Substellar Companions to Evolved Intermediate-Mass Stars: HD 145457 and HD 180314

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Abstract

We report on the detection of two substellar companions orbiting around evolved intermediate-mass stars by precise Doppler measurements at Subaru Telescope and Okayama Astrophysical Observatory. HD 145457 is a K0 giant with a mass of 1.9M⊙, and has a planet of minimum mass, m sin i = 2.9MJ, orbiting with a period of P = 176d and eccentricity of e = 0.11. HD 180314 is also a K0 giant with 2.6M⊙, and hosts a substellar companion of m sin i = 22MJ, which falls in the brown-dwarf mass regime, in an orbit with P = 396d and e = 0.26. HD 145457 b is one of the innermost planets and HD 180314 b is the seventh candidate of a brown-dwarf-mass companion found around evolved intermediate-mass stars.

Key words: stars: individual (HD 145457) — stars: individual (HD 180314) — stars: planetary systems — techniques: radial velocities

1. Introduction

Over 400 exoplanets have been discovered by various techniques during the past 15 years.1 Among the techniques, a precise Doppler technique has been the most powerful method for planet detection around various types of stars, including solar-type stars, evolved giants and subgiants, early-type stars, and so on (e.g., Udry & Santos 2007 and references therein). Recently, precise Doppler measurements in the infrared wavelength region have started to explore planets around very low-mass stars down to 0.1M⊙ (Bean et al. 2010). These surveys will help us to understand the properties of planets as a function of the stellar mass, age, evolutionary stage, and so on, and thus provide a more general picture of planet formation and evolution.

In particular, planets around giants and subgiants have been extensively surveyed over the past several years, mainly from the viewpoint of planet searches around intermediate-mass (1.5–5M⊙) stars (e.g., Frink et al. 2002; Setiawan et al. 2005; Sato et al. 2008a; Hatzes et al. 2005, 2006; Johnson et al. 2010; Lovis & Mayor 2007; Niedzielski et al. 2009a; Döllinger et al. 2009; de Medeiros et al. 2009; Liu et al. 2009; Omiya et al. 2009). Intermediate-mass dwarfs, namely BA-type dwarfs, are more difficult for Doppler planet searches because of a paucity of spectral features and their rotational broadening. It is thus difficult to achieve a high measurement precision in radial velocity (but see e.g., Galland et al. 2005, 2006). On the other hand, those in evolved stages, namely GK-type giants and subgiants, have many sharp absorption lines in their spectra suitable for precise radial velocity measurements, which make them promising targets for Doppler planet searches. Actually, more than 30 substellar companions to such evolved stars have already been found, and they have shown remarkable properties: more than a twice higher occurrence rate of giant planets for intermediate-mass subgiants than that for lower-mass stars (Johnson et al. 2007a; Bowler et al. 2010), a larger typical mass of giant planets (Lovis et al. 2007; Omiya et al. 2009), a lack of inner planets with semimajor axes < 0.6 AU (Johnson et al. 2007b; Sato et al. 2008b; Niedzielski et al. 2009b), and the lack of a metal-rich tendency in host stars (Pasquini et al. 2007;
Takeda et al. 2008). All of these statistical properties should be confirmed by collecting a larger number of samples.

Since 2001, we have been carrying out a Doppler planet search program targeting 300 GK giants at Okayama Astrophysical Observatory (OAO), and have discovered 9 planets and 1 brown dwarf so far from the program (Sato et al. 2003, 2007, 2008a, 2008b; Liu et al. 2008). In order to further extend the survey, we have established an international consortium between Chinese, Korean, and Japanese researchers using 2 m class telescopes in three countries (East-Asian Planet Search Network: Izumiura 2005), which recently announced discoveries of a planet (Liu et al. 2009) and a brown dwarf (Omiya et al. 2009) around GK giants. A total of about 600 GK giants are now being surveyed by the consortium.

In this paper, we report on the detections of two new substellar companions around intermediate-mass giants (HD 145457 and HD 180314) from our newly started planet search program using the Subaru 8.2 m telescope and the above-mentioned 2 m class telescopes. The substellar companions presented here were uncovered by initial screening with Subaru, and followed up with the OAO 1.88 m telescope. We describe an outline of the Subaru survey in section 2 and our observations in section 3. The stellar properties are presented in section 4, and radial velocities, orbital solutions, and results of line shape analysis are provided in section 5. Section 6 is devoted to a summary and discussion.

