A Massive Substellar Companion to the Massive Giant HD 119445

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Abstract

We detected a brown dwarf-mass companion around the intermediate-mass giant star HD 119445 (G6III) using the Doppler technique. This discovery is the first result from a Korean–Japanese planet search program based on precise radial velocity measurements. The radial velocity of this star exhibits a periodic Keplerian variation with a period, semi-amplitude, and eccentricity of 410.2 d, 413.5 m s⁻¹, and 0.082, respectively. Adopting a stellar mass of 3.9 $M_\odot$, we were able to confirm the presence of a massive substellar companion with a semimajor axis of 1.71 AU and a minimum mass of 37.6 $M_J$, which falls in the middle of the brown dwarf-mass region. This substellar companion is the most massive ever discovered within 3 AU of a central intermediate-mass star. The host star also ranks among the most massive stars with substellar companions ever detected by the Doppler technique. This result supports the current view of substellar systems that more massive substellar companions tend to exist around more massive stars, and may further constrain substellar system formation mechanisms.

Key words: stars: individual (HD 119445) — star: low-mass, brown dwarfs — techniques: radial velocities

1. Introduction

A brown dwarf is defined as an object that has a mass of between the deuterium-burning limit of $\sim 13 M_J$ and the hydrogen-burning limit of $\sim 80 M_J$ (e.g., Burrows et al. 1997). So far, brown dwarf-mass companions to normal stars have been searched for by using various techniques, such as precise Doppler measurements (e.g., Nidever et al. 2002; Patel et al. 2007), direct imaging (e.g., McCarthy & Zuckerman 2004; Lafrenière et al. 2007), spectroscopic observations (e.g., Neuhäuser & Guenther 2004), and astrometric ones (e.g., Halbwachs et al. 2000; Zucker & Mazeh 2001). Although some brown dwarf-mass companions have been detected by these methods, one intriguing result of these observations is that brown dwarf-mass companions close ($\lesssim 1000$ AU) to solar-type stars are conspicuously scarce compared to planetary and stellar companions (e.g., Gizis et al. 2001; McCarthy & Zuckerman 2004). Based on the combined results of various precise Doppler surveys of nearby FGK-type stars, Grether and Linewaver (2006) reported that less than 1% of solar-type stars harbor brown dwarf-mass companions with orbital periods of less than 5 yr, while 11% ± 3% and 5% ± 2% have stellar companions and giant planets, respectively. Moreover, according to a near-infrared imaging survey of the Sco OB2 association by Kouwenhoven, Brown, and Kaper (2007), the frequency of brown dwarf-mass companions ($\gtrsim 30 M_J$) with orbital separations of 130–520 AU around intermediate-mass A or late-B type stars is 0.5% ± 0.5%. This rate is lower than that of stellar companions by one order of magnitude. The paucity of brown dwarf-mass companions relative to both planetary companions and stellar companions is known as a “brown dwarf desert” (e.g., Marcy & Butler 2000; Grether & Linewaver 2006). The existence of the desert may be explained by orbital migration (Armitage & Bonnell 2002) or ejection (Reipurth & Clarke 2001) of brown dwarf-mass companions, or may suggest a bimodal mass function of substellar companions that could be produced by two distinct formation mechanisms: core-accretion in protoplanetary disks (e.g., Ida & Lin 2004; Alibert et al. 2005), forming mostly planetary companions, and gravitational fragmentation in molecular clouds or protoplanetary disks (e.g., Boss 1997; Bate 2000; Rice et al. 2003; Stamatellos & Whitworth 2009), forming mostly stellar or brown dwarf-mass companions.

