sin i lit.	Ref.
LHS2924	M9 V	2500/5.0	*18*	2600/5.0	*14*	11.0±2.0	MB03
VB10	M8 V	2800/5.0	*12*	2800/5.0	*10*	6.5±2.0	MB03
VB8	M6.5 V	2900/5.0	*10*	2800/5.0	*12*	9.0±2.0	MB03
GJ4281	M6.5 V	2800/5.0	*16*	2900/5.0	*13*	7.0±2.0	MB03
GJ569A	M2.5 V	3500/5.0	*12*	3400/5.0	*12*	4±0.6/2.9±0.8	MCh92
GJ806	M1.5	3600/5.0	*10*	3600/5.0	*12*	1.5±0.8/3.7±1.6	MCh92
HD131976	M1 V	3700/5.0	*11*	3700/5.0	*13*	10.6±2.5	DM88
HD184489	K5 V	4000/5.0	*15*	4000/5.0	*15*		
HD201091	K5 V	4200/5.0	*16*	4200/5.0	*15*		
HD157881	K5 IV	4200/5.0	*10*	4200/5.0	*11*		
ADS14636	K5 V	4000/5.0	*13*	4200/5.0	*14*		
HD219134	K3 V	4800/5.0	*10*	4800/5.0	*10*		
HD168387	K2 III	4400/4.0	*14*	4400/4.0	*12*		
HD166620	K2 V	5000/5.0	*12*	5000/5.0	*13*		
HD175225	G9 IV	4800/4.5	*14*	5000/5.0	*13*		
HD182572	G8 IV	4800/4.5	*13*	5000/5.0	*20*		

DM88 - Duquennoy & Mayor 1988; MCh92 - Marcy & Chen 1992; MB03 - Mohanty & Basri 2003

Mohanty & Basri (2003) used as template spectrum M6 dwarf Gl 406, Marcy & Chen (1992) spectra of two dwarfs: Gl 411 M2 and Gl 820B M0/K7. A choice of template can affect the result as it is seen in column 7 of Table 3. On the other hand the synthetic spectra method depends mainly on input parameters. In section 2 we have shown that model atmosphere parameters deviations in boundaries of standard model atmosphere grid steps will bring errors of as much as 10 per cent in the region around 2.2 μm .

For stars with rotational velocities above the resolution limit of observed data, our determinations of v sin i and results using the template method are within the error bar (Table 2). Unfortunately the spectral resolution of our observations corresponds to v sin i ~16 km s^{-1} which allows us to perform the accurate analysis only for the fast

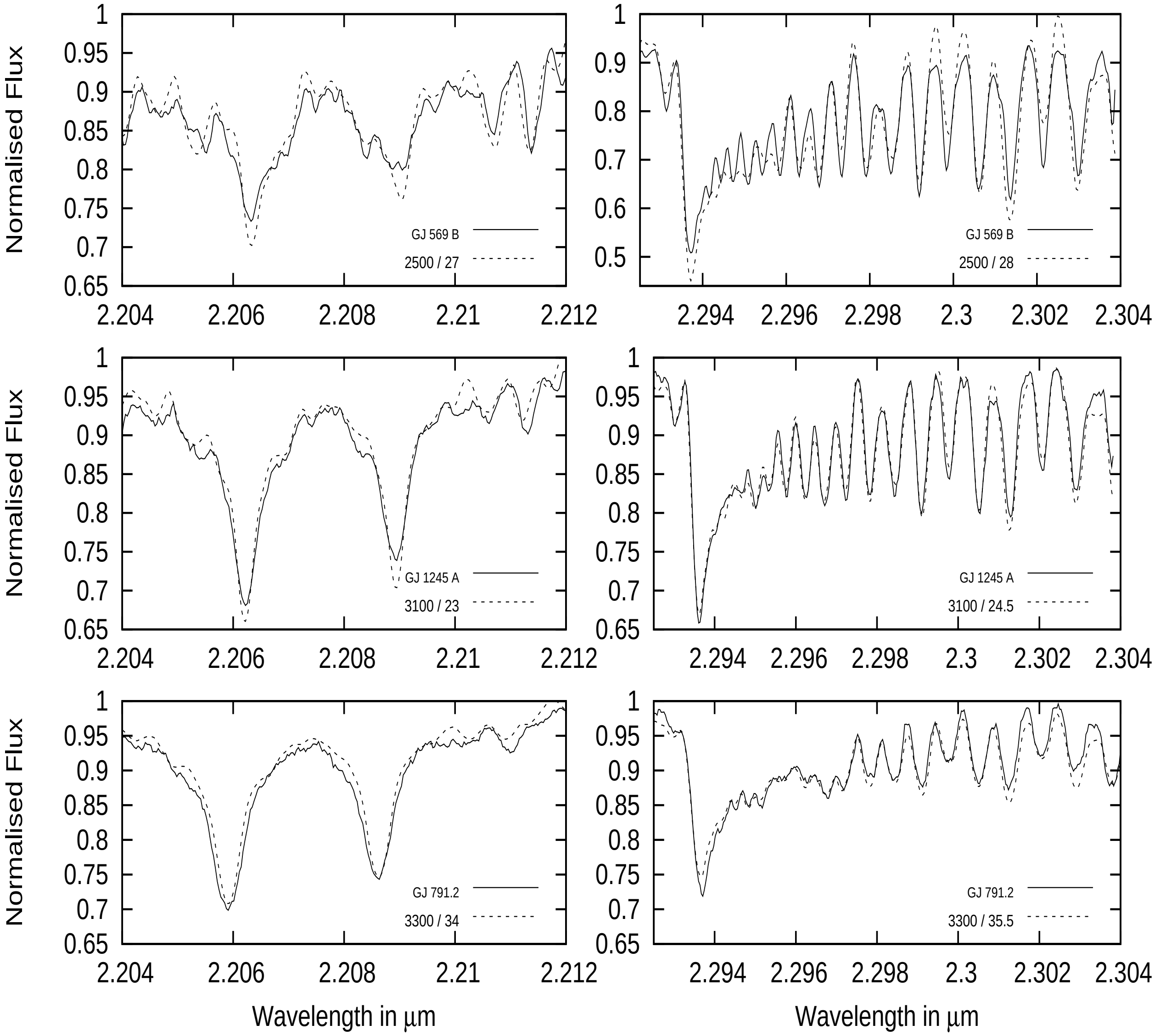

Figure 4. Synthetic spectra (dashed lines) of Na (left) and CO (right) lines fitting to the observed spectra (solid line). $T_{\rm eff}$, K / v sin i , km s^{-1} are shown for modelled spectra.

rotators. For determination of the rotational velocities of slow rotating M dwarfs with v sin i $\sim$ 5 km s^{-1} one should have the observations with spectral resolution better than ∼60000. It is worth noting that determination of rotational velocities on a level of a few km s^{-1} become complicated by uncertainties of model atmosphere parameters. Deviations of effective temperature, gravity, microturbulent or macroturbulent velocities and other parameters lead to errors of v sin i determination at the level of 1–2 km s^{-1} . But in spite of these uncertainties we are sure that synthetic spectra method applied to suitable spectra in infra red region will be useful in the determination of v sin i (and other parameters). When the new generation of infrared instruments, e.g. APOGEE-like projects (http://www.sdss3.org/surveys/apogee.php), start to work such techniques will enable reliable automated v sin i determination.

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