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Characterization of 36 late M-dwarfs using spectral energy distributions and near-infrared echelle spectra

C. del Burgo[1], Ch. Helling[2], E. L. Martín[3], S. Witte[4], M. R. Zapatero Osorio[3], and P. H. Hauschildt[4]

[1] Instituto Nacional de Astrofísica, Óptica y Electrónica, Luis Enrique Erro 1, Sta. Ma. Tonantzintla, Puebla, Mexico, e-mail: cburgo@inaoep.mx
[2] SUPA, School of Physics and Astronomy, University of St Andrews, St Andrews, KY16 9SS, UK
[3] CAB (CSIC-INTA), Ctra. Ajalvir km 4, 28850 Torrejón de Ardoz, Madrid, Spain
[4] Hamburger Sternwarte, Gojenbergsweg 112, 21029 Hamburg, Germany

Abstract. The aim of the study presented here is to determine the physical and kinematical properties of a sample of 36 nearby M-dwarfs, with spectral types M5-M9.5. Echelle spectra in the J-band were obtained using the *NIRSPEC* spectrograph on the Keck II telescope, with a resolving power of 22,000, at different epochs. The comparison of the observed spectra with stellar atmosphere models derived from the Phoenix and the Drift-Phoenix codes, has permitted the determination of the effective temperature ($T_{\rm eff}$), surface gravity ($\log g$), and rotational broadening ($v_{\rm rot} \sin i$) of the 36 M-dwarfs, assuming solar-like metallicity. This approach turned out to be quite insensitive to $T_{\rm eff}$ in the spectral type range from M5 to M9.5, which motivated us to use a different method. Thus, *2MASS* J, H and K, and *WISE* $W1$, $W2$ and $W3$ photometry, which covers a wide wavelength range that includes the emission peak of our targets, was compared with the BT-Settl-Phoenix code to alternatively derive $T_{\rm eff}$ for every M-dwarf. The so obtained values of $T_{\rm eff}$ are consistent with other near-infrared studies. Our investigation shows some limitations of current theoretical models and methods. Although late M-dwarfs are difficult to model given their intrinsic faintness and atmosphere complexity, a proper characterization of them is necessary to better conduct the next generation of radial velocity surveys, which are aimed at searching for rocky planets around those stars.

Key words. Stars: M-dwarfs – Stars: atmospheres – Stars: physical properties – Models: stellar atmospheres

1. Introduction

Most of the stars in the vicinity of the sun and our Galaxy are M-dwarfs (van de Kamp 1971; Bochanski 2010), which have $\lesssim$0.5 solar masses and effective temperatures below 4,000 K. Models of their atmospheres have been developed for quite some time (Auman 1969; Mould 1975). Their cool at-

Send offprint requests to: C. del Burgo mospheres permit the formation of molecules (e.g., TiO, VO, H_2O), which results on much more complex spectra than those of warmer stars. Very late M-dwarfs have convection-dominated structures, strong magnetic fields and high-levels of activity (e.g., flares and spots), which difficult even more the theoretical model synthesis to give account on their atmospheres.

Most stars with spectral types M5-M9.5 are expected to be very low-mass field dwarf stars, although some of them could be young brown dwarfs (Martín et al. 1999). In fact, it is observed that brown dwarfs start with spectral types M6.5 or later in the well-studied Pleiades cluster (Martín et al. 1996). It is also observed that late M-dwarfs are fast rotators that show activity. Precise measurements of the rotational broadening or projected rotational velocity of M-dwarfs is key to prepare radial velocity surveys to be carried out with the next generation of high-resolution near-infrared (NIR) spectrographs, which are developed to search for rocky planets around cool dwarfs. Accurate determinations of the other properties of these stars such as radius and mass are also necessary in order to precisely derive the properties of their hosted planets. Moreover, a better characterization of cool dwarfs will bring key information concerning stellar physics, galactic structure as well as its formation and evolution.

This study is an extension of the investigation carried out by del Burgo et al. (2011) and del Burgo et al. (2013). It is aimed at determining the physical and kinematical properties of a sample of 36 M-dwarfs with spectral types M5-M9.5. They are the targets of an observational program designed to search for exoplanets orbiting around them using the radial velocity method. We used two different approaches based on the comparison of stellar atmosphere theoretical predictions with: 1) moderate-resolution $J-$band spectroscopy, and 2) broad-band NIR photometry.

Section 2 summarizes the observations, stellar atmosphere models used, and data processing applied for the NIR echelle spectra. Sect. 3 describes the photometry and models used, and the data processing. Sect. 4 is devoted to the presentations of the results and their discussion. Sect. 5 summarizes our conclusions.

