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Infrared radial velocities of vB 10[*]

M. R. Zapatero Osorio[1,2], E. L. Martín[1,2,3], C. del Burgo[4], R. Deshpande[3], F. Rodler[5], and M. M. Montgomery[3]

[1] Centro de Astrobiología (CAB-CSIC), Ctra. Ajalvir km 4, 28850 Torrejón de Ardoz, Madrid, Spain
e-mail: zapateroor@inta.es
[2] Formerly at Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain
[3] University of Central Florida, Physics Department, PO Box 162385, Orlando, FL32816, USA
[4] School of Cosmic Physics, Dublin Institute for Advanced Studies, Dublin 2, Ireland
[5] Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain

ABSTRACT

We present radial velocities of the M8V-type, very low-mass star vB 10 obtained at four different epochs between 2001 and 2008. We use high-resolution ($R \sim 20\,000$) near-infrared (J-band) spectra taken with the NIRSPEC instrument on the Keck II telescope. Our data suggest that vB 10 shows radial velocity variability with an amplitude of $\sim$1 km s^{-1}, a result that is consistent with the recent finding of a massive planet companion around the star. More velocity measurements and a better sampling of the orbital phase are required to precisely constrain the orbital parameters and the individual masses of the pair.

Key words. stars: late-type – stars: low-mass, brown dwarfs – stars: individual: vB 10 – techniques: radial velocities – planetary systems – binaries: general

1. Introduction

Over 300 planets are known to orbit main-sequence and giant stars in the solar vicinity (e.g., Udry & Santos 2007). Most of them have been found or confirmed via the radial velocity technique (Mayor & Queloz 1995; Marcy 1998). Recent results suggest that less massive stars (M spectral types) tend to harbor less massive planets (e.g., Neptune-type and smaller). However, the report by Pravdo & Shaklan (2009) indicates that small stars can also have super-planets with masses several times larger than that of Jupiter. These authors present the discovery of an unseen companion (of likely planetary-mass) around the low-mass star vB 10, an object that is widely used as an M8V spectral standard star in the literature (Kirkpatrick et al. 1995; Martín et al. 1996). Actually, with a mass close to the frontier between stars and brown dwarfs, vB 10 is the least-massive star with a known planet. Planets with wider orbits have been found by direct imaging techniques around young brown dwarfs (Chauvin et al. 2004; Béjar et al. 2008). vB 10 is also one of the closest low-mass systems ($d = 5.9$ pc) to the Sun. Pravdo & Shaklan's (2009) work on vB 10 is based on long-term astrometric observations, from which the authors derive the total mass of the pair to be 0.0841 $M_\odot$ and estimate an orbital period of 0.744 yr. These authors discuss that the individual masses are likely 0.0779 $M_\odot$ for the star and 6.4 $M_{\rm Jup}$ for the planet; therefore, an amplitude of 1 km s^{-1} or larger is expected for the radial velocity curve of the primary component (vB 10 A) of the system. Accurate radial velocities of vB 10 are needed to confirm or rule out the presence of the massive planet.

Here, we report on radial velocities obtained from near-infrared, high-resolution spectra. These velocities are measured

to an accuracy below 1 km s^{-1}, which should be enough to study whether vB 10 shows variability and whether such velocity variability is consistent with the predictions of the Pravdo & Shaklan (2009) astrometric solution. vB 10 is brighter in the near-infrared wavelengths than in the optical ($R - J \sim 5.7$ mag). In addition, this object is known to be active with flare events correlating with X-ray and UV emission (Berger et al. 2008, and references therein). It has been discussed that radial velocity measurements of active cool dwarfs have the imprint of stellar activity if measured at optical wavelengths, while "near-infrared" values are less affected by a factor of at least 10 (Martín et al. 2006; Huélamo et al. 2008). We have recovered our past and recent near-infrared spectroscopic observations of vB 10 and we analyzed them in a consistent way to derive radial velocities for different epochs over the interval 2001–2008.

