A Substellar Companion to Pleiades HII 3441

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Abstract

We find a new substellar companion to the Pleiades member star, Pleiades HII 3441, using
the Subaru telescope with adaptive optics. The discovery is made as part of the high-contrast imaging survey to search for planetary-mass and substellar companions in the Pleiades and young moving groups. The companion has a projected separation of $0.′′49 \pm 0.′′02$ (66 $\pm$ 2 AU) and a mass of $68 \pm 5\,M_J$ based on three observations in the $J$, $H$, and $K_S$-band. The spectral type is estimated to be M7 ($\sim$2700 K), and thus no methane absorption is detected in the $H$ band. Our Pleiades observations result in the detection of two substellar companions including one previously reported among 20 observed Pleiades stars, and indicate that the fraction of substellar companions in the Pleiades is about $10.0^{+26.1}_{-8.8}$%. This is consistent with multiplicity studies of both the Pleiades stars and other open clusters.

**Key words:** stars:low-mass, brown dwarf, stars: imaging, stars: individual (Pleiades HII 3441)

### 1 Introduction

The Pleiades has long been recognized as one of the nearest young open clusters (135 pc and 120 Myr, as discussed later). Young brown dwarfs have been extensively searched for in the Pleiades for studying the low-mass end of the initial mass function through various deep, wide-field imaging surveys (e.g., Jameson & Skillen 1989; Stauffer et al. 1989; Stauffer et al. 1998b). Among these studies, Stauffer et al. (1994) confirmed one and Zapatero Osorio et al. (1997) confirmed two brown dwarfs in the Pleiades.

Adaptive optics imaging surveys are also a good tool for detection of faint companions such as brown dwarf and planetary-mass objects. Bouvier et al. (1997) directly imaged 144 G and K Pleiades members with the Canada-France-Hawaii telescope’s adaptive optics system in order to investigate the stellar multiplicity, and found 22 binary systems and 3 triples with a separation between $0.′08–6.′9$. They concluded that the binary fraction of the G- and K-type stars in the Pleiades ($28\% \pm 4\%$) is similar to that of G-type field stars (Duquennoy & Mayor 1991). However, the stellar multiplicity is still uncertain with respect to the low-mass and closely bound objects, due to the limited sensitivity to faint companions with small separations from the primary and lack of follow-up, proper motion measurements. Geißler et al. (2012) and Rodriguez et al. (2012) each discovered a substellar mass companion around Pleiades HII 1348 and HD 23514 with the adaptive optics system at the Keck observatory.

We report in this paper the discovery of a new substellar mass companion to the Pleiades member star Pleiades HII 3441 (2MASS J03444394+2529574), with the Subaru high-contrast instru-
Table 1. Pleiades HII 3441

| Other Names          | 2MASS J03444394+2529574 |
|---------------------|-------------------------|
|                     | TYC 1803-839-1          |
|                     | SRS 71291, SSH J121, PELS 41 |
| RA (h m s)          | 03 44 43.9              |
| DEC (d m s)         | +25 29 57.1             |
| $J$                 | 10.39 ± 0.3 mag$^a$     |
| $H$                 | 9.86 ± 0.03 mag$^a$     |
| $K_S$               | 9.74 ± 0.02 mag$^a$     |
| Proper Motion (RA)  | 16.4 ± 2.7 mas/yr$^b$   |
| (DEC)               | -48.8 ± 2.6 mas/yr$^b$  |
| Spectral Type       | K-type (K3 ± 1)$^c$     |
| Membership          | Pleiades (78%–98%)      |

Note: (a) Cutri et al. 2003. (b) Høg et al. 2000. (c) The spectral sub-type was estimated using VOSA. See Appendix for the details.

We note that the employed distance and age of the Pleiades in this paper are 135 pc and 120 Myr, respectively, considering the previous works described below. The distance of the Pleiades had been stated to be between ∼120 pc (e.g., van Leeuwen 2009) and 135 pc (e.g., Soderblom et al. 2005). The controversy was settled by Melis et al. (2014), and they showed the Pleiades to be at a distance of 136.2 ± 1.2 pc. The age of the Pleiades ranges from 115 to 135 Myr based on various previous works (e.g., Basri et al. 1996; Stauffer et al. 1998a; Barrado y Navascués et al. 2004; Bell et al. 2014).
Table 2. Observing Log of Pleiades HII 3441

| Obs. Date          | Mode       | Band | Sub Exposure | Coadd | Total Exposure | Angle<sup>a</sup> |
|--------------------|------------|------|--------------|-------|----------------|-------------------|
| (UT)               |            |      | (s)          |       | (minutes)      | (degree)          |
| 2011 September 4   | SDI+ADI    | $H_S$, $H_L$ | 10   | 1   | 48.3           | 120.8             |
| 2014 October 11    | DI+ADI     | $H$   | 1.5       | 30   | 15             | 75.9              |
| 2015 January 8     | DI         | $H$   | 10        | 3, 10| 4.7            | -                 |
|                    | DI         | $J$   | 20        | 1    | 4.7            | -                 |
|                    | DI+ADI<sup>b</sup> | $J$ | 20       | 1    | 13.7           | 18.6              |
|                    | DI+ADI<sup>b</sup> | $K_s$ | 10  | 1   | 2.2            | 2.3               |

Note: (a) Total rotational angle in case of the ADI mode. (b) ADI was used for dithering.

