STRONG CONSTRAINTS TO THE PUTATIVE PLANET CANDIDATE AROUND VB 10 USING DOPPLER SPECTROSCOPY*

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ABSTRACT

We present new radial velocity (RV) measurements of the ultra-cool dwarf VB 10, which was recently announced to host a giant planet detected with astrometry. The new observations were obtained using optical spectrographs (MIke/Magellan and ESPaDOns/CFHT) and cover 65% of the reported period of 270 days. The nominal precision of the new Doppler measurements is about 150 m s$^{-1}$ while their standard deviation is 250 m s$^{-1}$. However, there are indications that such a larger variation is due to uncontrolled systematic errors. We apply least-squares periodograms to identify the most significant signals and evaluate their false alarm probabilities (FAPs). We show that this method is the proper generalization to astrometric data because (1) it mitigates the coupling of the orbital parameters with the parallax and proper motion, and (2) it permits a direct generalization to include nonlinear Keplerian parameters in a combined fit to astrometry and RV data. Our analysis of the astrometry alone uncovers the reported 270 day period and an even stronger signal at ~50 days. We estimate the uncertainties in the parameters using a Markov chain Monte Carlo approach. Although the new data alone cannot rule out the presence of a candidate, when combined with published RV measurements, the FAPs of the best solutions grow to unacceptable levels strongly suggesting that the observed astrometric wobble is not due to an unseen companion. The new measurements put an upper limit of $m \sin i \sim 2.5 \, M_{\text{Jup}}$ for a companion with a period shorter than one year and moderate eccentricities.

Key words: astrometry – methods: statistical – stars: individual (VB 10) – techniques: radial velocities

Online-only material: color figures

1. INTRODUCTION

Pravdo & Shaklan (2009) recently announced the discovery of an astrometric companion to VB 10, an M dwarf with a mass of $\approx 0.08 \, M_{\odot}$. From a Keplerian fit to the motion, they determined a mass of $6 M_{\oplus}$ and a period of 270 days. Thus VB 10 became the lowest-mass star known to harbor a planetary companion. The mass ratio between VB 10 and its companion, $\sim 13$, also is intriguing. A similar mass ratio for a solar-type star would make the companion a brown dwarf, but brown dwarfs as small separation companions to stars are quite rare. VB 10 is itself the secondary in a wide binary with V1428 Aql, a M2.5 star (van Biesbroeck 1961). At a distance of 5.8 pc from the Sun, the $74^{\prime\prime}$ separation of this proper motion binary corresponds to a projected separation of 430 AU.

Such low-mass stars have not been the target of intensive precision radial velocity (PRV) monitoring because they have low visual fluxes and high stellar activity (e.g., the HARPS M-dwarf planet search observes stars only brighter than $V = 14$; Bonfils et al. 2007). VB 10 has $V = 9.1$ and is known to be a flare star (Berger et al. 2008). PRV and lensing planet searches have so far found only 13 stars under $0.5 \, M_{\odot}$ hosting 18 planets, and of these, more than half have masses below $0.1 M_{J}$.

Despite the challenges, searches for planetary companions to low-mass stars are of continuing interest. Low-mass stars appear less likely to have lower-mass stellar companions and less likely to harbor planets than solar-mass stars (Cumming et al. 2008). When they do have companions, they tend to be stars of nearly equal mass to the primary (Burgasser et al. 2007). The mass function of planets orbiting M dwarfs, and how it differs from the planet mass function for higher-mass stars, provides a constraint on the planet formation mechanism(s) in general. Disks sufficiently massive to form Jupiter-mass planets appear to be rare around brown dwarfs, whose disks generally look like lower-mass versions of T Tauri disks (Scholz et al. 2006). High-mass companions would have to form via a binary-like fragmentation mechanism (e.g., Font-Ribera et al. 2009). Thus how a $6M_{J}$ planet could form around an $\sim 80 M_{J}$ star and how common such high-mass ratio companions remain important questions (Boss et al. 2009).