2. Observations and data reduction

As part of our program of radial velocity monitoring of late M-type stars (Deshpande et al. 2008), we observed vB 10 on four different occasions between 2001 and 2008 using the Keck II telescope and the NIRSPEC instrument, which is a cross-dispersed, cryogenic echelle spectrometer employing a 1024 × 1024 ALADDIN InSb array detector (McLean et al. 1998). The 2001 observations were previously reported by us (Zapatero Osorio et al. 2006, 2007), and the two recent epochs (2007 and 2008) are presented here for the first time. We provide the log of the observations in Table 1, where the information related to the 2001 data is also included for completeness. In the echelle mode, we selected the NIRSPEC-3 (J-band) filter and an entrance slit width of 0.432″ (i.e., 3 pixels along the dispersion direction of the detector), except for the 2001 Jun. observations for which we used an entrance slit width of 0.576″. The length of both slits was 12″. All observations were performed at an echelle angle of

Table 1. NIRSPEC *J*-band observing log of vB 10.

Obs. date	UT ($^{h\ m}$)	Slit name	Echelle (deg)	Exposure (s)	Airmass
2001 Jun. 15	14:06	0.576×12	63.00	2×100	1.20
2001 Nov. 2	04:43	0.432×12	62.78	8×120	1.16–1.22
2001 Nov. 2	05:39	0.432×12	63.29	8×120	1.37–1.46
2007 Jun. 25	13:22	0.432×12	63.00	2×120	1.18
2008 Jul. 28	06:07	0.432×12	63.00	2×120	1.48

Fig. 1. NIRSPEC spectra (2007 Jun.) of vB 10 corresponding to the echelle order 60 (fully dominated by telluric line absorption). The *top and bottom* data correspond to vB 10 after and before correction for the telluric contribution. The *middle* spectrum is the hot, featureless star HD 181414 taken on the same date. No velocity shift has been applied, and data are wavelength calibrated in the air system. The total spectral flux is normalized to unity and spectra are shifted vertically by 1.

~63°. This instrumental setup provided a wavelength coverage from 1.148 up to 1.346 μm split into 10 different echelle orders, a nominal dispersion ranging from 0.164 (blue) to 0.191 Å pix^{-1} (red wavelengths), and a final resolution element of 0.55–0.70 Å at 1.2485 μm (roughly the central wavelength of the spectra), corresponding to a resolving power $R \sim 17\,800$ (2001 Jun.) and 22 700 (remaining epochs). Individual exposure times were typically 100 or 120 s for vB 10. Weather conditions (seeing and atmospheric transparency) were fine during the observations, except for the 2008 epoch, which was hampered by cirrus and strong wind.