To date, several precise Doppler surveys of subgiants, giants, and early-type dwarfs have uncovered 4 brown dwarf-mass companions ($13 M_J < M_2 \sin i_p \lesssim 25 M_J$) and 21 planetary companions ($0.6 M_J < M_2 \sin i_p \lesssim 13 M_J$) around intermediate-mass stars ($1.5 M_\odot \leq M \leq 5 M_\odot$) (Sato et al. 2003, 2007,

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The metallicity [Fe/H] of many planet-harboring intermediate-mass stars is lower than that typically observed for solar-type stars (Lovis & Mayor 2007; Hekker et al. 2008). The orbital semimajor axes of all substellar companions around solar-type stars (e.g., Butler et al. 2006). The masses of substellar companions orbiting intermediate-mass stars tend to be larger than those around solar-type stars (Lovis & Mayor 2007; Hekker et al. 2008). The orbital semimajor axes of all substellar companions detected around intermediate-mass giants are larger than \(\sim 0.6\) AU (Johnson et al. 2007; Sato et al. 2008a; Niedzielski et al. 2009). On the other hand, substellar companions of solar-type stars can also be found in much closer orbits (\(\geq 0.017\) AU). The metallicity [Fe/H] of many planet-harboring intermediate-mass stars is lower than that typically observed for solar-type stars with planetary companions (Fischer & Valenti 2005; Pasquini et al. 2007; Takeda et al. 2008). Additional comparisons between planetary systems orbiting intermediate-mass stars and other types of stars would be of great interest for an accurate understanding of the dependence of substellar system formation on the central star mass.

We report on the discovery of a brown dwarf-mass companion orbiting the intermediate-mass giant HD 119445. This is the first result of an ongoing Korean–Japanese planet search program carried out at Bohyunsan Optical Astronomy Observatory (BOAO, Korea) and Okayama Astrophysical Observatory (OAO, Japan). The planet search program is introduced in section 2. We describe the properties of the host star and the orbital motion in sections 3 and 4, respectively. The cause of the radial velocity variation and an upper limit on the companion mass are discussed in section 5. In section 6, we consider the implications of this discovery for the current picture of substellar companions.

2. Korean–Japanese Planet Search Program

In 2005, we started a joint planet search program between Korean and Japanese researchers to search for planets around GK-type giant stars using a precise Doppler technique with the 1.8 m telescope at BOAO and the 1.88 m telescope at OAO. This survey program is an extended version of the ongoing OAO planet search program (Sato et al. 2005) and part of an international collaboration among researchers from Korea, China, and Japan (an East-Asian Planet Search Network, EAPS-Net; Izumiura 2005). The collaboration aims to clarify the properties of planetary systems around intermediate-mass stars by surveying more than 800 GK giants for planets at OAO, BOAO, the Xinglong station (China), and the Subaru Telescope.

For the Korean–Japanese planet search program, we selected about 190 target stars from the Hipparcos catalog based on the following criteria: color-index \(0.6 < B - V < 1.0\), absolute magnitude \(-3 < M_V < 2\), declination \(\delta > -25^\circ\), and visual magnitude \(6.2 < V < 6.5\). These targets are fainter than those of the OAO and Xinglong program (Sato et al. 2005; Liu et al. 2008). We divided the targets into two parts: one for BOAO and the other for OAO. Each is observed independently at the assigned observatory, although the star that exhibits a large radial velocity variation is observed intensively at both observatories.

We will also carry out abundance analyses for all the target stars to derive fundamental stellar parameters and chemical compositions, and to investigate the connection between these stellar characteristics and the existence of orbiting planets.

2.1. BOES Observations

Radial velocity observations at BOAO were carried out with the 1.8 m telescope and BOAO Echelle Spectrograph (BOES: Kim et al. 2007), i.e., a fiber-fed high-resolution echelle spectrograph. For precise radial velocity measurements, we placed an iodine absorption cell (I\(_2\) cell) in the optical path in front of the fiber entrance of the spectrograph (Kim et al. 2002) and used a \(200 \mu m\) fiber, obtaining a wavelength resolution \(R = \lambda/\Delta\lambda \sim 51000\). The spectra covered a wavelength range of 3500–10500 Å. We used the range between 5000 Å and 5900 Å, a region covered by many I\(_2\) absorption lines, for precise radial velocity measurements. We also made use of Ca H lines around 3970 Å as chromospheric activity diagnostics. Echelle data reduction was performed by using the IRAF\(^1\) software package in the standard manner.