2. Subaru Survey for Planets around GK Giants

The main purpose of the Subaru program is to quickly identify planet-hosting candidates from hundreds of sample stars by taking advantage of the large telescope aperture. Our basic strategy is thus to observe each star three times in a semester with an interval of about 1.5 months for the first screening to identify stars showing large radial-velocity variations. Since it is known that planets with periods of less than 130 days seem to be rare among giants, we at first focus on the detection of planets with longer periods. For stars that turn out to show large radial-velocity variations, we conduct follow-up observations using the 1.88 m telescope with the High Dispersion Echelle spectrograph (HIDES: Izumiura 1999) at OAO. We collected a total of 23 and 21 data points for HD 145457 and HD 180314, respectively, from 2003 March to 2010 March. The wavelength region was set to cover 3750–7500 Å using the RED cross-disperser, and the slit width was set to 0.78 Å, giving a wavelength resolution of 67000 by about 3.3 pixels sampling. We used an I$_2$ cell for precise radial-velocity measurements and also took pure stellar spectra without the I$_2$ cell for abundance analysis. The typical S/N was 170 pixel$^{-1}$ for both stars with an exposure time of 1500 s. The reduction of echelle data for HIDES and HIDES was performed using the IRAF software package in the standard manner.

For precise Doppler analysis, we basically adopted the modeling technique of an I$_2$-superposed stellar spectrum (star + I$_2$) described by Butler et al. (2006), which is based on a method by Butler et al. (2006). In this technique, a star + I$_2$ spectrum is modeled as a product of a high-resolution I$_2$ and a stellar template spectrum convolved with a modeled instrumental profile (IP) of the spectrograph. The IP is modeled with the combination of a central and several satellite Gaussian profiles, which are placed at appropriate intervals and have suitable widths, depending on the properties of the spectrograph (e.g., Valenti et al. 1995; Sato et al. 2002). To obtain the stellar template, Sato et al. (2002) extracted a high-resolution stellar spectrum from several star + I$_2$ spectra. However, when we applied the technique to the HDS data, we found that systematic errors sometimes appeared in radial velocities derived by using the thus-obtained template. We finally found that such systematic errors disappeared when we used a stellar template derived from a HIDES spectrum that was obtained by deconvolving a pure stellar spectrum with the spectrograph IP estimated from a B-star + I$_2$ spectrum. Therefore, IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. under a cooperative agreement with the National Science Foundation, USA.
we decided to use the same stellar template thus obtained from HIDES data for the radial-velocity analysis of both the HDS and HIDES data.

4. Stellar Properties

HD 145457 (HIP 79219) is listed in the Hipparcos catalog as a K0 III giant star with a magnitude $V = 6.57$ and a color index $B - V = 1.037$ (table 1). The Hipparcos parallax, $\pi = 7.93 \pm 0.73$ mas, corresponds to a distance of $126 \pm 12$ pc and an absolute magnitude of $M_V = 0.967$. The color excess $E(B - V)$ was calibrated according to Beers et al. (2002), and the interstellar extinction was found to be $A_V = 0.099$. The effective temperature, $T_{\text{eff}} = 4757 \pm 100$ K, was derived from the color index $B - V$ and the metallicity [Fe/H] using the calibration of Alonso et al. (2001); also, a bolometric correction, $BC = -0.354$, was derived from a calibration of Alonso et al. (1999), depending on the temperature and the metallicity. The stellar luminosity was then estimated to be $L = 45.2 \pm 8.2 L_\odot$, and the radius to be $R = 9.9 \pm 0.5 R_\odot$. The stellar mass $M = 1.9 \pm 0.3 M_\odot$, was estimated from the evolutionary tracks of Yonsei-Yale (Yi et al. 2003). The surface gravity, $\log g = 2.77 \pm 0.1$, was determined via Hipparcos parallaxes (ESA 1997). The iron abundance was determined from the equivalent widths measured from a pure stellar spectrum taken with HIDES (5000–6100 Å and 6000–7100 Å) combined with the model atmosphere (Kurucz 1993). Microturbulent velocities were obtained by forcing Fe I lines with different strengths to give the same abundances. We iterated the whole procedure described above until the final metallicity from the measured equivalent widths became consistent with the one input as an initial guess. Finally, we obtained [Fe/H] = $-0.14 \pm 0.09$ and a microturbulent velocity of $v_t = 1.3 \pm 0.2$ km s$^{-1}$.