Raw data were reduced using the ECHELLE package within IRAF[1]. For consistency, the new observations and the 2001 data were reduced following the same procedure described in Zapatero Osorio et al. (2006). Spectra were collected at two different positions along the entrance slit. Nodded images were subtracted to remove sky background and dark current. White light spectra obtained with the same instrumental configuration and for each observation of vB 10 were used to flat-field the data. Individual spectra were optimally extracted with the APALL task, and calibrated in wavelength using the internal arc lamp lines of Ar, Kr, and Xe, which were always acquired after observing vB 10 and before pointing the telescope at the next target. The air wavelengths of the arc lines were identified using the NIST[2] database, and we produced fits using a third-order Legendre polynomial along the dispersion axis and a second-order one perpendicular to it. The mean rms of the fits was 0.03 Å, or 0.7 km s^{-1}. We note that this calibration method may produce systematic errors, or different zero-point shifts in velocity, that have to be removed before deriving precise radial velocities for vB 10. Individual spectra were combined to produce one spectrum for each observing epoch and instrumental setup. In order to correct for atmospheric telluric absorptions, near-infrared featureless stars of spectral types A0–A2 (HD 181414, HD 123233, and HD 189920) were observed close to the observations of our target, although they were not always acquired at the same airmass. The strong hydrogen line at 1.282 μm and other intrinsic lines to these hot stars were removed from the spectra before using them for division into the corresponding science data. Finally, we multiplied the science spectra of vB 10 by the blackbody spectrum for the temperature of 9480 K, which is adequate for A0V type (Allen 2000). All of our final spectra of vB 10 are characterized by a high signal-to-noise (S/N) ratio (S/N estimated at ≥50 for the red wavelenghts), except for the 2008 data, which have a factor of 3–5 lower quality.
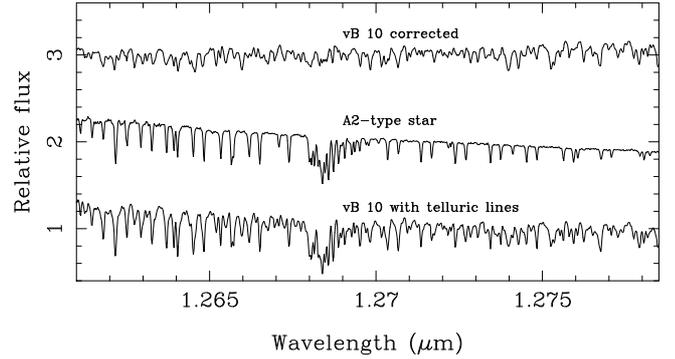
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[1] IRAF is distributed by National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

[2] http://physics.nist.gov/PhysRefData/ASD/lines_form. html

3. Radial velocities

To investigate whether vB 10 shows radial velocity variability, we have measured the object's velocity displacement at all observing epochs relative to a fixed reference, which we have chosen to be the 2007 epoch spectrum because of its high quality. The NIRSPEC data were corrected for any wavelength shift with respect to the reference epoch. To do this, we used the Earth's atmospheric telluric lines imprinted on the data; many of these lines are seen in sharp absorption and they profusely appear in the echelle orders 66, 60, 58, and 57 (from blue to red wavelengths; for the echelle order numbering see Mclean et al. 2007). Figure 1 depicts the spectra of vB 10 and one hot star corresponding to the echelle order 60. The telluric signal is clearly apparent in the spectra of vB 10 before division by the standard hot star, and it dominates over the target signal. The radial velocity of the telluric lines is constant in all wavelengths down to a level of ~±10 m s^{-1} (e.g., Seifahrt & Käufl 2008), which is ≥10 times smaller than the velocity precision we can achieve with NIRSPEC. Such a constancy is applicable over all epochs. These lines thus become excellent calibrators of the wavelength zero points and they can be employed to probe the intrinsic stability of the NIRSPEC spectrograph.

We have cross-correlated the echelle orders heavily covered by telluric lines against the 2007 epoch using the task FXCOR within IRAF. At this step, we cross-correlate only spectra uncorrected for the telluric contribution. Because of the good quality of our data and the marked strength of the telluric features, the cross-correlation functions show clearly defined narrow peaks. The velocity displacements are derived from the center of these peaks. The last column of Table 2 provides the shifts and their associated uncertainties, which are mathematically computed from the errors of the mean shifts. These errors are typically around 200–300 m s^{-1}. Two epochs (2001 Jun. and the first spectrum of 2001 Nov.) appear to share the same wavelength zero point, within 1-σ uncertainty, as the reference epoch.

To measure the relative radial velocities of vB 10, we have cross-correlated the telluric-free echelle orders 62 (central wavelength at 1.230 μm), 61 (1.250 μm), and 59 (1.2925 μm) against the 2007 epoch. The cross-correlation functions show a clear peak since vB 10 itself acts as the template. The derivations for the second spectrum of 2001 Nov. and 2008 Jun. have been corrected for the different wavelength zero points. Our results,

Table 2. NIRSPEC radial velocity measurements of vB 10.