Precise radial velocities for the BOES data were derived by using a modeling method detailed in Sato et al. (2002), based on a method of Butler et al. (1996), and were improved and optimized for BOES data analysis. We used seven Gaussian profiles with a common full width half maximum of 1.3 pixels, placed at 1 pixel intervals to reconstruct the BOES instrumental profile, and a fourth-order Legendre polynomial to describe the wavelength scale. The number of Gaussians, the width and interval of the Gaussian, and the order of the Legendre polynomial were chosen so as to minimize the long-term radial velocity dispersion of the standard star HD 57727, which is known to have a small radial velocity scatter of \(\leq 7\) m s\(^{-1}\) based on OAO observations over a period of 7 yr. We employed the extraction method described in Sato et al. (2002) to prepare a stellar template spectrum from some stellar spectra taken through the I\(_2\) cell (I\(_2\)+stellar spectra). The stellar radial velocity was determined by calculating the average of the radial velocities of \(\sim 200\) spectral segments (each \(\sim 5\) Å long), except those with the worst least-squares fit. This technique allowed us to achieve a Doppler precision of \(\sim 11\) m s\(^{-1}\) during the 2.3 yr period of this project (see figure 1).

2.2. HIDES Observations

Radial velocity observations at OAO were carried out with the 1.88 m telescope and HIgh Dispersion Echelle Spectrograph (HIDES: Izumiura 1999) attached to the coudé focus of the telescope. For radial velocity measurements, we observed over the 5000–6200 Å wavelength range with a slit width of 200 \(\mu m\) (0.76") giving a spectral resolution of 63000. An I\(_2\) cell (Kambe et al. 2002) was used for precise wavelength calibration. Echelle data reduction was performed by using the IRAF software package in the standard manner. Stellar radial velocities were derived from the I\(_2\)-superposed stellar

\(^1\) IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation, USA.
Table 1. Stellar parameters of the host star HD 119445.

| Parameter   | Value               |
|-------------|---------------------|
| Spectral Type | G6III               |
| V           | 6.30                |
| B - V       | 0.879 ± 0.004       |
| π           | 3.46 ± 0.71         |
| M_ν         | -1.03               |
| B.C.        | -0.23               |
| T_eff (K)   | 5083 ± 103          |
| L (L_☉)     | 251 ± 95            |
| M (M_☉)     | 3.9 ± 0.4           |
| R (R_☉)     | 20.5 ± 0.3          |
| log g       | 2.40 ± 0.17         |
| V_ν (km s⁻¹)| 1.49 ± 0.20         |
| [Fe/H]      | 0.04 ± 0.18         |
| v sin i_☉ (km s⁻¹)| 6.0 ± 0.6,* 6.9 ± 1.0† |

* Gray (1989).† de Medeiros and Mayor (1999).

spectrum modeling technique detailed in Sato et al. (2002), and gave a Doppler precision of ~7 m s⁻¹ during the 2.3 yr period of our program (see figure 1). We also obtained stellar spectra without the I_2 cell using the same spectrograph setting for abundance analysis.

