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A possible substellar companion to the intermediate-mass giant HD 175679 *

Liang Wang[1,2], Bun'ei Sato[3], Gang Zhao[1], Yu-Juan Liu[1], Kunio Noguchi[4], Hiroyasu Ando[4], Hideyuki Izumiura[5], Eiji Kambe[5], Masashi Omiya[3], Hiroki Harakawa[3], Fan Liu[1,2], Xiao-Shu Wu[1,2], Yoichi Takeda[4], Michitoshi Yoshida[6] and Eiichiro Kokubo[4]

[1] Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; *wangliang@nao.cas.cn*
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[3] Department of Earth and Planetary Sciences, Graduate School of Science and Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan
[4] National Astronomical Observatory of Japan, National Institutes of Natural Sciences, Mitaka, Tokyo 181-8588, Japan
[5] Okayama Astrophysical Observatory, National Astronomical Observatory of Japan, National Institutes of Natural Sciences, Asakuchi, Okayama 719-0232, Japan
[6] Hiroshima Astrophysical Science Center, Hiroshima University, 1-3-1 Kagamiyama, Higashi-Hiroshima 739-8526, Japan

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Abstract We report the discovery of a substellar companion around the intermediate-mass giant HD 175679. Precise radial velocity data of the star from the Xinglong Station and the Okayama Astrophysical Observatory revealed a Keplerian velocity variation with an orbital period of 1366.8 ± 5.7 d, a semiamplitude of 380.2 ± 3.2 m s^{-1} and an eccentricity of 0.378 ± 0.008. Adopting a stellar mass of $2.7 \pm 0.3\ M_{\odot}$, we obtain that the minimum mass of the HD 175679 b is $37.3\pm2.8\ M_{\rm J}$ and the semimajor axis is 3.36 ± 0.12 AU. This discovery is the second brown dwarf companion candidate from a joint planet-search program between China and Japan.

Key words: stars: individual (HD 175679) — stars: brown dwarfs — techniques: radial velocities

1 INTRODUCTION

Brown dwarfs are widely known as "failed stars," with masses falling between the deuterium-burning limit ($\sim 13\,M_{\rm J}$) and the hydrogen-burning limit ($\sim 80\,M_{\rm J}$). A brown dwarf with a mass of $15\,M_{\rm J}$ and a separation of ~ 3 AU in a circular orbit around a solar-mass star causes a radial-velocity semiamplitude of stellar motion of above $200\,{\rm m\,s^{-1}}$ if seen along the orbital plane, which is easy to be detected with precise radial velocity techniques. However, compared with the number of planetary and stellar companions, brown dwarf-mass companions revealed by Doppler surveys are rare.

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Grether & Lineweaver (2006) estimated that less than 1% of Sun-like stars harbor brown dwarf companions. This rate is significantly lower than that of harboring stellar ($11 \pm 3\%$) or giant planetary ($5 \pm 2\%$) companions (Grether & Lineweaver 2006). Marcy & Butler (2000) also reported that only 0.5% of main sequence stars have brown dwarf-mass companions within 3 AU. Such a deficit between planetary and stellar mass in the mass distribution of companions is called the "brown dwarf desert." The paucity of brown dwarf companions may imply two distinct formation mechanisms: the core-accretion model (e.g. Ida & Lin 2004; Alibert et al. 2005), which is thought to be the main mechanism of giant planet formation (e.g. Fischer & Valenti 2005 and references therein), and the disk instability model (e.g. Boss 1997), which may dominate the formation processes of brown dwarf or substellar companions.