HD 180314 (HIP 94576) is also a K0 III giant star with $V = 6.61$ and $B - V = 1.000$. The Hipparcos parallax, $\pi = 7.59 \pm 0.64$ mas, yields a distance of $132 \pm 11$ pc and $M_V = 0.931$, $A_V = 0.081$ (table 1). The atmospheric parameters for the star were derived by the same procedure as described above to be $T_{\text{eff}} = 4917 \pm 100$ K, $\log g = 2.98 \pm 0.1$, $v_t = 1.1 \pm 0.2$ km s$^{-1}$ and [Fe/H] = $0.2 \pm 0.09$; the other stellar parameters were $L = 44.0 \pm 7.2 L_\odot$, $R = 9.2 \pm 0.4 R_\odot$, $BC = -0.289$ and $M = 2.6 \pm 0.3 M_\odot$. Although we have not obtained projected rotational velocities for the stars, the absorption lines of HD 180314 are obviously narrower and deeper than those of HD 145457, which resulted in a better precision in the radial-velocity measurements for HD 180314 than for HD 145457, even with nearly the same S/N (see subsection 5.1 and tables 2–3).

Hipparcos made a total of 229 and 130 observations of HD 145457 and HD 180314, respectively, and revealed a photometric stability down to $\sigma = 0.009$ mag for both stars. Ca I H K lines of HD 145457 showed no significant emission in the line cores, but those of HD 180314 showed a slight core reversal, suggesting that the star is slightly chromospherically active. However, as shown in figure 1, the reversal of HD 180314 is not significant compared to those of other chromospherically active stars in our sample, such as HD 120048 (figure 1), which exhibits a velocity scatter of about 20 m s$^{-1}$, at most. Thus, the intrinsic radial velocity “jitter” of HD 180314 is probably expected to be no larger than that of HD 120048, which is consistent with the RMS scatters of the residuals to the Keplerian fit for the star (see section 5).

![Spectra in the region of Ca II H lines. HD 180314 exhibits a slight core reversal in the line, but it is not significant compared to that in the chromospheric active star HD 120048, which shows a velocity scatter of about 20 m s$^{-1}$. A vertical offset of about 0.7 is added to each spectrum.](https://example.com/spectra.png)

### Table 1. Stellar parameters.

| Parameter | HD 145457 | HD 180314 |
|-----------|-----------|-----------|
| Sp. Type  | K0        | K0        |
| $\pi$ (mas) | 7.93 ± 0.73 | 7.59 ± 0.64 |
| $V$       | 6.57      | 6.61      |
| $B - V$   | 1.037     | 1.000     |
| $A_V$     | 0.099     | 0.081     |
| $M_V$     | 0.967     | 0.931     |
| $BC$      | -0.354    | -0.289    |
| $T_{\text{eff}}$ (K) | 4757 ± 100 | 4917 ± 100 |
| $\log g$  | 2.77 ± 0.1 | 2.98 ± 0.1 |
| $v_t$     | 1.3 ± 0.2  | 1.1 ± 0.2  |
| [Fe/H]    | -0.14 ± 0.09 | +0.20 ± 0.09 |
| $L (L_\odot)$ | 45.2 ± 8.2 | 44.0 ± 7.2 |
| $R (R_\odot)$ | 9.9 ± 0.5 | 9.2 ± 0.4 |
| $M (M_\odot)$ | 1.9 ± 0.3 | 2.6 ± 0.3 |
5. Results

5.1. Radial Velocities and Orbital Solutions

The observed radial velocities for HD 145457 and HD 180314 are shown in figures 2 and 3, and are listed in tables 2 and 3, respectively, together with their estimated uncertainties. Each uncertainty was derived from an ensemble of velocities from individual ~400 spectral segments (each 3Å long) of each exposure. A Lomb-Scargle periodogram (Scargle 1982) of the data for HD 145457 and HD 180314 exhibits a dominant peak at a period of 176 d and 388 d, respectively. The false alarm probabilities (FAP) of the peaks were estimated by using a bootstrap randomization method in which the observed radial velocities were randomly redistributed, while keeping the observation time fixed. We generated 10⁵ fake datasets in this way, and applied the same periodogram analysis to them. Since no fake datasets exhibited a periodogram power higher than the observed ones, the FAPs were less than 1 × 10⁻⁵.