3. HD 119445 Stellar Parameters

HD 119445 (HR 5160, HIP 66892) is located at 289 pc from the Sun according to the Hipparcos parallax of π = 3.46 ± 0.71 mas. The star is classified as a G6III giant star with V = 6.30 and B - V = 0.879 ± 0.004 (ESA 1997). We derived an effective temperature, T_eff, of the star as being T_eff = 5083 ± 103 K using a (B - V) - T_eff calibration of Alonso, Arribas, and Martínez-Roger (1999, 2001). A luminosity of L = 251 ± 95 L_☉ was obtained from the absolute magnitude M_ν = -1.03 and the bolometric correction B.C. = -0.23 based on the calibration of Alonso, Arribas, and Martínez-Roger (1999). A stellar mass of M = 3.9 ± 0.4 M_☉ was estimated by interpolating the evolutionary tracks of Girardi et al. (2000) with the estimated T_eff and L. We determined the surface gravity to be log g = 2.40 ± 0.17 and the stellar radius R = 20.5 ± 0.3 R_☉ from M, L, and T_eff. A micro-turbulent velocity of V_ν = 1.49 ± 0.20 km s⁻¹ and [Fe/H] = 0.04 ± 0.18 were derived from an abundance analysis with a model atmosphere (Kurucz 1993) by using equivalent widths of the Fe I and Fe II lines measured from an I_2-free spectrum of HD 119445. We adopted qf-values of Fe I and Fe II lines from Takeda et al. (2005). The stellar rotational velocity, v sin i_☉, was found to be 6.0 ± 0.6 km s⁻¹ (Gray 1989) and 6.9 ± 1.0 km s⁻¹ (de Medeiros & Mayor 1999). These values are larger than the rotational velocities of most of late G-type giants. The stellar parameters are summarized in table 1.

Figure 2 shows Ca II H lines of HD 119445 and the radial velocity standard star HD 57727. There is a lack of significant emission in the Ca II H line core of HD 119445 and HD 57727, which suggests a chromospheric inactivity, although the correlation between chromospheric activity and intrinsic radial velocity jitter for giant stars is not yet well established. Moreover, Hipparcos photometry collected from 187 observation sources of the star demonstrates the photometric stability of HD 119445 down to σ ~ 0.008 mag, which also suggests a chromospheric inactivity for the star.

4. Orbital Solution

We monitored the radial velocity of HD 119445 over a period of 2.3 yr from the beginning of the survey at both observatories. We accumulated 9 BOAO data points with a typical signal-to-noise ratio (S/N) of 180 pixel⁻¹, given an exposure time of 900–1200 s, and 27 OAO data points with a typical S/N of 140 pixel⁻¹, given an exposure time of 1200–1800 s. The observed radial velocities of HD 119445 are shown in figure 3 and listed in tables 2 (BOAO) and 3 (OAO), together with estimated uncertainties. The best-fit Keplerian orbit derived from both the BOAO and the OAO
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Table 2. Radial velocities of HD 119445 at BOAO.

| JD          | Radial velocity (m s\(^{-1}\)) | Error (m s\(^{-1}\)) |
|-------------|-------------------------------|----------------------|
| 3427.3555  | 215.5                         | 11.6                 |
| 3730.3782  | −309.5                        | 10.6                 |
| 3756.3179  | −265.1                        | 14.2                 |
| 3809.2236  | 96.3                          | 9.9                  |
| 3831.2419  | 199.7                         | 11.7                 |
| 3888.0653  | 457.1                         | 13.3                 |
| 4081.3558  | −253.9                        | 12.6                 |
| 4123.2218  | −361.9                        | 14.3                 |
| 4224.1335  | 94.5                          | 15.2                 |

Fig. 3. Upper panel: radial velocities of HD 119445 observed at BOAO (filled circles) and OAO (open circles). The Keplerian orbital curve that we determined is drawn by the solid line. Lower panel: Residuals to the best Keplerian fit.

Table 3. Radial velocities of HD 119445 at OAO.