The reported planet’s astrometric orbit predicts a radial velocity (RV) amplitude of at least $1 \, \text{km s}^{-1}$ for a circular orbit and up to several $\text{km s}^{-1}$ for an eccentric orbit. This magnitude signal is detectable with ordinary RV measurements without requiring the adoption of precision techniques (e.g., iodine cell). Although several RV measurements of VB 10 exist in the literature before 2009, it is difficult to combine the historical RVs (see Table 4 of Pravdo & Shaklan 2009), as each observation used different calibration techniques and the typical uncertainties are also large ($\sim 1.5 \, \text{km s}^{-1}$). The most precise

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measurements in the literature were published by Zapatero Osorio et al. (2009, hereafter Z09), but provide only a “hint of variability.” These data did little to constrain the orbital parameters of the planet beyond what the astrometry had already done (Anglada-Escudé et al. 2009).

Here, we present a more precise set of RV observations over 175 days (or 65% of the reported orbital period). We also present general techniques for joint fitting of astrometric and RV data and show how they can be used to constrain the orbit of the candidate planet.

2. NEW DATA

We acquired spectra at eight epochs in 2009 with the MIKE spectrograph at the Magellan Clay telescope at Las Campanas Observatory (Chile). We used the 0′.35 and the 0′.5 slits which produce a spectral resolution of ∼45,000 and 35,000, respectively, across the 4900–10000 Å range of the red chip. The seeing was in the range from 0.5 to 1′.1. These data were reduced using the facility pipeline (Kelson 2003).

We also have in hand a single spectrum of VB 10 taken in 2006 using the High Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994) on the Keck I 10 m telescope. We used the 0′.861 slit to obtain a spectral resolution of λ/Δλ ≈ 58,000 at λ ∼ 7000 Å. We used the GG475 order-blocking filter and the red cross-disperser to maximize throughput in the red orders.

An additional spectrum was obtained using the ESPaDOnS on the Canada–France–Hawaii Telescope (CFHT) 3.6 m telescope. ESPaDOnS’ “star+sky” mode records the full spectrum over 40 grating orders covering 3700–10400 Å at a spectral resolution of λ/Δλ ≈ 68,000. The data were reduced using Libre Esprit (Donati et al. 1997, 2007).

Each stellar exposure is bias-subtracted and flat-fielded for pixel-to-pixel sensitivity variations. After optimal extraction, the one-dimensional spectra are wavelength calibrated with a thorium–argon arc. To correct for instrumental drifts, we used the telluric molecular oxygen A band (from 7620 to 7660 Å) which aligns the MIKE spectra to 40 m s⁻¹, after which we corrected for the heliocentric velocity. Consistency tests with the bluer oxygen band shows comparable values but with larger measurement error.

The final spectra are of moderate signal-to-noise ratio (S/N) reaching ≈25 pixel⁻¹ at 8000 Å. Each night, spectra were also taken of an M-dwarf RV standard, namely GJ 699 (Barnard’s star; SpT = M4V) and/or GJ 908 (SpT = M1V).

To measure VB 10’s RV, we cross-correlated each of nine or more spectra with a synthetic template spectrum of an M-dwarf RV standard of comparable brightness (SpT = M4-V). The zero point of the absolute RVs is uncertain at the 0.4 km s⁻¹ level. We measured the RVs from the Gaussian peak fitted to the cross-correlation function (CCF) of each order and adopt the average RV of all orders with a mean standard deviation of the individual measurements of 0.15 km s⁻¹. The average of all our measurements is 36.02 km s⁻¹ with a standard deviation of 0.25 km s⁻¹. An observing log with the measured RVs and uncertainties for VB 10 is shown in Table 1.

3. DATA ANALYSIS: COMBINING ASTROMETRY AND RADIAL VELOCITIES

In this section, we reanalyze the original astrometric data to calculate the likelihood of astrometrically allowed solutions, and then combine the astrometry and RV data sets in a consistent framework to quantify how the new RV measurements constrain the possible orbits of the candidate signals observed in the astrometry of VB 10b.