2 Observations and Data Reduction

We observed Pleiades HII 3441 as part of the SEEDS survey. A summary of our target samples is shown in the supplementary material, including our target list (Supplementary Table 1), the observing logs (Supplementary Table 2), and the companion candidates list (Supplementary Table 3).

2.1 Observations

We observed Pleiades HII 3441 using HiCIAO along with AO188 on the Subaru telescope. HiCIAO is a high contrast instrument for imaging exoplanets with a 2K×2K HAWAII2-RG array and a pixel scale of 9.5 mas. Three observations were conducted for Pleiades HII 3441, on 2011 September 4, on 2014 October 11, and on 2015 January 8, as shown in Table 2. In the 2011 observation, we used the simultaneous spectral differential imaging (SDI) mode in the $H$ band (e.g., see observations in Janson et al. 2013), as well as the angular differential imaging (ADI) mode (Marois et al. 2006). The $H$ band is divided into two narrow bands ($H_S$: 1.486–1.628 $\mu$m and $H_L$: 1.643–1.788 $\mu$m) in the SDI mode, to search for methane absorption that is seen in low temperature objects ($<\sim 1300$ K; Sharp & Burrows 2007). The ADI mode was used along with the SDI mode to achieve a high contrast at small angular separation. The other two observations were conducted as follow-up in order to measure the proper motion and photometric properties of the companion candidate. One was conducted in 2014, using the direct imaging (DI) + ADI mode in the $H$ band to check the proper motion of the companion candidate. Another was conducted in 2015, using the DI mode in the $J$, $H$, and $K_s$ bands to measure the colors. The rotation angle for the 2015 observations was small (see Table 2), because the ADI mode was used as replacement for dithering and not to achieve the highest possible contrast.
2.2 Data Reduction

In a pre-processing step, we conducted stripe removal, flat and dark corrections, bad pixels interpolation, and distortion correction according to the method described in Yamamoto et al. (2013). For the ADI dataset, we used standard ADI reduction (Marois et al. 2006) and Locally Optimized Combination of Imaging (LOCI; Lafrenière et al. 2007). In the SDI mode, $H_S$ and $H_L$ images were simultaneously taken on the left and right half of the detector. We divided each frame into two, and then performed ADI reduction on each filter separately. For these analyses, we used Image Reduction and Analysis Facility (IRAF)- and Interactive Data Language (IDL)-based tools.

3 Results and Discussion

Figure 1 shows the final Pleiades HII 3441 images taken in the 2011 and 2014 observations, reduced using standard ADI. Images reduced with LOCI were of similar sensitivity and are therefore not shown in addition. A companion candidate was detected southeast of the primary star, and subsequently confirmed as a companion object to the primary star.

3.1 Proper Motion Check

We measured the position of the companion candidate using the 2011, 2014, and 2015 observations (see Supplementary Table 3). Figure 2 shows the RA and DEC offsets of the companion candidate with the primary star at the origin. Pleiades HII 3441 and its companion candidate are co-moving within $1\sigma$ of the position errors, ruling out the possibility that the companion candidate is a back-
Table 3. Properties of Pleiades HII 3441B

| Property                  | Value                      |
|---------------------------|----------------------------|
| Projected Separation      | 0".49 ± 0".02 (66 ± 2 AU)*  |
| Position Angle            | 136.4° ± 3.2°              |
| J                         | 15.64 ± 0.14 mag (68 ± 3 MJ) |
| H                         | 15.23 ± 0.08 mag (65 ± 2 MJ) |
| K_s                       | 14.71 ± 0.06 mag (72 ± 2 MJ) |
| ΔH_s                      | 5.47 ± 0.19 mag            |
| ΔH_L                      | 5.29 ± 0.29 mag            |
| H_s - H_L                 | 0.18 ± 0.26 mag            |

Note: ΔH_s and ΔH_L are relative magnitudes to the primary star. (a) Projected separation is calculated using the Pleiades distance 135 pc. (b) Mass at 120 Myr is estimated using the BT-Settl model.

We also investigated the possibility that the companion candidate is another faint Pleiades member along the same line of sight, because the possibility cannot be ruled out completely due to the insufficient baseline of our observation to detect the orbital motion. The number of isolated Pleiades stars that could be chance aligned in the field of view of HiCIAO was estimated using the Pleiades stellar distribution (e.g., King 1962) and luminosity function (e.g., Bouvier et al. 1998; Jameson et al. 2002; Moraux et al. 2003; Bihain et al. 2006). The estimated number of stars with brightness similar to Pleiades HII 3441B (15–16 mag in the H band) is less than 0.03, when 21 Pleiades stars were observed. The likelihood of contamination is small, since the 21 targets are distant from the cluster center (∼1°).

We conclude that the companion candidate is indeed a bound companion to Pleiades HII 3441 and refer to it in the following discussion as Pleiades HII 3441B. The projected separation and position angle are shown in Table 3 as 0".49 ± 0".02 (66 ± 2 AU) and 136.4° ± 3.2°, respectively. These values were derived by averaging all observations.

