Letter to the Editor

Infrared radial velocities of vB 10

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ABSTRACT

We present radial velocities of the M8V-type, very low-mass star vB 10 that have been obtained at four different epochs of observations 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 $\sim 1 \text{ km s}^{-1}$, a result that is consistent with the recent finding of a massive planet companion around the star by Pravdo & Shaklan (2009). 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: individual (vB 10) — stars: late-type — stars: low-mass, brown dwarfs — planetary systems — techniques: radial velocities — binaries: general

1. Introduction

Over 300 planets are known orbiting main-sequence and giant stars of 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. Wider planets have been found by direct imaging techniques around young brown dwarfs (Chauvin et al. 2004; Béjar et al. 2003). 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 $M_\odot$ 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 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; Huelamo et al. 2008). We have recovered our past and recent near-infrared spectroscopic observations of vB 10 and we have analyzed them in a consistent way to derive radial velocities for different epochs that have been spread 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 have been 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 ~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

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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 $R \approx 17,800$ (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. For consistency issues, 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 for flat-fielding 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 to the next target. The air wavelengths of the arc lines were identified using the NIST 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. Intrinsic lines to these hot stars, like strong hydrogen at 1.282 µm, 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 wavelengths), except for the 2008 data, which have a factor of 3–5 lower quality.

### 3. Radial velocities

To investigate whether vB 10 shows radial velocity variability, we have measured the object’s velocity displacement of all observing epochs relative to a fixed reference, which we have chosen to be the 2007 epoch spectrum because of its high 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
Table 2. NIRSPEC radial velocity measurements of vB 10.

| MJD       | \( v_0 \) (km s\(^{-1}\)) | \( \delta v \) (km s\(^{-1}\)) | \( v_\text{shif} \) (km s\(^{-1}\)) |
|-----------|-----------------------------|-------------------------------|---------------------------------|
| 53705.58951 | 35.30 ± 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                   |
| 54726.55865\(^{a}\) | 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).

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, our 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-\( \sigma \) 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 have used the Earth transmission spectrum above Mauna Kea generated by the ATRAN modelling software (Lord 1992), and by using a large number of spectroscopic features in the wavelength zero point shifts error bars (last column of Table 2) and the errors of the mean relative velocities.

The cross-correlation technique in contrast to the few lines (only K) used for vB 10 in Zapatero Osorio et al. (2007) 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 with probably 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 \( T_{\text{eff}} = 2700 ± 250 \) 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-\( \sigma \) 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 the one of Table 2 and both measurements are consistent within 1-\( \sigma \) uncertainty, indicating that our procedure for measuring velocities is reliable.
4. Discussion and final remarks

The \texttt{nirspec} velocities of \textit{vB} 10 (Table 2) provide a hint for the presence of variability with a possible amplitude of \textasciitilde 1 km s\(^{-1}\). However, we caution that this is supported by one epoch measurement, which deviates by 3.2-\(\sigma\) from the remaining three epochs. This appears insufficient to unambiguously confirm the planet around \textit{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 on the velocity variability, amplitude, and periodicity. Our results do not suggest that \textit{vB} 10 contains a stellar-mass or a heavy brown-dwarf-mass companion in a short, not very eccentric orbit.

The origin of the \textasciitilde 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. \textit{vB} 10 shows X-ray flares at a rather low rate, which we have determined to be 2\% of the time for the strong events (log \(L_x/L_{bol}\) \(\geq -3\)) and 3\% for the faint ones (log \(L_x/L_{bol}\) \(\sim -4\)), Linsky et al. 1995. Fleming et al. 1993, 2000, 2003, Berger et al. 2008, and similar flare duty cycle frequencies (\textasciitilde 0.7\% and 6\%) were derived for LP 944–20 by Martin & Bouy (2002). Although the probability of observing \textit{vB} 10 while flaring is small (\textasciitilde 5\%), we cannot discard that the measured velocity change is influenced by a strong atmospheric activity during the first observing epoch.

We now focus on whether our velocities agree with or refute the predicted velocity curve of \textit{vB} 10 A obtained from the “most likely” astrometric solution and mass estimates of Pravdo & Shaklan (2009). Summarizing, these authors discuss that \textit{vB} 10 comprises a primary object near the substellar borderline (mass of 0.0779 \(M_{\odot}\)) and a massive planet (6.4 \(M_{\text{Jup}}\)), 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 \(w \sim 10^\circ\)–160\(^\circ\) for epochs in the range 52070–52150 (MJD) may provide a reasonable match to the observations.

The top panel of Fig. 2 shows the \texttt{nirspec} velocities as a function of the observing time and an example of a predicted velocity curve computed for \(e = 0.4\), \(w = 105^\circ\), and epoch = 52106 (MJD), which minimizes the expression \(\sum (\text{\texttt{nirspec}} - v_t)/\text{err}(v_t)\). This eccentricity is very close to the one derived from the solution of the combined astrometric and \texttt{nirspec} OBSERVATIONS PERFORMED BY PRAVDO & SHAKLAN (PRIVATE COMMUNICATION). The bottom panel depicts the velocity curve folded in phase with a periodicity of 0.744 yr. As regarding the systemic velocity of \textit{vB} 10, we have adopted the mean value of all \texttt{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 569 Bab (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 the observations is remarkably within 1-\(\sigma\) the uncertainties giving some credit 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 highly required for a detailed knowledge of the orbital parameters of the pair \textit{vB} 10 Ab. We have shown that \texttt{nirspec} can provide radial velocities with error bars of \(\geq 0.2\) km s\(^{-1}\), but significantly more accurate determinations (with uncertainties a factor of 10 smaller) or many more \texttt{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 to a very low-mass star like \textit{vB} 10 (planet-to-star mass ratio of \(\sim 0.08\)) 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 planetary-mass companions to brown dwarfs (e.g., Chaubin et al. 2004; Bejar et al. 2008) indicates that gravitational instabilities may play a role on the formation of super-planets and/or that these systems may also form like binary stars.

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