The best-fit Keplerian orbits for the stars were derived from the combined sets of the Subaru and OAO data using a Levenberg-Marquardt fitting algorithm to obtain a minimum chi-squared solution by varying the free parameters (orbital period, time of periastron passage, eccentricity, velocity amplitude, and argument of periastron). No velocity offsets were applied between the Subaru and OAO data, because we used the same stellar template to derive the radial velocities (see in section 2). The resulting Keplerian models are shown in figures 2 and 3 overplotted on the velocities, and their parameters are listed in table 4.

The radial velocities of HD 145457 can be well-fitted by an orbit with a period of $P = 176.30 \pm 0.39$ d, a velocity semi-amplitude of $K_1 = 70.6 \pm 3.1$ m s⁻¹, and an eccentricity of $e = 0.112 \pm 0.035$. The rms scatter of the residuals to the Keplerian fit was 9.7 m s⁻¹ and the reduced $\chi^2$ was 1.8. 

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### Table 2. Radial velocities of HD 145457.

| JD (−2450000) | Radial velocity (m s⁻¹) | Uncertainty (m s⁻¹) | Observatory |
|---------------|-------------------------|---------------------|-------------|
| 3843.85343    | −31.6                   | 6.3                 | Subaru      |
| 3886.92487    | 68.1                    | 4.6                 | Subaru      |
| 3928.93366    | 27.9                    | 5.4                 | Subaru      |
| 4554.20332    | −14.7                   | 6.2                 | OAO         |
| 4590.14827    | 71.9                    | 5.7                 | OAO         |
| 4624.13390    | 57.5                    | 5.6                 | OAO         |
| 4641.13561    | 14.9                    | 5.8                 | OAO         |
| 4675.03053    | −51.4                   | 7.0                 | OAO         |
| 4754.91967    | 39.6                    | 5.5                 | OAO         |
| 4757.91154    | 48.8                    | 6.4                 | OAO         |
| 4758.90361    | 41.2                    | 5.7                 | OAO         |
| 4759.90963    | 57.2                    | 8.0                 | OAO         |
| 4835.31110    | −25.6                   | 6.3                 | OAO         |
| 4852.30622    | −53.2                   | 7.8                 | OAO         |
| 4856.36498    | −61.1                   | 7.2                 | OAO         |
| 4864.34776    | −40.4                   | 5.5                 | OAO         |
| 4883.24232    | −74.1                   | 6.0                 | OAO         |
| 4924.09529    | 35.2                    | 6.8                 | OAO         |
| 4931.14786    | 63.2                    | 6.2                 | OAO         |
| 4949.14270    | 92.5                    | 6.3                 | OAO         |
| 4954.17821    | 71.7                    | 6.8                 | OAO         |
| 4983.02102    | 25.9                    | 6.0                 | OAO         |
| 5074.98880    | −60.6                   | 7.7                 | OAO         |
| 5133.89059    | 66.3                    | 6.7                 | OAO         |
| 5204.34017    | −54.1                   | 6.1                 | OAO         |
| 5233.29591    | −70.0                   | 5.5                 | OAO         |

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### Table 3. Radial velocities of HD 180314.

| JD (−2450000) | Radial velocity (m s⁻¹) | Uncertainty (m s⁻¹) | Observatory |
|---------------|-------------------------|---------------------|-------------|
| 3844.01193    | −292.1                  | 4.3                 | Subaru      |
| 3887.02601    | −255.7                  | 4.2                 | Subaru      |
| 3929.07331    | −70.4                   | 5.2                 | Subaru      |
| 4560.29990    | −162.5                  | 4.9                 | OAO         |
| 4624.23036    | −268.2                  | 4.8                 | OAO         |
| 4672.12211    | −281.5                  | 4.2                 | OAO         |
| 4755.04398    | 247.9                   | 4.0                 | OAO         |
| 4759.93750    | 296.7                   | 4.3                 | OAO         |
| 4763.95272    | 325.1                   | 4.7                 | OAO         |
| 4796.92531    | 387.4                   | 3.6                 | OAO         |
| 4800.87738    | 376.4                   | 4.2                 | OAO         |
| 4817.90163    | 334.0                   | 4.3                 | OAO         |
| 4884.35171    | 107.6                   | 5.0                 | OAO         |
| 4927.26199    | −71.8                   | 4.4                 | OAO         |
| 4949.26487    | −143.8                  | 4.2                 | OAO         |
| 4983.10598    | −198.8                  | 4.6                 | OAO         |
| 4983.14016    | −216.7                  | 4.4                 | OAO         |
| 5101.05269    | −142.1                  | 4.3                 | OAO         |
| 5132.01703    | 66.4                    | 4.2                 | OAO         |
| 5160.92845    | 295.3                   | 5.2                 | OAO         |
| 5162.89520    | 308.1                   | 4.8                 | OAO         |
| 5182.87567    | 379.4                   | 4.9                 | OAO         |
| 5234.38093    | 287.3                   | 4.8                 | OAO         |
| 5267.30944    | 133.4                   | 4.2                 | OAO         |
The uncertainty for each orbital parameter was determined using a bootstrap Monte-Carlo approach, by scrambling the residuals, adding the theoretical fit to parallel shifts of the spectral lines, and then refitting. Adopting a stellar mass of 1.9 $M_\odot$, we obtained a minimum mass for the companion of $m_2 \sin i = 2.9 M_j$ and a semimajor axis of $a = 0.76$ AU.