3.1. Least-squares Periodograms

The most popular method to look for periodicities in data is the so-called Lomb–Scargle periodogram. A version adapted to deal with astrometric two-dimensional data developed by Catanzarite et al. (2006, Joint Lomb–Scargle periodogram) was

Table 1

| Telescope + Instrument | UT Date      | HID     | Slit Width (') | RV (w/ GJ 699) (km s⁻¹) | RV (w/ GJ 908) (km s⁻¹) | Heliocentric RV (km s⁻¹) |
|------------------------|--------------|---------|----------------|-------------------------|-------------------------|--------------------------|
| Keck I + HIRES         | 2006 Aug 12  | 3959.57 | 0.86           | 35.59 ± 0.15            | 35.59 ± 0.45            |
| Clay+MIKE              | 2009 Jun 6   | 4988.74 | 0.35           | 35.99 ± 0.15            | 36.12 ± 0.44            |
| Clay+MIKE              | 2009 Jun 7   | 4999.88 | 0.50           | 35.99 ± 0.15            | 36.12 ± 0.44            |
| Clay+MIKE              | 2009 Jun 8   | 4990.75 | 0.50           | 36.09 ± 0.20            | 36.17 ± 0.44            |
| Clay+MIKE              | 2009 Sep 4   | 5012.72 | 0.35           | 35.72 ± 0.11            | 35.72 ± 0.44            |
| Clay+MIKE              | 2009 Jul 25  | 5037.66 | 0.50           | 35.96 ± 0.11            | 35.99 ± 0.43            |
| Clay+MIKE              | 2009 Oct 15  | 5119.54 | 0.35           | 36.03 ± 0.11            | 36.02 ± 0.44            |
| Clay+MIKE              | 2009 Oct 26  | 5130.51 | 0.50           | 35.96 ± 0.09            | 35.99 ± 0.43            |
| CFHT+ESPaDOnS          | 2009 Nov 29  | 5164.69 | ...            | 36.17 ± 0.20            | 36.02 ± 0.44            |

Notes.

a Uncertainties are the standard deviation of the RV measurements obtained from the cross-correlation of 9 individual orders, except for the Keck I + HIRES which also used 9 orders on the green chip.

b Weighted mean of the absolute heliocentric RV measurement and its uncertainty. Uncertainties include a 0.4 km s⁻¹ uncertainty in the zero point of the standard stars, 0.04 km s⁻¹ uncertainty on the telluric line calibration, and 0.15 km s⁻¹ to account for the observed systematic jitter, all added in quadrature.

c ESPaDOnS is a fiber-fed spectrograph with an effective resolution of R ∼ 68000 in the wavelength range of interest.

IRAF (Image Reduction and Analysis Facility), http://iraf.noao.edu/.
implemented in the discovery paper of VB 10b (Pravdo & Shaklan 2009). Any method based on the Lomb–Scargle periodogram performs optimally only under an important implicit assumption: all other signals (e.g., linear trend, an average offset, etc.) can be subtracted from the data without affecting the significance of the signal under investigation. This assumption does not hold for astrometry because the proper motion and the parallax are also a significant part of the signal and they typically correlate with the periodic motion of a planet (see Black & Scargle 1982).

We use instead a least-squares periodogram. The weighted least-squares solution is obtained by fitting all the free parameters in the model for a given period. The sum of the weighted residuals divided by $N$ is the so-called $\chi^2$ statistic. Then, each $\chi^2_P$ of a given model with $k_P$ parameters can be compared to the $\chi^2_0$ of the null hypothesis with $k_0$ free parameters by computing the power, $z$, as

$$z(P) = \frac{(\chi^2_0 - \chi^2_P)/(k_P - k_0)}{\chi^2_P/(N_{\text{obs}} - k_P)},$$

(1)

where a large $z$ is interpreted as a very significant solution. The values of $z$ follow a Fisher $F$-distribution with $k_P - k_0$ and $N_{\text{obs}} - k_P$ degrees of freedom (Scargle 1982; Cumming 2004). Even if only noise is present, a periodogram will contain several peaks (see Scargle 1982, as an example) whose existence have to be considered in obtaining the probability of a spurious detection. Assuming Gaussian noise, the probability that a peak in the periodogram has a power higher than $z(P)$ by chance is the so-called false alarm probability (FAP):

$$\text{FAP} = 1 - (1 - \text{Prob}[z > z(P)])^M,$$

(2)

where $M$ is the number of independent frequencies. In the case of uneven sampling, $M$ can be quite large and is roughly the number of periodogram peaks one could expect from a data set with only Gaussian noise and the same cadence as the real observations. We adopt the recipe $M \approx 2\Delta T/P_{\text{min}}$ given in Cumming (2004, Section 2.2), where $\Delta T$ is the time span of the observations and $P_{\text{min}}$ is the minimum period searched. One still has to select $P_{\text{min}}$ arbitrarily. Assuming a $P_{\text{min}} = 20$ days, the astrometric data alone have $M \sim 300$, and the combination of astrometry and RVs has $M \sim 360$.