MJD	v_r (km s^{-1})	Relative v_r (km s^{-1})	v_{shift}^a (km s^{-1})
52075.58951	35.50 ± 0.60	+1.13 ± 0.30	−0.08 ± 0.23
52215.20560	34.45 ± 0.60	+0.08 ± 0.30	−0.17 ± 0.22
52215.24225	34.40 ± 0.60	+0.03 ± 0.30	+0.51 ± 0.23
54276.55865^b	34.37 ± 0.30	−	−
54675.25669	34.00 ± 0.83	−0.37 ± 0.53	+1.07 ± 0.24

^{a} Relative offset in velocity zero point, ^{b} reference epoch (see text).

obtained from the average of the various echelle orders, are given as a function of the Modified Julian Date in the third column of Table 2. These values have been properly corrected for the diurnal (Earth's rotation), lunar (motion of the Earth's center about the Earth-Moon barycenter), and annual (motion of the Earth-Moon barycenter about the Sun) velocities. As a test of consistency, we have also cross-correlated the telluric-corrected spectra of vB 10, including the echelle orders that were heavily "obscured" by the telluric lines, deriving very similar values within 1-σ errors. The uncertainties associated with the relative radial velocities are computed from the additive combination of the wavelength zero point shift error bars (last column of Table 2) and the errors of the mean relative velocities.

The two spectra of vB 10 taken in 2001 Nov., separated by ~50 min, indicate that the star had a "constant" velocity (within ±300 m s^{-1}) in that short time interval. However, the first epoch measurement shows a non-zero relative radial velocity, suggesting some variability with an amplitude of around 1 km s^{-1}. The significance of such variability is estimated at the 3.2-σ level when compared to the mean of all velocity measurements.

To derive the absolute heliocentric velocities of vB 10 we need to correct the reference epoch for any possible zero point offset in its corresponding wavelength calibration solution. We used the Earth transmission spectrum above Mauna Kea generated by the ATRAN modelling software (Lord 1992) in the wavelength interval of our observations as a template in the cross-correlation of the 2007 spectrum of vB 10 (only echelle orders containing strong telluric absorption lines). A velocity shift of −0.88 km s^{-1} is found with a dispersion of ±0.27 km s^{-1} (error of the mean = 0.14 km s^{-1}). The heliocentric radial velocity is then computed by measuring the centroids of 11 atomic lines due to K I, Fe I, Ti I, and Mn I (McLean et al. 2007), and by correcting for the diurnal, lunar and annual velocities, obtaining $v_r = 34.37 ± 0.30$ km s^{-1} for the reference 2007 epoch. The uncertainty is derived as the mean error of the observed velocity (atomic line centroids) plus the mean error of the velocity zero point shift. The final heliocentric velocities for all epochs are given in the second column of Table 2.

Our heliocentric velocity measurements confirm that the "mean" radial velocity of vB 10 is indeed near 35 km s^{-1} as it has been frequently claimed in the literature (e.g., Tinney & Reid 1998; Martín 1999; Basri & Reiners 2006; Zapatero Osorio et al. 2007). We note that the heliocentric radial velocities of vB 10 given in Table 1 by Zapatero Osorio et al. (2007), which correspond to the first two lines of Table 2, were not corrected for any wavelength zero point offset. Pravdo & Shaklan (2009) also referred to these measurements out of a total of six published velocities obtained in the interval 1992–2001. Interestingly, the velocity difference between the first two epochs 2001 Jun. and 2001 Nov. was already apparent in Zapatero Osorio et al. (2007), but the associated error bars were too large for a firm assesment. We reduced the uncertainties by applying careful zero point corrections in the wavelength solutions and by using a large
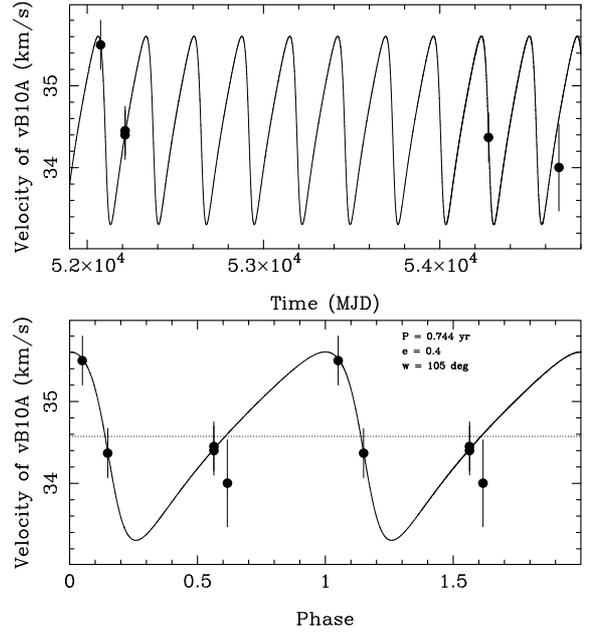

