A Substellar Companion to Pleiades HII 3441

Mihoko Konishi[1,*], Taro Matsuo,[2,*], Kodai Yamamoto[3], Matthias Samland[4], Jun Sudo[2], Hiroshi Shibai[2], Yoichi Itoh[5], Misato Fukagawa[6], Takahiro Sumi[2], Tomoyuki Kudo[7], Jun Hashimoto[8], Masayuki Kuzuhara[8, 9], Nobuhiko Kusakabe[8], Lyu Abe[10], Eiji Akiyama[1], Wolfgang Brandner[4], Timothy D. Brandt[11], Joseph C. Carson[12], Markus Feldt[4], Miwa Goto[13], Carol A. Grady[14, 15], Olivier Guyon[7, 16, 8], Yutaka Hayano[1], Masahiko Hayashi[1], Saeko S. Hayashi[7], Thomas Henning[4], Klaus W. Hodapp[17], Miki Ishii[1], Masanori Iye[1], Markus Janson[18], Ryo Kandori[1], Gillian R. Knapp[19], Jungmi Kwon[20, 21], Michael W. McElwain[15], Kyle Mede[20], Shoken Miyama[22], Jun-Ichi Morino[1], Amaya Moro-Martín[23], Tetsuo Nishimura[7], Daehyeon Oh[24, 1, 25], Tae-Soo Pyo[7], Eugene Serabyn[26], Joshua E. Schlieder[27, 4], Takuya Suenaga[1, 25], Hiroshi Suto[1, 8], Ryuji Suzuki[1], Yasuhiro H. Takahashi[20, 1], Michihiro Takami[28], Naruhisa Takato[7], Hiroshi Terada[1], Christian Thalmann[29], Edwin L. Turner[19, 30], Makoto Watanabe[31], John P. Wisniewski[32], Toru Yamada[21], Hideki Takami[1], Tomonori Usuda[1] and Motohide Tamura[20, 1, 8]

[1]National Astronomical Observatory of Japan, Tokyo, Japan

[2]Department of Earth and Space Science, Graduate School of Science, Osaka University, Osaka, Japan

[3]Department of Astronomy, Faculty of Science, Kyoto University, Kyoto, Japan

[4]Max Planck Institute for Astronomy, Heidelberg, Germany

[5]Nishi-Harima Astronomical Observatory, Hyogo, Japan

[6]Division of Particle and Astrophysical Science, Graduate School of Science, Nagoya University, Nagoya, Japan

[7]Subaru Telescope, National Astronomical Observatory of Japan, HI, USA

[8]Astrobiology Center, Tokyo, Japan

[9]Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Tokyo, Japan

[10]Laboratoire Lagrange, Université de Nice-Sophia Antipolis, Nice, France

[11]Astrophysics Department, Institute for Advanced Study, NJ, USA

[12]Department of Physics and Astronomy, College of Charleston, SC, USA

[13]Universitäts-Sternwarte München, Ludwig-Maximilians-Universität, München, Germany

[14]Eureka Scientific, CA, USA

[15]Exoplanets and Stellar Astrophysics Laboratory, code 667, Goddard Space Flight Center, MD, USA

[16]The University of Arizona, AZ, USA

[17]Institute for Astronomy, University of Hawaii, HI, USA

[18]Department of Astronomy, University of Stockholm, Stockholm, Sweden

[19]Department of Astrophysical Science, Princeton University, NJ, USA

[20]Department of Astronomy, The University of Tokyo, Tokyo, Japan

[21]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Kanagawa, Japan

[22]Hiroshima University, Hiroshima, Japan

[23]Space Telescope Science Institute, MD, USA

[24]National Meteorological Satellite Center, Chungbuk, Republic of Korea

[25]Department of Astronomical Science, The Graduate University for Advanced Studies, Tokyo, Japan

[26]Jet Propulsion Laboratory, California Institute of Technology, CA, USA

[27]NASA Exoplanet Science Institute, California Institute of Technology, CA, USA

[28]Institute of Astronomy and Astrophysics, Academia Sinica, Taipei, Taiwan

[29]Swiss Federal Institute of Technology, Institute for Astronomy, Zurich, Switzerland

[30]Kavli Institute for Physics and Mathematics of the Universe, The University of Tokyo, Chiba, Japan

[31]Okayama University of Science, Okayama, Japan

[32]H. L. Dodge Department of Physics and Astronomy, University of Oklahoma, OK, USA