3.2 Multiband Photometry

The ADI-reduced images typically suffer from the self-subtraction which biases the brightness measurements if not taken into account. To avoid effects caused by the self-subtraction, we used each image before the ADI reduction for photometry. We performed aperture photometry using the `apphot` task in IRAF, with an 8 pixels-radius aperture corresponding to the FWHM of the point spread function. The halo of the primary star affects the accuracy of the photometry of Pleiades HII 3441B due to its small angular separation. Therefore, we estimated the offset value contributed by the halo at the position of Pleiades HII 3441B, assuming the halo is azimuthally symmetric. The offset value is
calculated in an annulus at the same angular separation as HII 3441B and centered on the primary star. We performed relative photometry to the primary star based on its infrared magnitudes reported in Cutri et al. (2003), in order to obtain the brightness of Pleiades HII 3441B. For data taken in 2015, the $J$, $H$, and $K_S$-band magnitudes are $15.64 \pm 0.14$, $15.23 \pm 0.08$, and $14.71 \pm 0.06$, respectively (see Table 3). The $J$-band magnitude corresponds to a mass of $68 \pm 3 \, M_J$ and a temperature of $\sim 2700$ K at 120 Myr according to the BT-Settl model (Baraffe et al. 2015). The mass is below the hydrogen-burning limit ($72 \, M_J$; e.g., Chabrier et al. 2000), and therefore Pleiades HII 3441B classifies as a brown dwarf. The spectral type is estimated to be M7 from the photometry-derived temperature (Pecaut & Mamajek 2013). Figure 3 shows a color-magnitude diagram of three substellar companions in the Pleiades that have been reported (HD 23514B; Rodriguez et al. 2012 and Pleiades HII 1348B; Geißler et al. 2012). The properties of Pleiades HII 3441B are consistent with the other two substellar companions and substellar members in the Pleiades reported in Lodieu et al. (2007).
While the mass estimate derived from the $J$- and $H$-band magnitudes ($68 \pm 3 \, M_J$, $65 \pm 2 \, M_J$) falls into the highest mass brown dwarf regime, the mass derived from the $K_s$-band magnitude ($72 \pm 2 \, M_J$) potentially crosses the hydrogen-burning limit. We note that this is an object that is close to the boundary between the stellar and substellar regime.

### 3.3 Methane Absorption

We tested for the existence of methane absorption using the SDI observation. The aperture photometry was performed using the same procedures as described in Section 3.2, and the results are shown in Table 3. We obtained an $H_S - H_L$ color of $0.18 \pm 0.26$, which means that there is no methane absorption in the atmosphere of Pleiades HII 3441B. This is consistent with our conclusion about the object being an M7-type dwarf ($\sim 2700$ K), because methane is considered to condense below $\sim 1300$ K (Sharp & Burrows 2007). We also compared its color with theoretical values derived from simulated BT-Settl spectra generated using the PHOENIX web simulator\(^1\) and assuming stellar parameters of Pleiades HII 3441B (the effective temperature of 2700 K, logarithm of the surface gravity of 5.0, and solar metallicity). The theoretical $H_S - H_L$ color is 0.04 and is consistent with our measurements within $1\sigma$. There is no contradiction between Pleiades HII 3441B and a late M-dwarf spectrum.

\(^1\) https://phoenix.ens-lyon.fr/simulator/index.faces
3.4 Discussion: Fraction of Substellar Companions in the Pleiades

As introduced in Section 1, the Pleiades multiplicity is well investigated except for low-mass and close companions. Deriving a fraction of close substellar companions is therefore an essential key for the determination of the initial mass function, and might help to understand the formation mechanisms in the cluster.

We detected three substellar companions and a stellar companion among 21 observed stars in the Pleiades including two companions reported in Yamamoto et al. (2013) (see also Supplementary Table 3). To discuss an unbiased sample, we consider 20 stars after removing Pleiades HII 1348 since we intended to observe its companion for the comparison with the previous work (Geißler et al. 2012) for this source. The binary fraction of $3/20 = 15\%$ has a strong bias, because known binaries have been removed from the target sample (see Yamamoto et al. 2013). Therefore, we focus on substellar companions to the Pleiades stars. The fraction of detected substellar companions is $2/20 = 10\%$ in our survey. If we assume Poisson statistics and the 95% confidence interval, the fraction ranges from 1.2% to 36.1%. The companion mass and projected separation range that our survey probed spans roughly from 10 to $75 M_J$ and from 65 to $\sim 1000$ AU, respectively, according to detection limits reported in Yamamoto et al. (2013).

We compare the fraction with those of the other works shown in Table 4. Bouvier et al. (1997) found that the fraction at a mass ratio of $< 0.1$ is 4.9% ($1''0–2''0$) and 6.1% ($2''0–6''9$) using 144 Pleiades stars. Recent studies also reported similar fractions. For example, using only substellar companions (absolute $J > 10$ mag) among 17 observed stars reported in Richichi et al. (2012), a fraction of 5.9% is obtained. Small sample high-contrast-imaging observations conducted in the Pleiades resulted in no detection of substellar companions within their 10 samples (Itoh et al. 2011). In other open clusters, we only note that a large imaging survey revealed that the multiplicity with a mass ratio of $> 0.25$ and a projected separation range of 26 to 581 AU is 9% and 10% using 142 $\alpha$ Persei stars and 100 Praesepe stars, respectively (Patience et al. 2002). Our fraction is consistent.

| Table 4. Fractions of Substellar Companions |
|---------------------------------------------|
| Bouvier et al. (1997) | Pleiades | 4.9–6.1% |
| Richichi et al. (2012) | Pleiades | 5.9% (re-calculated) |
| Patience et al. (2002) | $\alpha$ Persei | 9% |
| Patience et al. (2002) | Praesepe | 10% |
| Metchev & Hillenbrand (2009) | including field stars | 3.2% |
| Brandt et al. (2014) | including field stars | 1–3.1% |
| This Work | Pleiades | $10.0^{+2.6}_{-8.8}$% (95% confidence interval) |
with those of the previous studies, although the parameter space explored by those previous surveys is not the same as in our observations. In addition, we point out that there is no large deviation of the fraction among open clusters, which has already been reported in Duchêne and Kraus (2013).