In the past few decades, seven brown dwarf-mass companions and more than 20 planetary companions around intermediate-mass stars have been detected by several Doppler survey programs (e.g. Frink et al. 2002; Sato et al. 2003, 2008a,b; Setiawan et al. 2003; Hatzes et al. 2005; Lovis & Mayor 2007; Niedzielski et al. 2007; Johnson et al. 2007; Liu et al. 2008, 2009; Omiya et al. 2009; Han et al. 2010). Although the number is still small compared with those around solar-mass stars, some remarkable properties have already been revealed, providing important clues on the physical properties of the protoplanetary disks. For instance, the planet occurrence rate around intermediate-mass stars ($1.3 \sim 1.9\ M_{\odot}$) is 10%–15% (Döllinger et al. 2009), which is significantly higher than that around solar-mass stars (e.g. Cumming et al. 2008). This can be interpreted by the higher surface densities of protoplanetary disks around more massive stars (Ida & Lin 2005). Nearly all the substellar companions discovered around intermediate-mass giants have semimajor axes larger than 0.6 AU. The lack of inner planets can be explained through the engulfment by central stars due to tidal torque during the RGB phase (Sato et al. 2008a), or being formed primordially (Burkert & Ida 2007). The planet-metallicity correlation for planets around solar-type stars does not seem to exist for those around intermediate giants (Pasquini et al. 2007; Takeda et al. 2008), and therefore constrains the planet formation model (e.g. Ida & Lin 2004; Boss 1997).

In this paper, we report the detection of a brown dwarf-mass companion candidate to the intermediate-mass giant HD 175679. This is the second brown dwarf candidate and the third discovery of the China-Japan planet search program carried out at the Xinglong Station (National Astronomical Observatories, China) and the Okayama Astrophysical Observatory (OAO, Japan).

2 OBSERVATIONS

2.1 OAO observations

The Okayama Planet Search Program started in 2001. The program has been carrying out a precise Doppler planet survey of 300 G and K giants using the 1.88m telescope with the High Dispersion Echelle Spectrograph (HIDES: Izumiura 1999) at OAO. In 2007 December HIDES was upgraded from a single CCD (2 K×4 K) to a mosaic of three CCDs, which can simultaneously cover a wavelength range of 3750–7500 Å using the RED cross-disperser. We set the slit width to 200 μm ($0.76''$), giving a spectral resolution ($\lambda/\Delta\lambda$) of 67 000 with 3.3 pixel sampling, and used an iodine absorption cell (I_2 cell: Kambe et al. 2002) for precise wavelength calibration. The reduction of the echelle spectra was performed using the IRAF software package in the standard manner.[1]

The I_2-superposed ("star+I_2") spectra are modeled based on the algorithm given by Sato et al. (2002). The stellar template used for radial velocity analysis was extracted by deconvolving an instrumental profile, which was determined by a B-star+I_2 spectrum, from a pure stellar spectrum taken without the I_2 cell. The Doppler precision was less than $6\ \mathrm{m\ s^{-1}}$ over a time span of 9 yr. We

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

used the stellar spectra without the I_2 cell for abundance analysis (e.g. Takeda et al. 2008; Liu et al. 2010).

2.2 Xinglong Observations

To extend the Okayama Planet Search Program, the Xinglong Planet Search Program started in 2005 under a framework of international collaboration between China and Japan. About 100 G-type giants with magnitudes of $6.0 < V < 6.2$ are being monitored with the 2.16 m telescope and the Coudé Echelle Spectrograph (CES: Zhao & Li 2001) at Xinglong. Part of the sample is also being monitored at OAO in order to confirm the stars' radial-velocity variability independently and HD 175679 presented in this paper is included in the sample observed both at Xinglong and OAO. The iodine absorption cell attached to CES is a copy of that of HIDES at OAO. We used the blue arm of CES for precise radial velocity measurements, which covers a wavelength range of 3900–7260 Å with a spectral resolution of $\sim 40\,000$ by 2 pixel sampling. Due to the small format of the CCD (1 K×1 K, with a pixel size of 24×24 $\mu\mathrm{m}^2$), only about 470 Å are available for precise radial velocity measurements. The modeling of the star+I_2 spectra and template extraction is based on the method by Sato et al. (2002), giving a radial velocity precision of $20 - 25\ \mathrm{m\,s^{-1}}$ over a time span of 3 yr, which is limited by the low resolution of the spectrograph and the narrow wavelength coverage of the CCD. In 2009 March, the CCD was replaced by Princeton Instrument's VersAarray: 2048B equipped with an e2v CCD42-40 image sensor having a pixel size of $13\times13\ \mu\mathrm{m}^2$, which was provided by the National Astronomical Observatory of Japan (NAOJ). The sampling rate was increased to about 3.9 pixels, although the wavelength coverage hardly changed. Radial velocity analysis for the data with the new CCD was basically the same as that for the data with the old CCD, but we used the stellar template obtained with the OAO data for the analysis of the new Xinglong data. We achieved a Doppler precision of about $15\,\mathrm{m\,s^{-1}}$ with a typical S/N of 150–200 over a time span of 1 yr.