In our case, the null hypothesis is the basic kinematic model with $k_0 = 6$ parameters: two coordinates, two proper motions, parallax and systemic RV. As a first approach, our simplest non-null hypothesis considers circular orbits, astrometric data only and one RV. For a given period, the number of free parameters is then $k_P = 10$: the six kinematic ones plus the four Thiele Innes elements $A, B, F,$ and $G$ (e.g., Wright & Howard 2009). Since the model is linear in all 10 parameters, the power can be efficiently computed for many periods between 20 days and 4000 days to obtain a familiar representation of the periodogram that we call a circular least-squares periodogram (CLP). The CLP of the astrometric data, shown at top in Figure 1, displays two obvious peaks: the reported one at 270 days (Pravdo & Shaklan 2009) and a more significant one at 49.9 days, both with high power and low FAPs.

To find the full Keplerian solution for both periods and estimate their FAPs, we perform a least-squares periodogram sampling a grid of fixed eccentricity–period (eP) pairs and fitting all other parameters. For each eP pair $k_P$ is 11: the null-hypothesis ones plus all the other Keplerian elements: mass of the planet, $\Omega$, $\omega$, $i$, and the initial mean anomaly $M_0$. We analyze both astrometry only and astrometry+RVs. The $\chi^2$ of the best-fit solution is then used to obtain each FAP as previously described. Figure 1 shows the resulting color-coded FAPs for each eP pair (eP map).

### 3.1.1. Astrometry Only

A value of $M = 300$ has been used to obtain the FAP, and our result at 270 days qualitatively agrees with Pravdo & Shaklan (2009); however, the more significant period is at $\sim 50$ days. For both periods, there are regions with FAP $< 1\%$ spanning all possible eccentricities (second row in Figure 1). The best fits and their $\chi^2$ per degree of freedom ($\chi^2/2$) are summarized in Table 2. The obtained results for the 270 day period are in agreement with those reported in the discovery paper by Pravdo & Shaklan (2009). The best-fit solution for the 50 day period has mass $\sim 15M_J$, which would be a very low mass brown dwarf. It is important to point out that the best-fit inclination is close to 90 (edge on) for both solutions. The uncertainties on the orbital parameters are quantified in Section 3.2.

### 3.1.2. Astrometry+RVs

We now fit for the best orbital solution to the astrometry and RVs jointly. Our RVs campaign covered about 65% of the 270 day orbit. The standard deviation of all our RV measurements is 250 m s$^{-1}$ (null hypothesis) which is larger than the individual uncertainties in Table 1. When we cross-correlate our standards, we measure a similar rms of 200 m s$^{-1}$, which indicates that the difference is due to an uncontrolled or unmeasured systematic. The rms of the RVs for the best-fit solution is 200 m s$^{-1}$, which is not statistically different from the rms of the null hypothesis. This is another indication that our measurements contain systematic errors at the level of 100–200 m s$^{-1}$. Despite that, we use the nominal errors in the least-squares solution as the best estimates for the individual uncertainties we can provide. In Figure 2, we show the best solutions to both signals including all the data.

For the 270 day period, our RV non-detection cannot exclude a small region of orbital solutions around $e \sim 0.8$ with a FAP between 1%–5% (see Figure 1, third row, right panel). We now add the RV measurements by Z09 and solve for a joint solution. A zero-point offset between data sets is added as an additional free parameter. The combined RV measurements force the eccentricity to large values which apparently still provides a reasonable fit to the astrometry (see top panels in Figure 2). However, the FAPs are now all higher than 10% (Figure 1, bottom right panel), which indicates that the signal can be barely distinguished from the noise fluctuations. The “hint” of detection in Z09 based on one discrepant value at 3.1$\sigma$ out of five can be due to random errors with a non-negligible probability.