2. NIR echelle spectroscopy

2.1. Observations and data reduction

Observations of 36 M-dwarfs, with $7.09 < J < 13.24$, were performed with the NIR echelle spectrograph NIRSPEC/Keck II at different epochs: 2007 April 30th, June 24th, 25th, October 25th, 26th and December 23rd, 24th. The instrumental setup was fixed to obtain ten echelle orders in the $J-$band, from 1.148 to $1.346\,\mu m$. The nominal dispersion varies from 0.164 Å pix^{-1} to 0.191 Å pix^{-1} towards longest wavelengths, and the final resolution element is $0.55 - 0.70$ Å at $1.2485\,\mu$m, corresponding to a resolving power $R \approx 22,000$. Data reduction was performed with the *echelle* package of IRAF[1]. More detailed descriptions of the observations and data processing can be found in Deshpande et al. (2012) and Zapatero Osorio et al. (2006).

2.2. Stellar atmosphere models

Two distinct grids of stellar atmosphere models have been considered in our analysis. For $T_{\rm eff} <$ 3000 K, we used the Drift-Phoenix (Witte et al. 2009) code, which solves the classical 1D model atmosphere problem (radiative transfer, mixing length theory, hydrostatic equilibrium, gas-phase chemistry). It makes use of the general-purpose stellar atmosphere Phoenix code (Hauschildt & Baron 1999) coupled to a cloud formation model (nucleation, surface growth and evaporation, gravitational settling, convective replenishment, element conservation (Helling et al. 2006). Each of the model atmospheres is determined by $T_{\rm eff}$, $\log g$ (with g in cm s^{-2}), and a set of element abundances, which have been chosen to be solar. These element abundances are altered where dust forms. The cloud's opacity is calculated applying Mie

[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

and effective medium theory. For $T_{\rm eff} \geq 3000$ K, we used the version v16 of Phoenix. This version includes a number of improvements compared to previous ones, such as a complete new equation of state for ions, molecules and condensation, updated opacity databases, and improved line profiles for atomic lines.

2.3. Data processing

The range of $T_{\rm eff}$ considered for this analysis was from 1500 to 3500 K (steps of 100 K). For the surface gravities $\log g$ values between 3.5 and 5.5 (steps of 0.5 dex) were used. The models were transformed in order to mimic the observing set-up of the NIRSPEC spectra and make possible their comparison. First, the formalism of Gray (1992) was applied to the models to take into account the rotational broadening $v_{\rm rot} \sin i$, with values between 0 and 100 km s^{-1} (steps of 1 km s^{-1}). The resulting models were convolved with a Gaussian to match the instrumental profile along the dispersion axis, and then rebinned to the wavelength step of the observations. Finally, models and observed spectra were normalized, dividing by the flux integrated over the wavelength range for every echelle order.

All observed spectra were Doppler shifted for a proper comparison with the grid of models. The resulting radial velocities are not presented here. In order to constrain the number of possible solutions (in the parameter space of $v_{\rm rot} \sin i$, $T_{\rm eff}$ and $\log g$) provided by our large grid of models, the root-mean-squares RMS of the differences between observed spectra and models are obtained in the same fashion as in del Burgo et al. (2009). Thus, the best model is that for which RMS is minimum. Uncertainties are half of the steps used to create the grid for $v_{\rm rot} \sin i$, $T_{\rm eff}$ and $\log g$.

We used the strong absorption doublet at 12432 and 12522 Å for the determination of the stellar parameters because we observed that the other echelle orders are not so sensitive to $T_{\rm eff}$ (del Burgo et al. 2013). The synthetic models reproduce reasonably well the haze of absorption features, which is particularly significant in the wavelength range 1.327-1.346 μm, with abundant water vapor, although the strength of some faint features is not so well reproduced. This is partly due to line modeling, but also to flat-fielding and telluric line subtraction issues.

3. NIR photometry

2MASS J, H and K and *WISE* W1, W2 and W3 photometry for our sample of M-dwarfs were downloaded from the NASA/IPAC Infrared Science Archive (IRSA).

3.1. Stellar atmosphere models

For the comparison with the collected NIR photometry BT-Settl-Phoenix models (Allard et al. 2012) were used. At the time of performing this analysis they were the only models with theoretical predictions for the long wavelengths corresponding to WISE bands. Rajpurohit et al. (2013) found a good consistenty between the BT-Settl-Phoenix models and the Drift-Phoenix models. Both models use the Phoenix code, although they present some differences when describing cloud formation in cool dwarfs.

3.2. Data processing

2MASS J-band and *WISE* $W1$ images for every single object were checked to make sure its position and photometry for both systems match well, which is particularly important for those M-dwarfs with a high proper motion.

Tables with the photometric data corresponding to every M-dwarf were created to feed the spectral energy analyzer VOSA (Bayo et al. 2008), which includes the BT-Settl-Phoenix to compare with the photometry and extract the properties of the object as given by the best fit.