3 STELLAR PROPERTIES

HD 175679 (HR 7144, HIP 92968, BD +02 3730) is a G8III star with $V = 6.14$, $B - V = 0.96$, and a *Hipparcos* parallax of $\pi = 6.23 \pm 0.8\,\mathrm{mas}$ (ESA 1997), giving a distance of $161 \pm 21\,\mathrm{pc}$ from the Sun, and an absolute magnitude $M_V = 0.52$. The physical parameters ($T_{\rm eff}$, [Fe/H], $\log g$, $v_{\rm t}$, and M_*) are taken from Liu et al. (2010), who used the stellar spectra obtained without the I_2 cell at OAO. The effective temperature ($T_{\rm eff} = 4844 \pm 100\,\mathrm{K}$) was derived from the color index $B - V$ and the empirical calibration relations of Alonso et al. (1999), and the metallicity [Fe/H]= -0.14 was derived from the equivalent widths measured from the I_2-free spectrum. Surface gravity, $\log g = 2.59 \pm 0.10$, was determined via the *Hipparcos* parallax (ESA 1997). The stellar mass $M_* = 2.7 \pm 0.3\,M_\odot$ was estimated from the Yonsei-Yale stellar evolutionary tracks (Yi et al. 2003). Microturbulent velocity $v_{\rm t} = 1.4 \pm 0.2\,\mathrm{km\,s^{-1}}$ was obtained by forcing Fe I lines with different strengths to give the same abundances. The stellar parameters are summarized in Table 1.

4 RADIAL VELOCITIES AND ORBITAL SOLUTION

The observation of HD 175679 was started at OAO and the Xinglong Station in 2005. Over a time span of five years, we collected a total of 22 radial velocity data points at OAO, with a typical S/N of 250 and 31 data points at Xinglong (23 with the old CCD and 8 with the new CCD) with a typical S/N of 150–200. The radial velocity points are shown in Figure 1 and are listed in Table 2 together with their estimated uncertainties. The best-fit Keplerian orbit was derived from both the OAO and Xinglong data using a least-squares method, and is shown in Figure 1 overplotted on the velocity data points. We applied the velocity offset of -177 m s^{-1} and -318 m s^{-1} to Xinglong's old and new data, respectively, relative to the OAO data in order to minimize reduced χ-squared $(\sqrt{\chi^2_\nu})$

Table 1 Stellar Parameters of HD 175679

Parameter	Value
Spectral Type	G8III
π (mas)	6.23 ± 0.80
V	6.14
$B - V$	0.961
M_V	0.52
BC	−0.318
$T_{\rm eff}$ (K)	4844 ± 100
$\log g$	2.59 ± 0.10
[Fe/H]	-0.14 ± 0.10
$v_{\rm t}$ (km s^{-1})	1.4 ± 0.2
L ($L_\odot$)	66 ± 17
R ($R_\odot$)	11.6 ± 1.6
M_*($M_\odot$)	2.7 ± 0.3
Age (Gyr)	$0.5^{+0.4}_{-0.2}$