The radial-velocity variations of HD 180314 can be well-reproduced by a Keplerian orbit with $P = 396.03 \pm 0.62 \text{ d}$, $K_1 = 340.8 \pm 3.3 \text{ m s}^{-1}$ and $e = 0.257 \pm 0.010$. The uncertainty of each parameter was estimated using the same method as described above. By adopting a stellar mass of 2.6 $M_\odot$, we obtained a minimum mass for the companion of $m_2 \sin i = 22 M_j$ and a semimajor axis of $a = 1.4$ AU. The rms scatter of the residuals to the Keplerian fit was 12.9 m s$^{-1}$ and the reduced $\chi^2$ was 3.1. As can be seen in figure 3, we found that the residuals showed a possible non-random variability. A periodogram analysis for the residuals exhibits a peak at around 112 d, as shown in figure 4, but the peak is not considered to be significant at this stage because of the high FAP value (14%). When we assume that the periodicity originated from rotational modulation, the period corresponds to a stellar rotational velocity of about 4 km s$^{-1}$. This value is slightly large compared with those of typical GK giants (see figure 10 in Takeda et al. 2008), but is still possible by taking into account the moderate stellar activity of this star. More frequent observations will enable us to confirm the periodicity and to clarify the origin, stellar activity or additional companion.

### Table 4. Orbital parameters.

| Parameter | HD 145457 | HD 180314 |
|-----------|-----------|-----------|
| $P$ (d)   | 176.30±0.39 | 396.03±0.62 |
| $K_1$ (m s$^{-1}$) | 70.6±3.1 | 340.8±3.3 |
| $e$       | 0.112±0.035 | 0.257±0.010 |
| $\omega$ (°) | 300±26 | 303.1±2.3 |
| $T_p$ (JD – 2450000) | 3518±13 | 3565.9±3.1 |
| $a_i \sin i$ $(10^{-3}$ AU) | 1.137±0.051 | 11.99±0.12 |
| $f_i (m)$ $(10^{-7}M_\odot)$ | 0.0630±0.0086 | 14.65±0.46 |
| $m_2 \sin i$ ($M_j$) | 2.9 | 22 |
| $a$ (AU)  | 0.76 | 1.4 |
| $N_{\text{obs}}$ | 26 | 24 |
| rms (m s$^{-1}$) | 9.7 | 12.9 |
| Reduced $\sqrt{\chi^2}$ | 1.8 | 3.1 |

5.2. Line-Shape Analysis

We performed a spectral line-shape analysis by using high-resolution stellar templates to investigate other possible causes that would produce apparent radial-velocity variations, such as pulsation and rotational modulation, rather than orbital motion. For this purpose, we followed a procedure described in Sato et al. (2007), in which we used high-resolution I$_2$-free stellar templates extracted from several star+I$_2$ spectra. Details of the template extraction technique are described in Sato et al. (2002).

At first, we extracted two stellar templates from five star+I$_2$ spectra at the peak and valley phases of the observed radial velocities for each star. Then, cross-correlation profiles of the two templates were calculated for about 80 spectral segments (4–5Å width each) in which severely blended lines or broad lines were not included. Three bisector quantities were calculated for the cross-correlation profile of each segment: the velocity span (BVS), which is the velocity difference between two flux levels of the bisector; the velocity curvature (BVC), which is the difference of the velocity span of the upper half and lower half of the bisector; and the velocity displacement (BVD), which is the average of the bisector at three different flux levels. We used flux levels of 25%, 50%, and 75% of the cross-correlation profile to calculate the above three bisector quantities. As a result, both BVS and BVC for the stars were identical to zero, which means that the cross-correlation profiles are symmetric, and the average BVD agreed with the velocity difference between the two templates at the peak and valley phases of the observed radial velocities ($\pm 2K_1$). These results mean that the observed radial velocity variations are due to parallel shifts of the spectral lines, and are thus consistent.
with the planetary hypothesis. The resulting bisector quantities are summarized in table 5.