Recently, several works have derived the fractions of substellar companions which included young field stars. Metchev & Hillenbrand (2009) revealed that the fraction is 3.2% using 266 solar-type stars. The SEEDS results also support this with a fraction of 1–3.1% using 250 high-contrast-imaging stars (Brandt et al. 2014). These studies included field stars and derived smaller fractions than ours using Bayesian statistics. This might be due to the difference in sample size (insufficient sample size for open cluster stars) and the estimation method, because these fractions are roughly within our large uncertainty. A much larger survey of the Pleiades would be needed to draw general conclusion on the multiplicity differences between open clusters and field star populations.

4 Summary

We discovered a substellar companion to Pleiades HII 3441 as part of the SEEDS survey using Subaru/HiCIAO together with AO188. Pleiades HII 3441B has a separation of 0′′.49 ± 0′′.02 (66 ± 2 AU) and a mass of 68 ± 5 M_J, based on J-, H-, K_S-band observations, that is below but very close to the hydrogen-burning limit. We also confirmed two previously known companions among the 21 observed Pleiades stars reported by Yamamoto et al. (2013). After an object which was observed for comparison with the previous study was removed from our sample, the fraction of substellar companion detections is 10^{+26.1}_{-8.8}% if we assume Poisson statistics and the 95% confidence interval. Our result is consistent with previous studies of the Pleiades and other clusters.

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Appendix. Estimation of Pleiades HII 3441 Spectral Type

The spectral type of the primary star has been known as K-type, but has not been investigated in more detail. We therefore constructed the spectral energy distribution (SED) using published photometric results in the literature, and estimated the spectral type by fitting the black body spectrum. The flux
at each wavelength is taken from GALEX (Galaxy Evolution Explorer; Bianchi et al. 2000), APASS (the AAVSO Photometric All-Sky Survey; Henden et al. 2009), Tycho2 (Tycho-2 Catalogue; Høg et al. 2000), 2MASS (Two Micron All-Sky Survey; Cutri et al. 2003), and WISE (Wide-field Infrared Survey Explorer; Wright et al. 2010) catalogues. The black body spectrum was fitted by $\chi^2$ minimization using the VOSA web tool\(^2\). The fitted SED is shown in Figure 4. The effective temperature was estimated as $4550 \pm 10$ K using all data, and as $4850 \pm 20$ K without GALEX data. For an additional level of characterization, we estimated the spectral type and effective temperature of the star by interpolating its optical and near-IR photometric colors within the main-sequence color-temperature conversion table of Pecaut & Mamajek (2013). We find an effective temperature of $4800 \pm 160$ K. The uncertainties were calculated using Monte Carlo methods. This temperature is consistent with the SED determination. We concluded that Pleiades HII 3441 has an effective temperature of $4700 \pm 200$ K, and corresponds to a spectral type of K3 $\pm 1$ (Pecaut & Mamajek 2013).

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\(^2\) http://svo2.cab.inta-csic.es/theory/vosa/
Fig. 4. SED of Pliades HII 3441 generated by VOSA. Black lines indicate the 4550 K and 4850 K black bodies that are most fitted model using the data with and without GALEX, respectively. Circles are published photometric results in the literature (Bianchi et al. 2000; Høg et al. 2000; Cutri et al. 2003; Henden et al. 2009; Wright et al. 2010). Open mark was not used for SED fitting because it is upper limit.

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Supplement: Our Survey (Subsamples of SEEDS observations)

Our survey is conducted as part of the SEEDS program. The SEEDS survey results have been reported in numerous works (e.g., Janson et al. 2013b; Brandt et al. 2014b; Uyama et al. 2016). The supplement contains results of subsamples that we obtained, including previously reported results of Pleiades stars (Yamamoto et al. 2013). Supplementary Table 1 represents our target list. We focused on young stars whose ages are well known. Each target belongs to one of the moving groups (MG) or associations: the Pleiades (120 Myr, 135 pc), Ursa Major MG (500 Myr, ~25 pc; King et al. 2003), Octans-Near association (<100 Myr, ~90 pc; Zuckerman et al. 2013), and AB Doradus MG (~50 Myr, 30 pc; López-Santiago et al. 2006). One target (GJ 212) is considered to belong to either Hercules-Lyra association (~200 Myr, <25 pc; López-Santiago et al. 2006) or Local association (20–150 Myr: Montes et al. 2001). Supplementary Table 2 shows the observing logs of data taken after September 2012, excluding the ones reported in (Yamamoto et al. 2013). Supplementary Table 3 is the companion candidates list including their projected separation, position angle (PA), and photometric results. The companion status is determined by confirmation of their proper motion.