| JD          | Radial velocity (m s\(^{-1}\)) | Error (m s\(^{-1}\)) |
|-------------|-------------------------------|----------------------|
| 3412.2214  | 119.9                         | 10.5                 |
| 3429.1852  | 208.0                         | 12.6                 |
| 3461.2184  | 334.6                         | 6.3                  |
| 3519.0496  | 451.6                         | 11.8                 |
| 3581.0147  | 295.5                         | 8.9                  |
| 3598.9982  | 184.2                         | 8.0                  |
| 3607.9722  | 123.7                         | 6.8                  |
| 3611.9573  | 88.0                          | 10.3                 |
| 3614.9515  | 87.7                          | 7.1                  |
| 3644.9092  | −123.8                        | 10.6                 |
| 3695.3348  | −366.1                        | 8.0                  |
| 3709.3600  | −373.1                        | 8.9                  |
| 3730.3545  | −377.2                        | 11.7                 |
| 3743.3350  | −330.3                        | 6.8                  |
| 3805.1203  | 0.4                           | 10.7                 |
| 3824.1283  | 116.4                         | 8.4                  |
| 3831.1425  | 138.5                         | 9.7                  |
| 3931.1190  | 401.2                         | 12.9                 |
| 3947.0120  | 423.0                         | 10.3                 |
| 4075.2883  | −232.4                        | 8.7                  |
| 4131.2517  | −385.6                        | 7.4                  |
| 4151.2616  | −343.3                        | 7.0                  |
| 4176.2334  | −225.9                        | 9.2                  |
| 4199.2797  | −96.4                         | 8.1                  |
| 4214.1939  | −4.2                          | 12.8                 |
| 4243.0711  | 166.6                         | 6.6                  |
| 4261.9704  | 262.2                         | 8.0                  |

Table 4. Orbital parameters of HD 119445b.

| Parameter          | Value               |
|--------------------|---------------------|
| \(K_1\) (m s\(^{-1}\)) | 413.5 ± 2.6     |
| \(P\) (days)        | 410.2 ± 0.6     |
| \(e\)               | 0.082 ± 0.007    |
| \(\omega\) (deg)   | 160.5 ± 4.3      |
| \(T\) (JD)          | 2452873.9 ± 5.6  |
| \(\Delta RV^*\) (m s\(^{-1}\)) | −43.0 ± 5.1 |
| \(rms\) (m s\(^{-1}\)) | 13.7             |
| \(\sqrt{N_{obs}}\) | 1.7              |
| \(N_{obs}\)         | 36               |
| \(a_1 sin \theta\) (10\(^{-3}\) AU) | 15.54 ± 0.10 |
| \(f_1(m)\) (10\(^{-7}\) M\(_\odot\)) | 29.75 ± 0.58 |
| \(M_2 sin \theta\) (M\(_\odot\)) | 37.6 ± 2.6      |
| \(a\) (AU)          | 1.71 ± 0.06      |

* Offset between BOAO and OAO velocities.

5. Line Shape Analyses and an Upper Limit of a Mass

Spectral-line shape analyses were performed by using techniques described in Sato et al. (2007) to investigate other causes of the apparent radial velocity variation, such as the rotational...
modulation and pulsation. For these analyses, we used two high-resolution stellar templates extracted from I+stellar spectra obtained at OAO. One template was constructed from four spectra with observed radial velocities ranging from 330 to 450 m s$^{-1}$ (peak), and the other from four spectra of around –370 m s$^{-1}$ (valley). Cross-correlation profiles of the templates were calculated for 27 spectral segments (4- to 5-Å width each) that did not include severely not only blended lines but also broad lines. 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; the velocity displacement (BVD), which is the average of the bisector values at three different flux levels. We used flux levels of 25%, 50%, and 75% of the cross-correlation profile to calculate the above quantities. These bisector quantities for HD 119445 are shown in figure 4. As expected under the planetary hypothesis, both the BVS and the BVC (each average to $-7.3 \pm 18.1$ m s$^{-1}$ and $-1.1 \pm 6.2$ m s$^{-1}$, respectively) are essentially identical to zero, meaning that the cross-correlation profiles are symmetric. The dispersions of the BVS and BVD are relatively large. This is probably due to the broad absorption lines in the stellar spectra caused by the large rotational velocity. However, the average value of the BVD ($-766.4 \pm 32.3$ m s$^{-1}$) is consistent with the velocity difference between the two templates. The value is more than 20 times larger than the dispersions; thus, the velocity difference between the templates is considered to be due to a parallel shift of spectral lines caused by the orbital motion, not to variations in the spectral line shapes. Hence, the observed radial velocity variation of HD 119445 is best explained by the orbital motion of a companion, not by intrinsic activity, such as the rotational modulation and pulsation.