[*]E-mail: mihoko.konishi@nao.ac.jp, matsuo@ess.sci.osaka-u.ac.jp

Received ; Accepted

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 ± 2 AU) and a mass of 68 ± 5 M_J based on three observations in the J-, H-, and K_S-band. The spectral type is estimated to be M7 (∼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% ± 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, SSHJ K121, PELS 41
RA (h m s)	03 44 43.9
DEC (d m s)	+25 29 57.1
J	10.39 $\pm$ 0.3 mag^a
H	9.86 $\pm$ 0.03 mag^a
K_S	9.74 $\pm$ 0.02 mag^a
Proper Motion	(RA) 16.4 $\pm$ 2.7 mas/yr^b
	(DEC) -48.8 $\pm$ 2.6 mas/yr^b
Spectral Type	K-type (K3 $\pm$ 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.

ment HiCIAO (High Contrast Instrument for Subaru Next Generation Adaptive Optics; e.g., Tamura et al. 2006; Suzuki et al. 2010) combined with the adaptive optics system AO188 (e.g., Hayano et al. 2008) in the Subaru strategic program, the SEEDS (Strategic Exploration of Exoplanet and Disks with Subaru; Tamura 2009) project. Table 1 shows the properties of Pleiades HII 3441. This object is a K-type star with membership probability between 78% (Belikov et al. 1998) and 98% (Schilbach et al. 1995) confirmed through both kinematic and photometric selection procedures. The portion of our Pleiades planet search was introduced in Yamamoto et al. (2013). Pleiades HII 3441B was confirmed after the conclusion of their survey. In addition, the companion status of unconfirmed companion candidates in Yamamoto et al. (2013) is substantiated in this paper, and new observations after that are introduced in the supplement.

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 $\pm$ 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 (UT)	Mode	Band	Sub Exposure (s)	Coadd	Total Exposure (minutes)	Angle[a] (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[b]	J	20	1	13.7	18.6
	DI+ADI[b]	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$\times$2K HAWAII2-RG array and a pixel scale of 9.5 mas. Three observations were conducted for Pleiades HII 3441, on 2011 September 4, on 2014 October 11, and on 2015 January 8, as shown in Table 2. In the 2011 observation, we used the simultaneous spectral differential imaging (SDI) mode in the H band (e.g., see observations in Janson et al. 2013), as well as the angular differential imaging (ADI) mode (Marois et al. 2006). The H band is divided into two narrow bands (H_S: 1.486–1.628 μm and H_L: 1.643–1.788 μm) in the SDI mode, to search for methane absorption that is seen in low temperature objects ($<\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.

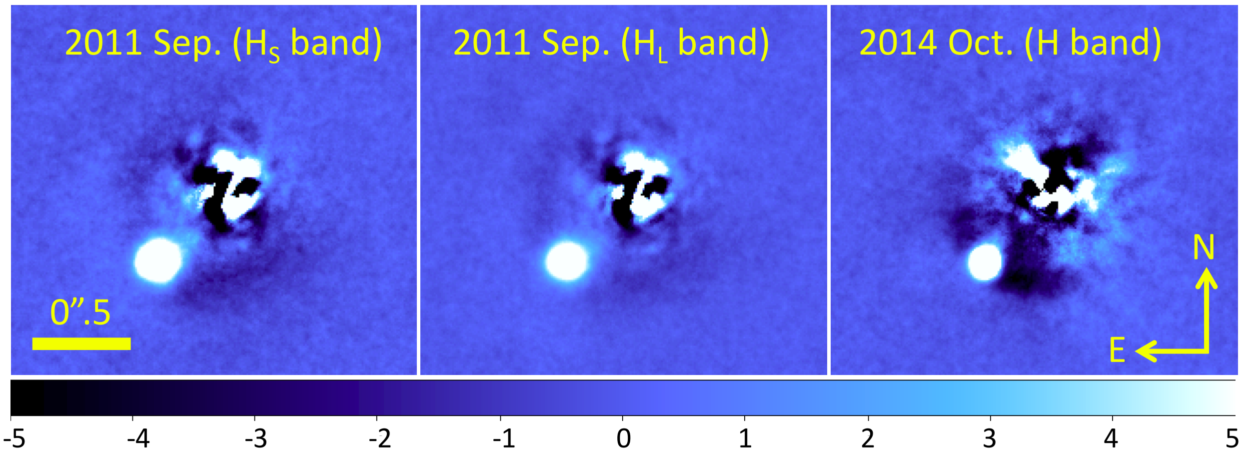

Fig. 1. Final Pleiades HII 3441 images. (Left) reduced H_S-band image taken in the 2011 observation. (Middle) reduced H_L-band image taken in the 2011 observation. (Right) reduced H-band image taken in the 2014 observation. All images were analyzed using standard ADI. Pleiades HII 3441B can be seen southeast of the primary star. There is no methane absorption in Pleiades HII 3441B when left and middle panels are compared.