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## Supplementary Table 1. Target List

| Name       | HD Number | RA (h m s) | DEC (d m s) | Sp.T | Group       | Distance (pc) | R (mag) | J (mag) | H (mag) | K_s (mag) |
|------------|-----------|------------|-------------|------|-------------|---------------|---------|---------|---------|-----------|
| HIP 6276   | -         | 01 20 32.3 | -11 28 03.7 | G9   | AB Dor      | 35.1          | 7.90    | 7.03    | 6.65    | 6.55      |
| Chi Cet B  | 11131     | 01 49 23.4 | -10 42 12.9 | G1   | UMa         | 23.0          | 6.39    | 5.54    | 5.29    | 5.15      |
| HD 23061†  | 23061     | 03 42 55.1 | +24 29 35.1 | F5   | Pleiades    | 135           | 9.01    | 8.51    | 8.33    | 8.26      |
| HII 3456†  | -         | 03 43 27.1 | +25 23 15.3 | G2   | Pleiades    | 135           | 11.21   | 9.75    | 9.31    | 9.22      |
| HD 23247†  | 23247     | 03 44 23.5 | +24 07 57.6 | F3   | Pleiades    | 135           | 8.85    | 8.08    | 7.81    | 7.77      |
| HII 3441   | -         | 03 44 39.3 | +25 29 57.1 | K    | Pleiades    | 135           | 11.41   | 10.39   | 9.86    | 9.74      |
| HII 636†   | -         | 03 45 22.2 | +23 18 18.2 | K    | Pleiades    | 135           | 11.69   | 10.47   | 9.96    | 9.85      |
| V855 Tau†  | -         | 03 45 40.2 | +24 37 38.1 | F8   | Pleiades    | 135           | 9.37    | 8.62    | 8.34    | 8.29      |
| BD+23 514† | -         | 03 45 41.9 | +25 25 35.3 | G5   | Pleiades    | 135           | 11.15   | 9.80    | 9.53    | 9.40      |
| V1171 Tau† | -         | 03 46 28.4 | +24 26 02.1 | G8   | Pleiades    | 135           | 10.51   | 9.64    | 9.27    | 9.16      |
| HD 23514†  | 23514     | 03 46 38.4 | +22 55 11.2 | G0   | Pleiades    | 135           | 8.96    | 8.48    | 8.29    | 8.15      |
| HD 282954† | 282954    | 03 46 38.8 | +24 57 34.7 | G0   | Pleiades    | 135           | 9.98    | 9.11    | 8.85    | 8.76      |
| HII 1348†  | -         | 03 47 18.1 | +24 23 26.8 | K5   | Pleiades    | 135           | 12.43   | 10.49   | 9.83    | 9.72      |
| TYC 1800-2144-1† | - | 03 48 34.5 | +23 26 05.3 | G0   | Pleiades    | 135           | 10.37   | 9.20    | 8.98    | 8.87      |
| HD 23863†  | 23863     | 03 49 12.2 | +23 53 12.5 | A7   | Pleiades    | 135           | 7.98    | 7.67    | 7.60    | 7.58      |
| HII 2311†  | -         | 03 49 28.7 | +23 42 44.1 | G2   | Pleiades    | 135           | 10.91   | 9.91    | 9.54    | 9.43      |
| HD 23912†  | 23912     | 03 49 32.7 | +23 22 49.5 | F3   | Pleiades    | 135           | 8.88    | 8.26    | 8.10    | 8.04      |
| HII 2366†  | -         | 03 49 36.5 | +24 17 46.1 | G2   | Pleiades    | 135           | 10.88   | 10.03   | 9.63    | 9.55      |
| HII 2462†  | -         | 03 49 50.4 | +23 42 20.2 | G2   | Pleiades    | 135           | 11.50   | 10.07   | 9.70    | 9.60      |
| BD+22 574† | -         | 03 49 56.5 | +23 13 07.0 | F8   | Pleiades    | 135           | 10.02   | 9.15    | 8.85    | 8.80      |
| V1174 Tau† | -         | 03 50 34.6 | +24 30 28.2 | G8   | Pleiades    | 135           | 11.61   | 10.70   | 10.20   | 10.08     |
| HD 24132†  | 24132     | 03 51 27.2 | +24 31 07.1 | F2   | Pleiades    | 135           | 8.49    | 8.06    | 7.93    | 7.88      |
| V1054 Tau† | -         | 03 51 39.3 | +24 32 56.1 | K    | Pleiades    | 135           | 12.35   | 10.42   | 9.92    | 9.81      |
| BD-01 565  | 24916     | 03 57 28.7 | -01 09 34.1 | K4   | UMa         | 15.8          | 7.34    | 6.06    | 5.49    | 5.34      |
| ome Tau    | 27045     | 04 17 15.7 | +20 34 42.9 | A3   | ONA         | 29            | 4.77    | 4.79    | 4.58    | 4.36      |
| GJ 212     | 233153    | 05 41 30.7 | +53 29 23.3 | M0   | HLA/LA      | 12.5          | 6.81    | 6.59    | 5.96    | 5.76      |
| V1386 Ori  | 41593     | 06 06 40.5 | +15 32 31.6 | K0   | UMa         | 15.5          | 6.24    | 5.32    | 4.94    | 4.82      |
| HIP 36624  | 59507     | 07 31 55.6 | +38 53 45.8 | A2   | ONA         | 80.4          | 6.53    | 6.41    | 6.47    | 6.42      |
| CCDM J08316+3458A | 71974 | 08 31 35.0 | +34 57 58.4 | G5   | UMa         | 28.7          | 6.82    | 5.92    | 5.50    | 5.47      |
| BD-13 2855 | 81659     | 09 26 42.8 | -14 29 26.7 | G6   | UMa         | 39.9          | 7.44    | 6.69    | 6.41    | 6.31      |
**Supplementary Table 1. (Continued)**