Fig. 2. Our radial velocity measurements (filled dots) are plotted against the Modified Julian Date of the observations (*top panel*), and the orbital phase (*bottom panel*). Overplotted on the data is the "most likely" astrometric Keplerian solution by Pravdo & Shaklan (2009), for which we have assumed an orbital eccentricity of 0.4 and an argument of periapsis of 105°. These spectroscopic observations cannot constrain the orbital solution precisely, but they are consistent with the presence of a small (planetary-mass) body aroud vB 10. The horizontal dotted line denotes the "systemic" velocity of the pair. Note that two periods are depicted in the bottom diagram.

number of spectroscopic features in the cross-correlation technique, in contrast to the few lines (only K I) used for vB 10 in Zapatero Osorio et al. (2007). Unfortunately, the remaining four velocities compiled by Pravdo & Shaklan (2009, see their Table 4), which include those by Basri & Reiners (2006), who claimed that vB 10 is a star probably with constant velocity based on a velocity dispersion of 0.3 ± 1.4 km s^{-1}, are not precise enough to further constrain the nature of the M8V-type star.

An alternative method to obtain the absolute heliocentric velocity of vB 10 is via the comparison of the observed spectra to theoretical spectra. Following the procedure described in del Burgo et al. (2009), we have found that vB 10 is well matched by the $T_{eff} = 2700 ± 250$ K, $\log g = 4.8 ± 0.5$ [cm s^{-2}], solar metallicity models (further details will be provided in del Burgo et al., in preparation). The wavelength cross-correlation of the 2007 spectrum of vB 10 against the synthetic data yields an heliocentric velocity of $33.17 ± 0.17$ km s^{-1}, where the uncertainty stands for the standard deviation of the radial velocities obtained from the various synthetic models within the 1-σ error range of the atmospheric parameters. After applying the velocity zero point offset, the final value is $34.05 ± 0.30$ km s^{-1}. This determination compares with that of Table 2, and both measurements are consistent within 1-σ uncertainty, indicating that our procedure for measuring velocities is reliable.

4. Discussion and final remarks

The NIRSPEC velocities of vB 10 (Table 2) provide a hint for the presence of variability with a possible amplitude of ~1 km s^{-1}. However, we caution that this is supported by one epoch measurement, which deviates by 3.2-σ from the remaining three

epochs. This appears insufficient to unambiguously confirm the planet around vB 10 since there is no evidence for a periodic signal in the spectroscopic data. It would be desirable to have more velocity measurements for a definitive analysis of the velocity variability, amplitude, and periodicity. Our results do not suggest that vB 10 contains a stellar-mass or a heavy brown-dwarf-mass companion in a close, not very eccentric orbit.