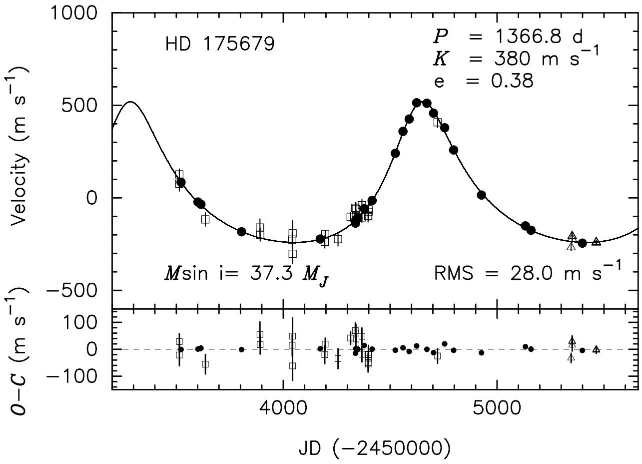

Fig. 1 Radial velocities of HD 175679 observed at OAO (*solid dots*) and Xinglong with the old CCD (*open squares*) and the new CCD (*open triangles*). The Keplerian orbit (*solid line*) was determined using both the OAO and Xinglong data.

when fitting a Keplerian model to the combined Xinglong and OAO data. The orbital parameters are listed in Table 3, and their uncertainties were estimated using a bootstrap Monte-Carlo approach, subtracting the theoretical fit, scrambling the residuals, adding the theoretical fit back to the residuals and then refitting.

The radial velocity variability can be well fitted as a Keplerian orbit with period $P = 1366.8 \pm 5.7$ d, a velocity semiamplitude $K_1 = 380.2 \pm 3.2$ m s^{-1}, and an eccentricity $e = 0.378 \pm 0.008$. Adopting a stellar mass of $2.7 \pm 0.3\,M_\odot$ (Liu et al. 2010), we obtain for the companion a minimum mass $m_2 \sin i = 37.3 \pm 2.8\,M_{\rm J}$ and a semimajor axis $a = 3.36 \pm 0.12$ AU. Overall RMS scatter of the residuals was 28.0 m s^{-1}, which was due to the low precision of the old Xinglong data. If we only use the OAO data, the RMS scatter is decreased to 8.4 m s^{-1}, which is consistent with the radial velocity jitter ($\sim 6\,{\rm m\,s^{-1}}$) due to stellar oscillations estimated using the scaling relations of Kjeldsen & Bedding (1995).

Table 2 Radial Velocities of HD 175679

JD (−2 450 000)	Radial velocity (m s^{-1})	Error (m s^{-1})	Observatory
3514.29867	76.7	40.2	Xinglong (old)
3514.31969	126.6	29.8	Xinglong (old)
3522.16608	84.5	6.4	OAO
3601.15072	−22.3	6.9	OAO
3615.14723	−34.8	10.0	OAO
3636.04337	−116.4	36.4	Xinglong (old)
3805.33702	−183.1	6.1	OAO
3891.30602	−160.4	47.0	Xinglong (old)
3892.31025	−198.8	35.4	Xinglong (old)
4042.02550	−225.7	40.4	Xinglong (old)
4043.94178	−191.9	68.6	Xinglong (old)
4043.96374	−302.3	54.4	Xinglong (old)
4173.34589	−222.3	5.0	OAO
4194.34042	−237.4	33.8	Xinglong (old)
4196.36671	−197.3	22.7	Xinglong (old)
4256.27293	−222.8	37.8	Xinglong (old)
4315.14228	−102.6	24.0	Xinglong (old)
4337.08455	−53.8	28.7	Xinglong (old)
4338.03334	−136.7	4.8	OAO
4339.99129	−117.3	4.5	OAO
4340.06605	−59.6	32.7	Xinglong (old)
4340.07325	−103.4	38.5	Xinglong (old)
4348.98057	−109.7	4.5	OAO
4368.01697	−39.1	31.8	Xinglong (old)
4368.03145	−105.5	29.0	Xinglong (old)
4379.03102	−58.2	5.5	OAO
4396.96580	−95.7	35.4	Xinglong (old)
4397.94288	−99.2	22.8	Xinglong (old)
4397.95442	−62.7	27.2	Xinglong (old)
4398.97764	−76.1	28.2	Xinglong (old)
4398.99416	−62.7	34.6	Xinglong (old)
4415.89851	−14.3	5.0	OAO
4524.34441	241.0	5.7	OAO
4560.32605	359.0	4.8	OAO
4589.27815	426.0	4.7	OAO
4624.11627	514.0	5.7	OAO
4672.08312	511.3	5.1	OAO
4703.09453	457.6	4.4	OAO
4722.06738	408.2	27.8	Xinglong (old)
4754.97696	379.1	4.8	OAO
4796.88244	258.7	4.9	OAO
4927.32075	15.1	5.0	OAO
5132.92161	−151.7	4.6	OAO
5158.93295	−174.9	9.2	OAO
5346.30620	−267.9	17.9	Xinglong (new)
5351.26229	−208.5	21.9	Xinglong (new)
5351.28343	−220.8	22.3	Xinglong (new)
5351.30453	−205.6	20.3	Xinglong (new)
5399.05791	−244.7	4.5	OAO
5464.00346	−242.4	11.5	Xinglong (new)
5464.02484	−239.0	10.7	Xinglong (new)
5464.04632	−241.5	12.0	Xinglong (new)
5464.06775	−239.4	10.4	Xinglong (new)