| Name      | HD Number | RA       | DEC       | Sp.T | Group  | Distance | R    | J    | H    | K<sub>S</sub> |
|-----------|-----------|----------|-----------|------|--------|----------|------|------|------|-------------|
| DS Leo    | 95650     | 11 02 38.3 | +21 58 01.7 | M2   | UMa    | 11.7     | 8.64 | 6.52 | 5.90 | 5.69        |
| BD+52 1638 | 109647    | 12 35 51.3 | +51 13 17.3 | K0   | UMa    | 26.3     | 7.94 | 6.73 | 6.25 | 6.16        |
| HR 4803   | 109799    | 12 37 42.3 | -27 08 20.0 | F1   | UMa    | 34.6     | 5.23 | 4.76 | 4.63 | 4.54        |
| BD+22 2522 | 112196    | 12 54 40.0 | +22 06 28.6 | F8   | UMa    | 34.3     | 6.67 | 5.88 | 5.63 | 5.55        |
| GJ 516    | -         | 13 32 44.8 | +16 48 40.9 | M3   | UMa    | 13.8     | 12.04 | 7.64 | 7.07 | 6.83        |
| HR 5148   | 119124    | 13 40 23.2 | +50 31 09.9 | F8   | ONA    | 25       | 6.02 | 5.28 | 5.11 | 5.02        |
| GJ 9457B  | 119124B   | 13 40 24.5 | +50 30 57.6 | K7   | ONA    | 25       | 9.98 | 7.79 | 7.16 | 7.01        |
| HR 7451   | 184960    | 19 34 19.8 | +51 14 11.8 | F7   | UMa    | 25.6     | 5.43 | 4.70 | 4.59 | 4.49        |
| BD-00 4333 | 211575    | 22 18 04.3 | -00 14 15.6 | F3   | UMa    | 41.5     | 6.12 | 5.59 | 5.35 | 5.33        |

Note: † Previously reported in Yamamoto et al. (2013).

Group column abbreviations

AB Dor: AB Doradus moving group (López-Santiago et al. 2006)

UMa: Ursa Major moving group (King et al. 2003)

Pleiades: Pleiades open cluster (Yamamoto et al. 2013)

HLA: Hercules-Lyra moving group (López-Santiago et al. 2006)

LA: Local Association (Montes et al. 2001)

ONA: Octans-Near Association (Zuckerman et al. 2013)

R magnitude: NOMAD database (Zacharias et al. 2005)

J, H, K<sub>S</sub> magnitudes: 2MASS (Cutri et al. 2003)