The origin of the ~1 km s^{-1} amplitude may be due to stellar activity, uncontrolled systematic errors in our measurements, or the presence of a massive planet. In the case of the active, young, M9-type brown dwarf LP 944−20, near-infrared velocity variations are below 360 m s^{-1} (Martín et al. 2006). Yet, we do not know the impact of flares on the determination of velocities. vB 10 shows X-ray flares at a rather low rate, which we have determined to be 2% of the time for strong events (log L_X/L_{bol} ≥ −3) and 3% for faint ones (log L_X/L_{bol} ~ −4, Linsky et al. 1995; Fleming et al. 1993, 2000, 2003; Berger et al. 2008), and similar flare duty cycle frequencies (~0.7% and 6%) were derived for LP 944−20 by Martín & Bouy (2002). Although the probability of observing vB 10 while it is flaring is small (~5%), we cannot exclude that the measured velocity change is influenced by strong atmospheric activity during the first observing epoch.

We now focus on whether our velocities agree with or refute the predicted velocity curve of vB 10 A obtained from the "most likely" astrometric solution and mass estimates of Pravdo & Shaklan (2009). Summarizing, these authors discuss that vB 10 is formed by a primary object near the substellar borderline (mass of 0.0779 $M_\odot$) and a massive planet (6.4 M_{Jup}), both of which orbit around the center of mass of the system with a periodicity of 0.744 yr. The orbital separation between the two pair members is astrometrically measured at 0.36 AU. Additional orbital parameters are provided in Table 5 of Pravdo & Shaklan (2009). We note that the orbital eccentricity (e), epoch, and argument of periastron (w) are not constrained by the astrometric solution. Our spectroscopic data are sparse and insufficient to provide additional strong restrictions to the orbital solution. However, from the visual inspection of several tens of computed velocity curves produced by varying the orbital epoch, e, and w, we infer that $e \leq 0.8$ and $w \sim 10°$–160° for epochs in the range 52070–52150 (MJD) may provide a reasonable match to the observations.

The top panel of Fig. 2 shows the NIRSPEC velocities as a function of the observing time and an example of a predicted velocity curve computed for $e = 0.4$, $w = 105°$, and epoch = 52106 (MJD), which minimizes the expression $\sum[|v_{computed} - v_r|/err(v_r)]$. This eccentricity is very close to the one derived from the solution of the combined astrometric and NIRSPEC observations performed by Pravdo & Shaklan (priv. communication). The bottom panel depicts the velocity curve folded in phase with a periodicity of 0.744 yr. For the systemic velocity of vB 10, we have adopted the mean value of all NIRSPEC velocities: 34.57 km s^{-1}, with an uncertainty of 0.30 km s^{-1}. A relatively high eccentricity of $e \leq 0.8$ is found in many giant planets orbiting solar-type stars (e.g., Udry & Santos 2007; Butler et al. 2006) as well as in the brown dwarf-low-mass star pair GJ 569Bab (Lane et al. 2001); therefore, it appears to be common in Nature and indicates that low-mass (planetary) companions can be found with a rich variety of orbital shapes around stars independently of the mass ratio of the system. As illustrated in Fig. 2, the agreement between the velocity curve prediction and observations is remarkably within 1-σ the uncertainties, giving some support to the mass estimates and the astrometric solution obtained by Pravdo & Shaklan (2009).

More radial velocity measurements with a better time sampling of the orbital period in addition to the astrometric data are required for a detailed knowledge of the orbital parameters of the pair vB 10 Ab. We have shown that NIRSPEC can provide radial velocities with error bars of ≥0.2 km s^{-1}, but significantly more accurate determinations (with uncertainties of a factor of 10 smaller) or many more NIRSPEC measurements would be necessary for the precise characterization of the individual masses of this planetary system.

The discovery of a likely massive planetary companion of a very low-mass star like vB 10 (planet-to-star mass ratio of ~0.08) inside the region where circum(sub)stellar disks are present at very young ages adds a new constraint to models of planet formation. This together with the previous findings of wide-orbit planetary-mass companions to brown dwarfs (e.g., Chauvin et al. 2004; Béjar et al. 2008) indicates that gravitational instabilities may play a role in the formation of super-planets and/or that these systems may also form like binary stars.

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