Table 3 Orbital Parameters of HD 175679 Determined from both Xinglong and OAO Data

Parameter	Value
P (d)	1366.8±5.7
K_1 (m s^{-1})	380.2±3.2
e	0.378± 0.008
ω (°)	346.4±1.3
$T_{\rm p}$ (JD − 2 450 000)	3263.9± 7.6
$a_1 \sin i$ (10^{-3}AU)	44.23± 0.43
$f_1(m)$ ($10^{-7} M_\odot$)	61.8± 1.7
$M_{\rm p} \sin i$ ($M_{\rm J}$)	37.3± 2.8
a (AU)	3.36± 0.12
$N_{\rm obs}$	53
RMS (m s^{-1})	28.0
Reduced $\sqrt{\chi^2_\nu}$	1.5

5 LINE SHAPE ANALYSES

We performed a spectral line-shape analysis to investigate other causes that could produce apparent radial-velocity variations, such as rotational modulation and pulsation. The high-resolution I_2-free stellar templates at the peak and valley phases of the observed radial velocities are extracted from several star + I_2 spectra obtained at OAO. Cross-correlation profiles of the templates were calculated for about 80 spectral segments (4–5 Å in width each) in which severely blended lines or broad lines were excluded. We calculated three bisector quantities for the cross-correlation profile of each segment: the velocity span (BVS), which is the velocity difference between two flux levels of the bisecter, the velocity curvature (BVC), which is the difference in velocity span between 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 quantities, and the results are plotted in Figure 2. Both BVS and BVC for HD 175679 are identical to zero ($+0.3\,{\rm m\,s^{-1}}$ and $-0.1\,{\rm m\,s^{-1}}$ on average, respectively), which means that the cross-correlation profiles are symmetric. The average BVD of $-603.9\,{\rm m\,s^{-1}}$ is consistent with the velocity difference between the two templates at the peak and valley phases of the observed radial velocities. As a result, we concluded that the observed radial velocity variations are due to parallel shifts of the spectral lines caused by orbital motion.

6 SUMMARY AND DISCUSSION

We report the discovery of a brown dwarf-mass companion candidate to the intermediate-mass giant HD 175679. This is the second brown dwarf discovered by the joint China-Japan planet search program. It also needs to be emphasized that the unknown orbital inclination i leaves the true mass of HD 175679 b uncertain. If the orbit is randomly oriented, there is a 10% chance that the true mass exceeds 80 $M_{\rm J}$ ($i < 28°$), which is the border between brown dwarf and stellar mass regimes.