If we assume that the orbit is randomly oriented, the probability that the true mass exceeds the brown dwarf-mass limit of 80 $M_J$ ($i_p \approx 28^\circ$) can be 12%. If we assume that the orbit of the companion is coplanar with the stellar equatorial plane, a small orbital inclination of less than 28° can imply a stellar rotational velocity larger than 12 km s$^{-1}$. Single G-type giants with such a high rotational velocity are rare, and would be identified as X-ray sources in ROSAT observations. However, no X-ray emissions from HD 119445 have been detected (Hünsch et al. 1998), which suggests that the rotational velocity of HD 119445 is not fast and that the orbital inclination, $i_p$, is not so small. Thus, the true mass of the companion may be smaller than 80 $M_J$, which is the upper-limit mass for a brown dwarf.

6. Discussion

We detected a brown dwarf-mass companion orbiting the intermediate-mass giant star HD 119445. This discovery is the first result from our Korean–Japanese planet search program. The host star HD 119445 has a mass of 3.9 $M_{\odot}$. It is one of the most massive stars hosting substellar companions. HD 119445 is the fifth brown dwarf-mass companion with a semimajor axis of less than 3 AU and the most massive brown dwarf-mass companion among those discovered around intermediate-mass stars. Now we have found two brown dwarf-mass companions and ten planetary companions from the surveys at OAO, Xinglong, and BOAO from a total of ~500 targets of the surveys (Sato et al. 2003, 2007, 2008a, 2008b; Liu et al. 2008, 2009; this work). The ratio between the numbers of brown dwarf-mass companions and planetary companions detected from the surveys of our GK-type giants seems comparable to that (~1% to ~5%; Grether & Lineweaver 2006) for solar-type stars, although the surveys are not yet complete and detection limits differ between solar-type and giant stars. This result may support the existence of a brown dwarf desert, a deficit of brown dwarf-mass companions relative to planetary companions, around intermediate-mass stars inside a ~3 AU orbital separation.

However, the existence of the desert may depend on the host star’s mass. In figure 5, we plot the masses of the companions detected within a semimajor axis of 3 AU by precise Doppler surveys against their host star’s masses; solar-mass stars ($0.7 M_{\odot} \leq M < 1.5 M_{\odot}$, open triangles), intermediate-mass subgiants and giants (1.5 $M_{\odot} \leq M \leq 5 M_{\odot}$, filled circles), an intermediate-mass dwarf (A-type star HD 180777, open circle), and HD 119445 (star) (The Extrasolar Planets Encyclopedia; Halbwachs et al. 2000; Tinney et al. 2001; Nidever et al. 2002; Vogt et al. 2002; Endl et al. 2004; Galland et al. 2006; Liu et al. 2008; Sato et al. 2008a, 2008b; this work). The detectable companion mass for a given host star mass depends on the orbital separation of its companion and the radial velocity jitter of the host star. Assuming that typical radial velocity jitters $\sigma$ for solar-mass stars, intermediate-mass subgiants (1.5–1.9 $M_{\odot}$), and giants (1.9–5 $M_{\odot}$) are ~5 m s$^{-1}$, ~7 m s$^{-1}$, and ~20 m s$^{-1}$, respectively, we estimated the lower limits of companion masses detectable by precise Doppler surveys around a solar-mass star.

\[\text{http://exoplanet.eu/}, \text{version of 24/April/2008.}\]
We exclude a brown dwarf-mass companion orbiting a possible high mass giant HD 13189 (M = 4.5 ± 2.5 M⊙; Hatzes et al. 2005) from the following discussion because of the large uncertainty in its host star’s mass.