Other properties are taken from the above group citations.
| Name               | Date         | Mode      | Filter | Sub Exposure | Coadd | Total Exposure |
|--------------------|--------------|-----------|--------|--------------|-------|----------------|
| HIP 6276           | 2012 Nov. 7  | DI+ADI    | $H$    | 15           | 10    | 40             |
| Chi Cet B          | 2013 Jan. 3  | DI+ADI    | $H$    | 5            | 10    | 31.7           |
| HII 3441           | 2011 Sep. 4  | SDI+ADI   | $H_S, H_L$ | 10 | 1 | 48.3 |
|                   | 2014 Oct. 11 | DI+ADI    | $H$    | 1.5          | 30    | 15             |
|                   | 2015 Jan. 8  | DI        | $J, H, K_S$ | 20, 10, 10 | 1, 3/10, 1 | 18.4, 4.7, 2.2 |
| V1174 Tau          | 2012 Sep. 12 | DI        | $H$    | 10           | 3     | 25             |
|                   | 2013 Oct. 16 | DI        | $J, H, K_S$ | 30, 30, 30 | 1, 1, 1 | 8, 9, 8 |
|                   | 2013 Nov. 24 | DI+ADI    | $H$    | 10, 1.5      | 5, 50 | 28.8           |
|                   | 2014 Oct. 7, 9 | DI    | $H$  | 60, 30       | 1, 1  | 15, 25         |
| V1054 Tau          | 2012 Sep. 11, 12 | DI | $H$  | 10, 10       | 1, 3  | 8.5, 10        |
|                   | 2013 Feb. 26* | DI | $H$  | 20           | 3     | 36             |
| BD-01 565          | 2012 Nov. 5  | DI+ADI    | $H$    | 1.5          | 10    | 13             |
| Beta Tau           | 2014 Jan. 20 | DI+ADI    | $H$    | 1.5          | 10    | 17.5           |
|                   | 2014 Oct. 10 | DI        | $H$    | 30           | 1     | 12.5           |
| GJ 212             | 2013 Jan. 2  | DI+ADI    | $H$    | 15           | 3     | 43.5           |
|                   | 2013 Oct. 17 | DI        | $H$    | 15           | 10    | 15             |
| V1386 Ori          | 2013 Jan. 3* | DI+ADI    | $H$    | 10           | 3     | 61             |
| HIP 36624          | 2013 Nov. 23 | DI+ADI    | $H$    | 10           | 10    | 48.3           |
|                   | 2015 Jan. 7  | DI, DI+ADI| $H$    | 60, 20       | 1, 1  | 50, 21.3       |
| CCDM J08316+3458A  | 2013 Nov. 24 | DI+ADI    | $H$    | 10           | 10    | 45             |
|                   | 2015 Jan. 8  | DI+ADI    | $H$    | 10           | 10    | 38.3           |
| BD-13 2855         | 2013 Jan. 1  | DI+ADI    | $H$    | 15           | 3     | 33.8           |
|                   | 2014 Jan. 20 | DI+ADI    | $H$    | 15           | 2     | 13             |
|                   | 2014 Apr. 23 | DI        | $J, H$ | 60, 30       | 1, 1  | 13, 10         |
| DS Leo             | 2014 Jan. 21 | DI+ADI    | $H$    | 1.5          | 10    | 17.3           |
| BD+52 1638         | 2013 Feb. 26 | DI+ADI    | $H$    | 20           | 3     | 33             |
| HR 4803            | 2013 Jan. 2  | DI+ADI    | $H$    | 10           | 10    | 51.7           |
| BD+22 2522         | 2013 May 18  | DI+ADI    | $H$    | 5            | 10    | 33.3           |
| GJ 516             | 2014 Jun. 8  | DI+ADI    | $H$    | 5            | 10    | 21.7           |
| HR 5148            | 2014 Apr. 23 | DI+ADI    | $H$    | 1.5          | 10    | 26.3           |
| Name     | Date          | Mode       | Filter | Sub Exposure (s) | Coadd | Total Exposure (minutes) |
|----------|---------------|------------|--------|------------------|-------|--------------------------|
| GJ 9457B | 2014 Jun. 7   | DI+ADI     | $H$    | 15               | 3     | 33.7                     |
| HR 7451  | 2012 Sep. 14  | DI+ADI     | $H$    | 1.5              | 10    | 19                       |
|          | 2014 Apr. 24  | DI         | $H$    | 60               | 1     | 31                       |
| BD-00 4333 | 2012 Nov. 5  | DI+ADI     | $H$    | 1.5              | 10    | 20.8                     |
|          | 2013 Oct. 16* | DI         | $K_S$  | 10               | 1     | 5.3                      |
|          | 2014 Jun. 7   | DI         | $J, H, K_S$ | 60, 30, 60 | 1, 1, 1 | 3, 10, 2               |

Note: * Extremely poor condition
### Supplementary Table 3. Companion Candidates List