4. Results and discussion

4.1. Stellar kinematics

Figure 1 shows rotational broadenings $v_{\rm rot} \sin i$ obtained by us versus those of Deshpande et al. (2012). They correlated the M-dwarf spectra with templates of slowly rotating dwarfs of similar spectral type. We find that our values of

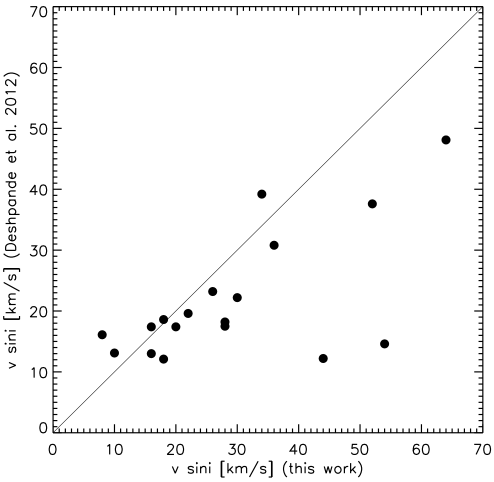

Fig. 1. Rotational broadenings $v_{\rm rot}\sin i$ determined here versus those of Deshpande et al. (2012) for all M-dwarfs where these authors could derive a value. The solid line correspond to the 1:1 relation.

$v_{\rm rot}\sin i$ for LP412-31 and LP413-53 are significantly larger. Note that the resolution element is $\sim 12\,{\rm km\,s^{-1}}$. We also note the $v_{\rm rot}\sin i$ scatter increases towards late spectral types. These findings are consistent with those found in the literature (Konopacky et al. 2012). We will discuss these results in more detail in a forthcoming paper (del Burgo et al. 2013, in prep.).

4.2. Stellar physics

Figure 2 plots the spectral type versus $T_{\rm eff}$. It is observed that $T_{\rm eff}$ as obtained in Sect. 2 only decreases slowly with spectral type. Thus, there are significant differences in the values of $T_{\rm eff}$ estimated from the two methods (see Sections 2 and 3) for late M-dwarfs. The values of $\log g$ obtained from both methods are between 4.5 and 5.5.

The low sensitivity of the $J-$band to $T_{\rm eff}$ was already observed by del Burgo et al. (2009) in a sample of T dwarfs observed with NIRSPEC too. They found that the eleven brown dwarfs have nearly the same effective temperature of about 1000 K. We also note that the temperature gradient in our sample of M dwarfs is similar to that found by Rajpurohit et al. (2013) from low-resolution spectroscopy in the wavelength range 385-950 nm, with an offset of ~300 K. Current stellar atmosphere models seem to feature a too low overall dust opacity for the late M-dwarfs, which is likely due to the lack of introducing porous or aspherical grains in the modelling.

There is a significant drop of $T_{\rm eff}$ for spectral types later than M8.0 when applying the method described in Sect. 3. It is observed that the values of $T_{\rm eff}$ found by Testi (2009) are in good agreement with our results for late M-dwarfs (see Fig. 2). Both datasets are enclosed by the temperature scales obtained by Bessell (1991) and Luhman et al. (2003). Note that Testi (2009) used low-resolution (R ~100) spectra in the wavelength range 0.85-2.45 μm, which resembles more our observations than those of Rajpurohit et al. (2013).

5. Conclusions

Based on our results, we conclude that:

- NIR echelle spectroscopy is useful to determine the kinematical properties of M-dwarfs. However, a narrow wavelength range around the emission peak of the stars does not seem adequate to determine all their physical properties.
- Studies based on optical photometry may be also affected by systematics since M-dwarfs have their peak at longer wavelengths, around the $J-$band.
- The determination of $T_{\rm eff}$ for M-dwarfs is likely well determined by broad-band near-infrared photometry in a wide spectral range around their emission peaks.

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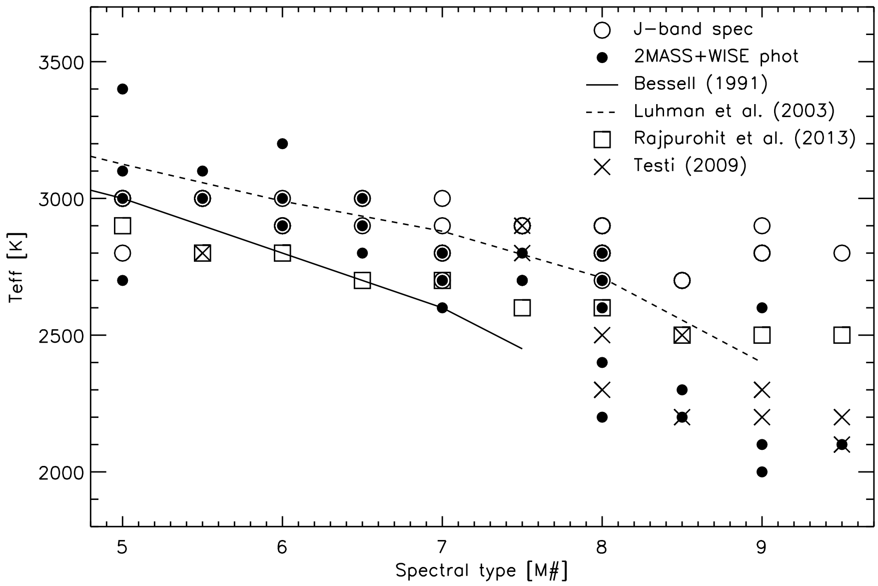

Fig. 2. Spectral type versus T_{eff} according to our two approaches and other authors.

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