For the 50 day period, there are still several orbits that provide a decent fit to the combined astrometry and the new RV data with a FAP lower than 1%. These occupy a small space around the best joint solution, with $e = 0.90$ (see Figure 1, third row, left panel) and an inclination close to 0. Large eccentricity causes the duration of fast RV variation to be very short (and difficult to catch); an inclination close to 0 tends to suppress any RVs signal. Such inclination is in apparent contradiction with the one obtained using the astrometry alone ($\sim 90^\circ$). The reason is the following: while the new fit to the astrometry forced by the RVs is much worse than the one obtained from the astrometry alone, such solution still represents an improvement compared to the null hypothesis. Adding Z09 data to the fit increases the FAP of
Figure 1. Top panel: CLP showing the two most significant periods with their corresponding FAPs. Second row: FAPs obtained for a grid of eP pairs around the 50 days (left) and the 270 days (right) when only astrometry is considered. Third row: FAPs obtained when our new RVs are included to the fit. Bottom row: final FAPs obtained when all published RV data are combined in a joint fit.

(A color version of this figure is available in the online journal.)

Table 2

| Parameter          | Astrometry 50 days | Astrometry 270 days | Astro+ all RV 50 days | Astro+ all RV 270 days |
|--------------------|--------------------|--------------------|------------------------|------------------------|
| X0 (mas)           | −16.6 ± 1.6        | −14.18 ± 3.2       | −21.15 ± 2.3           | −17.9 ± 4.7            |
| Y0 (mas)           | −408.0 ± 1.9       | −406.18 ± 3.5      | 409.52 ± 2.8           | −410.5 ± 5.51          |
| μRA (mas yr⁻¹)     | −588.98 ± 0.25     | −589.08 ± 0.25     | −588.66 ± 0.29         | −589.21 ± 0.26         |
| μDec (mas yr⁻¹)    | −1360.95 ± 0.25    | −1361.08 ± 0.24    | −1361.02 ± 0.25        | −1361.36 ± 0.20        |
| π (mas)            | 168.3 ± 1.51       | 169.5 ± 1.4        | 169.95 ± 1.37          | 169.24 ± 1.30          |
| v0 (km s⁻¹)        | 35.2 ± 1.4         | 35.4 ± 1.05       | 36.06 ± 0.11           | 36.05 ± 0.08           |
| v0 offset (km s⁻¹) | …                  | …                 | 1.5 ± 0.42             | 1.5 ± 0.36             |
| P (d)              | 49.7 ± 0.5         | 272.1 ± 4.1        | 49.84 ± 0.11           | 278.5 ± 2.7            |
| Mass (MJ)          | 17.5 ± 4.4         | 7.1 ± 2.7          | 13.7 ± 6.4             | 5.0 ± 2.9              |
| e                  | 0.22 ± 0.30        | 0.48 ± 0.31        | 0.91 ± 0.13            | 0.90 ± 0.16            |
| i (deg)            | 93 ± 5             | 90 ± 15            | 4 ± 5                  | 110° ± 50              |
| Ω1 (deg)           | 40 ± 20            | 220 ± 25           | 134 ± 100              | 40° ± 66               |
| ω (deg)            | 20 ± 40            | 30° ± 80           | 122° ± 60              | 17° ± 90               |
| M0 (deg)           | 270 ± 0            | 170° ± 108         | 340° ± 70              | 156° ± 80              |
| a (AU)             | 0.12               | 0.36               | 0.12                   | 0.36                   |
| e²                 | 2.28               | 2.28               | 2.75                   | 2.75                   |
| K (Km s⁻¹)         | 0.87               | 0.93               | 1.62                   | 1.76                   |

Notes. Uncertainties obtained from an MCMC with 10⁶ steps.

a The mass of VB 10 is assumed to be 0.078 M⊙ according to Pravdo & Shaklan (2009).
b Derived quantity using Kepler equations.
c Large uncertainty due to correlation with the eccentricity.
d Unconstrained or poorly constrained.
Figure 2. Best-fit (lowest \( \chi^2 \)) joint solutions to the Pravdo & Shaklan (2009) astrometry and used RVs for the two signals. Top panels contain the astrometric offsets after the removal of the parallax and proper motion. The lower panels contain all RVs used. Each RV point represents the weighted average of the values obtained using both reference stars if available. The best-fit offset has been applied to Z09 data (green triangles). Phase 0 corresponds to the first astrometric epoch at JD 2451438.64 and the corresponding folding periods are given on the top.

(A color version of this figure is available in the online journal.)

Figure 3. Left: steps in period–eccentricity space of a Markov chain of 10^6 steps applied to the astrometry only (black) and to the astrometry+all RV data (brown). Right: histogram reproducing the marginalized density distributions in \( e \) around the 270 d solution.