3 We exclude a brown dwarf-mass companion orbiting a possible high mass dwarf-mass companion orbiting the A-type dwarf HD 180777 (Galland et al. 2006) regarded as a unique and interesting correlation considered from unpopulated regions (a) and (b). A possible host star–companion mass of companions orbiting at 3 AU, corresponding to three times the typical radial velocity jitters. Solid lines indicate the detection limits for the mass of companions orbiting at 3 AU, corresponding to three times the typical radial velocity jitters, σ, of 5 m s⁻¹ for solar-mass stars (0.7 M⊙ ≤ M < 1.5 M⊙), 7 m s⁻¹ for intermediate-mass subgiants (1.5 M⊙ ≤ M < 1.9 M⊙), and 20 m s⁻¹ for intermediate-mass giants (1.9 M⊙ < M ≤ 5 M⊙). Dotted and dot-dashed lines indicate the detection limits for companions at 0.02 AU and 0.6 AU in solar mass stars and intermediate-mass evolved stars, respectively. Two regions devoid of substellar companions are denoted by (a) and (b).

and intermediate-mass subgiant and giant at 3 AU (solid lines in figure 5), corresponding to companion masses that provide an amplitude of three times the typical radial velocity jitters. We also indicate detectable masses for these stars at 0.02 AU (dotted lines) and 0.6 AU (dot-dashed lines), corresponding to the semimajor axes of the known innermost planets orbiting solar-type and intermediate-mass evolved stars.

Two unpopulated regions of substellar companions orbiting intermediate-mass subgiants and giants seem to exist in regions (a) and (b). A possible host star–companion mass correlation considered from unpopulated regions (a) and (b) supports the current view that more massive substellar companions tend to exist around more massive stars, which is derived from the results of planet searches around various mass stars (Lovis & Mayor 2007; Hekker et al. 2008).

All of the brown dwarf-mass companions to intermediate-mass evolved stars were found around those with ≥ 2.7 M⊙, and there seems to be a paucity of such companions around those with 1.5–2.7 M⊙ [region (a) in figure 5]. A brown dwarf-mass companion orbiting the A-type dwarf HD 180777 (Galland et al. 2006) is regarded as a unique and interesting one since it populates region (a). Such early-type dwarfs have larger typical radial velocity jitters σ (≥ 66 m s⁻¹ for late A-type dwarfs: Lagrange et al. 2009) than that of evolved stars due to more rapid rotation and pulsation, and thus the planet mass distribution in early-type dwarfs is less well defined than that of intermediate-mass evolved stars. If we consider the smaller number of survey targets of ≥ 2.7 M⊙ (e.g., 35% of the 300 OAO targets: Takeda et al. 2008) compared with that of 1.5–2.7 M⊙, frequencies of brown dwarf companions may become higher as the stellar mass increases. This might favor a gravitational instability in protostellar disks (Rice et al. 2003), rather than fragmentation of protostellar clouds (Bate 2000) as the formation mechanism of brown dwarf-mass companions, because stellar systems with larger differences in mass between primary and secondary stars are more difficult to be formed by the latter mechanism (Bate 2000).

Also, there seems to be a possible paucity of lower-mass companions around 2.4–4 M⊙ stars [region (b) in figure 5]. Although it is basically difficult to detect planets around such “noisy” stars with large intrinsic radial velocity variability (σ = 20 m s⁻¹), planets with mass ≥ 2.6–3.3 Mj (∼ 5.7–7.4 Mj) and a = 0.6 AU (a = 3.0 AU) should be above the current detection limit (3 σ = 60 m s⁻¹). Recently, Kennedy and Kenyon (2008) predicted that the frequency of giant planets has a peak near 3 M⊙ stars based on a core accretion scenario taking account of the movement of snow line along the evolution of accretion and the central stars. Moreover, if a formation mechanism that invokes capturing of solid bodies migrating inward at the inner edge of the inactive magnetorotational instability-dead zone inside of the protoplanetary disk works, gas giant planets could be formed efficiently at around 1 AU around intermediate-mass stars before the planetary disks are depleted (Kretke et al. 2009). Increasing the number of known massive planetary companions around massive intermediate-mass stars with further radial velocity surveys would be very important in understanding the formation mechanisms of giant planets around intermediate-mass stars.

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