In Table 4, we listed the parameters of the discovered brown dwarf-mass companions around intermediate-mass giants, and the properties of their host stars. The semi-major axes versus eccentricities of the brown dwarf companions above are plotted in Figure 3, together with those of the planetary companions around the intermediate-mass stars ($1.5\ M_\odot \leq M \leq 5\ M_\odot$). The parameters of the companions and host stars are taken from Table 4 and *The Extrasolar Planets Encyclopedia*[2]. As seen in the figure, brown dwarf-mass companions reside in orbits with $a \geq 1.3$ AU, while planetary ones exist in more inner orbits with $a \geq 0.6$ AU. This may reflect the different history of formation and evolution between brown dwarfs and planets.

[2] *http://exoplanet.eu/, retrieved on 09/May/2010.*

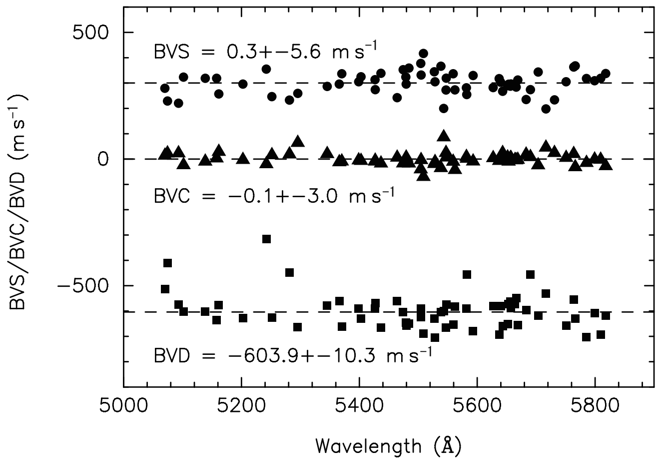

Fig. 2 Bisector quantities of the cross-correlation profiles between the templates of HD 175679 at peak and valley phases of the observed radial velocities. The bisector velocity span (BVS, *circles*), bisector velocity curvature (BVC, *triangles*), and bisector velocity displacement (BVD, *squares*) with average values (*dashed lines*) and standard errors are shown in the figure.

Table 4 Planetary and Stellar Parameters of Discovered Brown Dwarf Companions ($13\,M_\mathrm{J} < M_\mathrm{p}$ $\sin i < 80\,M_\mathrm{J}$) to Intermediate-mass Giants

Planet	$M_\mathrm{p}\sin i$ (M_J)	a (AU)	P (d)	e	M_* ($M_\odot$)	$M_\mathrm{p}\sin i/M_*$ ($M_\mathrm{J}/M_\odot$)	[Fe/H]	Reference
HD 13189 b	14	1.5−2.2	472	0.27	2−6	2.3−7		Hatzes et al. (2005)
NGC 4349 No. 127 b	19.8	2.38	678	0.19	3.9	5.1	−0.12	Lovis & Mayor (2007)
11 Com b	19.4	1.29	326	0.23	2.7	7.2	−0.35	Liu et al. (2008)
BD +20 2457 b	21.42	1.45	380	0.15	2.8	7.7	−1.00	Niedzielski et al. (2009)
BD +20 2457 c *	12.47	2.01	622	0.18	2.8	4.5	−1.00	Niedzielski et al. (2009)
HD 119445 b	37.6	1.71	410	0.08	3.9	9.6	+0.04	Omiya et al. (2009)
HD 180314 b	22	1.4	396	0.26	2.6	8.5	+0.20	Sato et al. (2010)
HD 175679 b	37.3	3.4	1367	0.38	2.7	13.8	−0.14	This paper

* BD +20 2457 c has a minimum mass $M_\mathrm{p}\sin i = 12.47\,M_\mathrm{J}$, very close to the lower mass limit ($\sim 13\,M_\mathrm{J}$) of a brown dwarf. Here we listed BD +20 2457 c as a brown dwarf companion.