| Primary Name   | CC Number | Status       | Date        | Separation (arcsec) | PA (degree) | $H$ (mag) |
|----------------|-----------|--------------|-------------|--------------------|-------------|-----------|
| Chi Cet B     | CC1       | C (known)    | 2013 Jan. 3 | 0.278              | 349.7       | 8.68      |
|               | CC2       | maybe C      | 2013 Jan. 3 | 6.15               | 353.4       | 9.39      |
| HD 23247      | CC1‡      | C (stellar)  | 2011 Jan. 27| 3.86               | 267.2       | 11.0      |
|               |           |              | 2011 Dec. 24| 3.83               | 267.0       | -         |
| HII 3441      | CC1       | C            | 2011 Sep. 4 | 0.493              | 135.9       | -         |
|               |           |              | 2014 Oct. 11| 0.491              | 136.9       | 15.2      |
|               |           |              | 2015 Jan. 8 | 0.491              | 136.5       | -         |
| V855 Tau      | CC1†      | maybe FG     | 2011 Jan. 28| 8.05               | 19.5        | 17.2      |
| V1171 Tau     | CC1†      | BG           | 2012 Dec. 31| 12.52              | 134.6       | 17.8      |
|               | CC2†      | BG           | 2012 Dec. 31| 12.63              | 135.5       | 18.5      |
|               | CC3†      | BG           | 2009 Nov. 1 | 9.08               | 125.9       | 19.0      |
| HD 23514      | CC1†      | C            | 2010 Dec. 1 | 2.65               | 227.6       | 15.4      |
| HD 282954     | CC1†      | BG           | 2012 Sep. 12| 8.94               | 103.3       | 14.4      |
| HII 1348      | CC1†      | C            | 2011 Dec. 23| 1.12               | 346.1       | 15.7      |
| HD 23912      | CC1†      | BG           | 2011 Jan. 27| 3.44               | 14.5        | 17.2      |
| BD+22 574     | CC1†      | BG           | 2009 Oct. 31| 3.29               | 92.6        | 19.2      |
|               | CC2†      | BG           | 2009 Oct. 31| 8.50               | 50.0        | 17.4      |
| V1174 Tau     | CC1†      | BG           | 2012 Sep. 12| 6.47               | 63.6        | 18.0      |
|               |           |              | 2013 Oct. 16| 6.51               | 63.2        | -         |
|               |           |              | 2013 Nov. 24| 6.46               | 63.3        | -         |
|               |           |              | 2014 Oct. 7, 9| 6.46               | 62.9        | -         |
|               | CC2‡      | BG           | 2012 Sep. 12| 9.24               | 37.5        | 18.5      |
|               |           |              | 2013 Oct. 16| 9.35               | 37.2        | -         |
|               |           |              | 2013 Nov. 24| 9.26               | 37.3        | -         |
|               |           |              | 2014 Oct. 7, 9| 9.28               | 36.9        | -         |
| V1054 Tau     | CC1‡      | BG           | 2012 Sep. 12| 7.05               | 110.1       | 18.1      |
|               |           |              | 2013 Feb. 26| *                 | *           | *         |
|               | CC2‡      | BG           | 2012 Sep. 12| 7.33               | 75.9        | 16.0      |
|               |           |              | 2013 Feb. 26| *                 | *           | *         |
| Primary Name    | CC Number | Status      | Date (UT)   | Separation (arcsec) | PA (degree) | $H$ (mag) |
|----------------|-----------|-------------|-------------|--------------------|-------------|-----------|
| BD+01 565      | CC1       | C (known)   | 2012 Nov. 5 | 10.98              | 14.3        | 7.28      |
|                |           |             | 2014 Oct. 10| 7.52               | 305.3       | -         |
|                | CC2       | BG          | 2014 Jan. 20| 9.47               | 51.8        | 16.2      |
|                |           |             | 2014 Oct. 10| 9.50               | 51.5        | -         |
|ome Tau         | CC1       | BG          | 2014 Oct. 10| 7.47               | 305.3       | -         |
|                | CC2       | BG          | 2014 Jan. 20| 9.47               | 51.8        | 16.2      |
|                |           |             | 2014 Oct. 10| 9.50               | 51.5        | -         |
|GJ 212          | CC1       | BG (extended)| 2013 Jan. 2 | 6.51               | 195.2       | 18.6      |
|                |           |             | 2013 Oct. 17| 6.08               | 197.4       | -         |
|                | CC2       | BG          | 2013 Jan. 2 | 7.72               | 232.8       | 19.3      |
|                |           |             | 2013 Oct. 17| 7.50               | 237.0       | -         |
|HIP 36624       | CC1       | BG          | 2013 Nov. 23| 1.45               | 128.7       | 16.6      |
|                |           |             | 2015 Jan. 7 | 1.47               | 126.3       | -         |
|                | CC2       | BG          | 2013 Nov. 23| 9.67               | 316.6       | 20.8      |
|                |           |             | 2015 Jan. 7 | 9.67               | 317.0       | -         |
|CCDM J08316+3458A| CC1  | C (known)   | 2013 Nov. 24| 0.205              | 341.2       | 6.31      |
|                |           |             | 2015 Jan. 8 | 0.150              | 314.9       | -         |
|                | CC2       | Artifact?   | 2013 Nov. 24| 3.608              | 303.7       | 20.8      |
|                |           |             | 2015 Jan. 8 | *                  | *           | *         |
|                | CC3       | U           | 2013 Nov. 24| 3.774              | 343.7       | 21.4      |
|                |           |             | 2015 Jan. 8 | 3.762              | 343.9       | -         |
|BD-13 2855      | CC1       | BG          | 2013 Jan. 1 | 8.374              | 332.2       | 17.4      |
|                |           |             | 2014 Jan. 20| 8.495              | 332.5       | -         |
|                |           |             | 2014 Apr. 23| 8.506              | 332.7       | -         |
|                | CC2       | BG          | 2013 Jan. 1 | 11.135             | 331.6       | 13.2      |
|                |           |             | 2014 Jan. 20| 11.250             | 331.8       | -         |
|                |           |             | 2014 Apr. 23| 11.264             | 332.0       | -         |
|                | CC3       | -           | -           | -                  | -           | -         |
|BD+52 1638      | CC1       | U           | 2013 Feb. 26| 1.194              | 185.1       | 8.62      |
|HR 4803         | CC1       | C (known)   | 2013 Jan. 2 | 2.571              | 198.1       | 8.53      |
|BD+22 2522      | CC1       | C (known)   | 2013 May 18 | 1.645              | 51.4        | 10.6      |
|GJ 516          | CC1       | C (known)   | 2014 Jun. 8 | 2.744              | 53.2        | 7.39      |
|HR 7451         | CC1       | BG          | 2012 Sep. 14| 9.318              | 140.5       | 19.3      |
| Primary Name | CC Number | Status | Date      | Separation (arcsec) | PA (degree) | $H$ (mag) |
|--------------|-----------|--------|-----------|---------------------|-------------|----------|
| BD-00 4333   | CC1       | BG     | 2012 Nov. 5 | 7.098               | 16.9        | 19.0     |
|              |           |        | 2013 Oct. 16 | ∗                  | ∗           | ∗        |
|              | CC2       | BG     | 2012 Nov. 5 | 8.959               | 14.8        | 17.5     |
|              |           |        | 2013 Oct. 16 | ∗                  | ∗           | ∗        |

Supplementary Table 3. (Continued)

Note: Status column abbreviations

BG: background objects, FG: foreground objects, C: companions, U: undefined objects

Typical uncertainties of separation, PA, and photometric results are 0′′01–0′′03, 0.1–1.0°, and 0.1–0.9 mag.

† Previously reported in Yamamoto et al. (2013), and only the latest properties are shown.

‡ Yamamoto et al. (2013) could not conclude the companion status of these objects.

∗ Data were not suitable for accurate measurements due to poor condition.

○ This was judged by comparison with the previous work (Ammler-von Eiff et al. 2016).

♯ This object locates very close to CC2. It has a possibility of artifacts.