6. Summary and Discussion

We here report two new substellar companions to K0 III giants from Subaru and OAO planet search programs. The discoveries add to the recent growing population of substellar companions around evolved intermediate-mass stars.

HD 145457 b ($m_2 \sin i = 2.9 M_J$, $a = 0.76$ AU) is one of the innermost planets found around giants. All of the planets currently known around evolved intermediate-mass stars orbit at $a \geq 0.6$ AU (Johnson et al. 2007b; Sato et al. 2008b; Niedzielski et al. 2009b). Two possible causes of the lack of inner planets has been proposed: they are originally deficient or engulfed by the central stars. In the case of intermediate-mass subgiants ($< 2 M_\odot$), the former scenario is considered to be appropriate because they are obviously less evolved and have stellar radii of $\lesssim 6 R_\odot$, which means that they could only have engulfed very short-period planets, like hot-Jupiters (e.g., Johnson et al. 2007b). It is not easy, however, to discriminate between the two scenarios in the case of intermediate-mass giants (typically $\geq 2 M_\odot$) because it is difficult to know the accurate evolutionary status of giants. The inner planets could be tidally engulfed by the central stars at the phase of the tip of a red giant branch (RGB). Thus, if we observe giants that have already passed through the tip of the RGB, namely core-helium burning stars, we could not find any inner planets around the stars, even if the planets originally existed (Sato et al. 2008b; Villaver & Livio 2009). However, it is apparently difficult to distinguish such giants from those ascending RGB for the first time because they locate at nearly the same region on the HR diagram (red clump region). Based on stellar evolutionary models (cf. evolutionary tracks by Girardi et al. 2000), core-helium burning giants stay at the clump region for $\sim 100$-times longer than do first ascending RGB stars. Therefore, if we can collect hundreds of intermediate-mass giants, it will become possible to verify the causes of a lack of inner planets statistically.

HD 180314 b has a minimum mass of $22 M_J$ and orbits around the central star with $2.6 M_\odot$. This is the 7th brown-dwarf-mass ($13-80 M_J$) companion to evolved intermediate-mass stars (Hatzes et al. 2005; Lovis & Mayor 2007; Liu et al. 2008; Omiya et al. 2009; Niedzielski et al. 2009a). Actually, all of their host stars are estimated to be more massive than $2.5 M_\odot$, suggesting that more massive stars tend to have more massive companions (Lovis & Mayor 2007; Omiya et al. 2009). Several scenarios have been proposed for the formation of brown-dwarf-mass companions, including gravitational collapse in protostellar clouds, like stellar binary systems (Bonnell & Bastien 1992; Bate 2000), and gravitational instability in protostellar disks (Boss 2000; Rice et al. 2003). Even by the core-accretion scenario in protoplanetary disks, super-massive companions with $\gtrsim 10 M_J$ could be formed based on a certain truncation condition for gas accretion (Ida & Lin 2004; Alibert et al. 2005; Mordasini et al. 2008). If the companions form like stellar binary systems, they are expected to have a wide variety of orbital eccentricity. The above 7 brown-dwarf candidates, however, have relatively low eccentricities of 0–0.3, which may be favored by the scenarios that they formed in circumstellar disks and have not experienced significant gravitational interactions with other companions. One more thing to note here is that the metallicity of the host stars of the above-mentioned brown-dwarf candidates range from $[\text{Fe/H}] = -1$ to 0.2. Although the number of samples is still small, this suggests that the formation mechanism is independent of, or less sensitive to, the metallicity in this range.

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| Bisector quantities | HD 145457 | HD 180314 |
|---------------------|-----------|-----------|
| Bisector Velocity Span (BVS) (m s\(^{-1}\)) | $-4.9 \pm 6.3$ | $-0.3 \pm 5.1$ |
| Bisector Velocity Curvature (BVC) (m s\(^{-1}\)) | $-0.2 \pm 4.0$ | $0.3 \pm 2.2$ |
| Bisector Velocity Displacement (BVD) (m s\(^{-1}\)) | $-128 \pm 11$ | $-519 \pm 12$ |

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\(^3\) BD+20 2457 has two brown-dwarf-mass companions in the system.
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