HD 175679 b has a minimum mass of $37.3\,M_\mathrm{J}$ orbiting an evolved star with $2.7\,M_\odot$, with a period of 1367 d. As the eighth brown dwarf-mass companion candidate to intermediate-mass giants (Hatzes et al. 2005; Lovis & Mayor 2007; Liu et al. 2008; Omiya et al. 2009; Niedzielski et al. 2009; Sato et al. 2010), HD 175679 b is somewhat unique in some respects. Although it has been well known that more massive stars tend to host more massive planets or brown dwarfs than lower-mass stars (Lovis & Mayor 2007; Johnson et al. 2010), HD 175679 b has the largest companion-to-host mass ratio ($M_\mathrm{p}\sin i/M_* = 13.8\,M_\mathrm{J}/M_\odot$) among those discovered brown dwarfs around intermediate-mass giants, and hence falls in the region (a) in figure 5 of Omiya et al. (2009), which is proposed to be a paucity of brown dwarf-mass companions around stars with $M_* = 1.5-2.7\,M_\odot$.

Furthermore, among the brown dwarf candidates found around evolved stars, HD 175679 b is the first with a semimajor axis $a > 2.5$ AU, and eccentricity $e > 0.3$. This case shows the diversity of substellar companions falling in the "brown dwarf desert" regime. Brown dwarfs are thought to form by gravitational collapse (Bonnell & Bastien 1992; Bate 2000), or gravitational instability

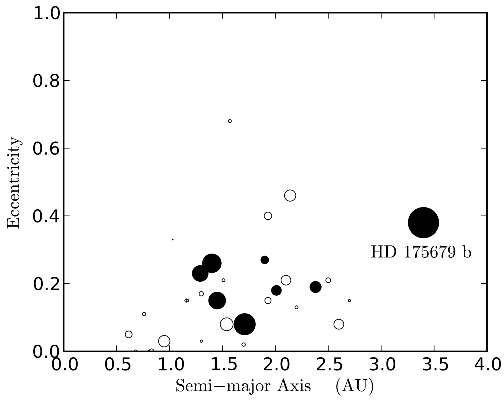

Fig. 3 Semi-major axes versus eccentricities of substellar companions around evolved intermediate-mass stars ($1.5\ M_\odot \leq M \leq 5\ M_\odot$). Open circles represent planetary companions and solid circles represent brown dwarf-mass companions, as listed in Table 4. The radii of the circles are proportional to their companion-to-host mass ratios ($M_\mathrm{p} \sin i / M_*$).

in protostellar disks (Boss 2000; Rice et al. 2003). The former scenario favors a wide variety of orbital eccentricities and small differences in mass between the host stars and their companions, which is contrary to the previous discoveries (e.g. Omiya et al. 2009; Sato et al. 2010). For the gravitational instability scenario, analytical models (e.g. Rafikov 2005; Matzner & Levin 2005) and numerical simulations (e.g. Stamatellos & Whitworth 2008) suggest that giant planets are formed at far more distant places ($\gtrsim$ 10 AU), and a high eccentricity can be produced (e.g. Muto et al. 2011) in this scenario. On the other hand, super-massive companions with $M_\mathrm{p} > 10\,M_\mathrm{J}$ can also form by the core-accretion scenario in protoplanetary disks (Ida & Lin 2004; Alibert et al. 2005). However, the wide metallicity span ($[\mathrm{Fe/H}] = -1.0 \sim +0.2$) of host stars of discovered brown-mass companions implies that they are inconsistent with the prediction of the core-accretion scenario that the probability of harboring planets is sensitive to the metallicity of a central star. Besides, the giant planets orbiting metal-poor stars discovered by Santos et al. (2010) and Moutou et al. (2011) suggest that long period giant planets are not rare around low-metallicity stars. It is difficult to say which scenario dominates the formation of brown dwarf mass companions due to the small number of discovered objects. However, the relatively large semimajor axis and relatively high eccentricity of HD 175679 b make it an important supplement to the parametric distribution of known brown dwarf companions. It also needs to be emphasized that HD 175679 b has the longest orbital period (1367 d) among those hitherto discovered brown dwarf-mass companions to intermediate-mass giants. Does the long period companion tend to have higher eccentricity? Ongoing projects and future discoveries will lead to a better understanding and characterization of the properties of substellar companions falling in the brown dwarf desert.

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