(A color version of this figure is available in the online journal.)

the most likely solution to 2\%, an eccentricity of 0.91 and the inclination close to 0 (see Table 2). This suggests that the signal at 50 days is also spurious, even though it has slightly better chances of survival than the one at 270 days.

As a last check, we produced the same FAP maps assuming an individual RV uncertainty of 250 m s\(^{-1}\) more in line with the apparent systematic errors in the data. Although the FAP improve slightly (get lower), no solutions with FAP lower than 1\% are found around either candidate signals. Assuming a circular orbit (or moderate eccentricities, e.g., \( e < 0.5 \)), our RV data rule out any planet with \( m \) \( \sin i \) larger than 2.5 \( m_{\text{jup}} \) with a period shorter than one year at a 3\( \sigma \) level in the amplitude.

3.2. A Posteriori Probability Distribution

We adapt the method developed by Ford (2005, 2006) to assess uncertainties in orbit determinations by obtaining the a posteriori probability distribution for the parameters using a Markov chain Monte Carlo approach (MCMC) with a Gibbs sampler strategy. Our problem is identical to the one described by Ford (2005), where now the \( \chi^2 \) contains both RV and astrometric observations and the model has a few more free parameters. Several properly adjusted MCMCs with 10^6 steps have been computed obtaining compatible results. The step sizes of the Gibbs sampler are initialized with the formal errors from the best-fit least-squares solution, and adjusted to obtain a transition probability between 10\% and 20\%. The first 10^5 steps of each chain are rejected. The final distributions match very well the areas of low FAPs in the eP maps (see Figure 3 as an example) giving further proof that the chains have converged to the equilibrium distributions. The MCMC contains 13 free parameters—the 11 from the least-squares periodogram plus eccentricity and period. When the RV measurements from Z09 are included, an additional offset parameter is included.

Table 2 presents the standard deviations obtained via the MCMC for both the 50 day and 270 day periods using astrometry
alone and astrometry + all RV data. As an example, we show the two-dimensional density of states in period–eccentricity space in Figure 3 (left) obtained in both cases around the 270 day signal. The marginalized distributions for $e$ in the form of histograms are shown in Figure 3 (right). For the astrometry-alone case, the distribution of $e$ is almost uniform. It becomes strongly peaked toward high eccentricities when all the RV data are included. Since the best-fit solution at 270 days is poor ($\chi^2 = 1.76$), the corresponding $\chi^2$ minimum is not very deep which is reflected in a significant increase in the derived uncertainties (see Table 2). The same happens to the signal at 50 days with the exception of the inclination that has a small uncertainty ($4^\circ$) close to 0. Even though this solution has a low FAP, the inclination has to be coincidentally very small to suppress any RV signal and very different from using astrometry only ($94^\circ$), raising serious doubts of its reality.

4. DISCUSSION AND CONCLUSIONS

The non-detection of a significant RV variation in our data set already discards most orbital configurations allowed by the astrometry. When combined with Z09 RV measurements, there are no remaining solutions with a FAP lower than 10% around the 270 day period, so the presence of a planet candidate at that period is not supported by the observations. For the 50 day period, the constraints become almost definitive when the Z09 data are included. Even highly eccentric solutions have a relatively large FAP (>2%). Some combinations of eccentricity, inclination, and argument of periastron can fit an almost flat RV curve indicating that the analytic methods applied to estimate FAPs for high eccentricities tend to give over optimistic results and that this issue should be studied in more detail.

We have developed and implemented useful tools for detailed analysis of combined astrometric and RV data: CLP as the proper generalization of the classic Lomb–Scargle periodogram to deal with astrometric data, eP maps to visualize the most likely period–eccentricity combinations, and a Bayesian characterization of the parameter uncertainties based on a MCMC approach.

VB 10 is also part of the Carnegie Astrometric Planet Search program (Boss et al. 2009). RV measurements with precision techniques in the near-infrared (Bean et al. 2009) may provide the required accuracy to put even stronger limits to the existence of VB 10b (Bean et al. 2010) or find other planets in the system. VB 10 will certainly be observed by the space astrometry mission Gaia (Perryman et al. 2001), which would be capable of finding a planet with a period of 270 days and as small as 0.2$M_J$.

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