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; Lafreniére 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 1σ of the position errors, ruling out the possibility that the companion candidate is a back-

Table 3. Properties of Pleiades HII 3441B

Projected Separation	$0.''49 \pm 0.''02$ (66 $\pm$ 2 AU)^a
Position Angle	136.4° $\pm$ 3.2°
J	15.64 $\pm$ 0.14 mag (68 $\pm$ 3 M_J)^b
H	15.23 $\pm$ 0.08 mag (65 $\pm$ 2 M_J)^b
K_S	14.71 $\pm$ 0.06 mag (72 $\pm$ 2 M_J)^b
ΔH_S	5.47 $\pm$ 0.19 mag
ΔH_L	5.29 $\pm$ 0.29 mag
$H_S - H_L$	0.18 $\pm$ 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.

ground star by $> 6\sigma$.

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 ($\sim$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 $0.''49 \pm 0.''02$ (66 $\pm$ 2 AU) and 136.4° $\pm$ 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

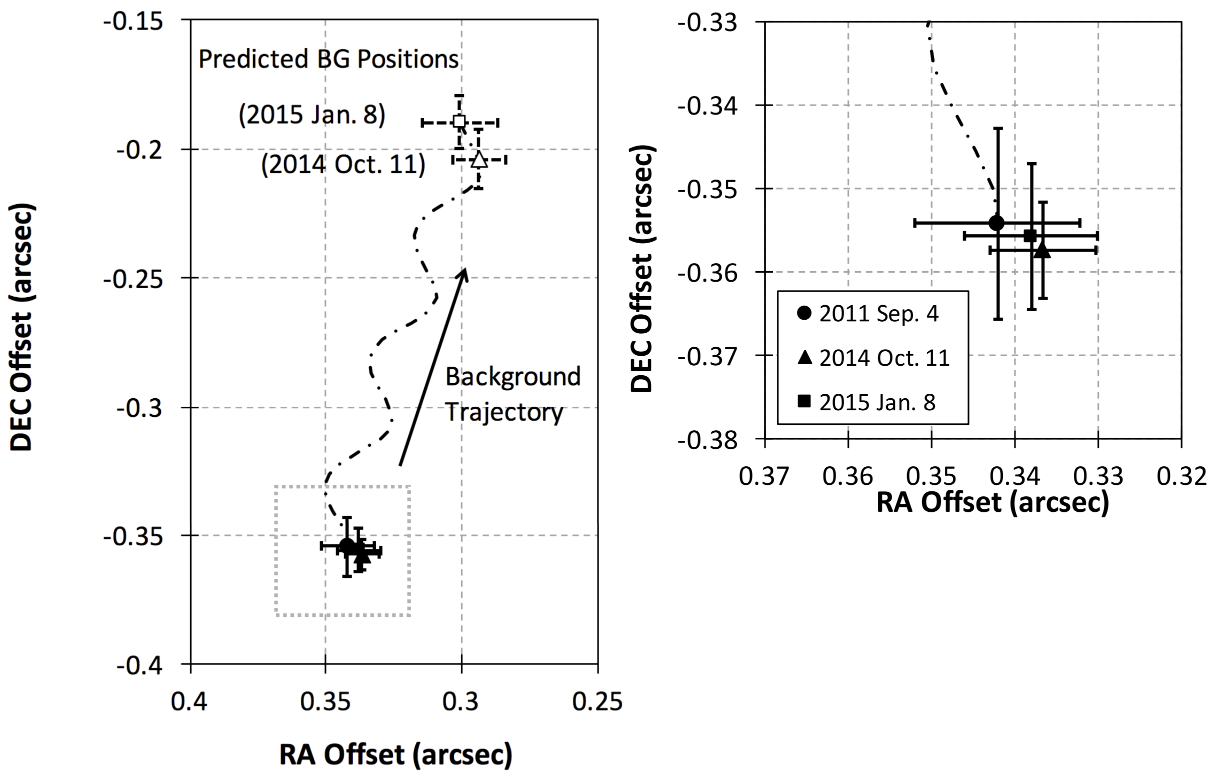

Fig. 2. (Left) Proper motion check of Pleiades HII 3441B. (Right) expanded view of the observed positions as marked by the gray box. Shown is the RA and DEC offset with respect to the primary star (Pleiades HII 3441) at the origin. Filled marks indicate observed positions of the companion candidate. If the companion candidate were a background (BG) star, it would move along the dashed-dotted line. The predicted BG-case position in each epoch is shown as open marks. The BG trajectory only takes into account the proper motion of Pleiades HII 3441 (see Table 1). Uncertainties are given as 1σ interval.

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 ± 0.14, 15.23 ± 0.08, and 14.71 ± 0.06, respectively (see Table 3). The J-band magnitude corresponds to a mass of 68 ± 3 M_J and a temperature of ∼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).

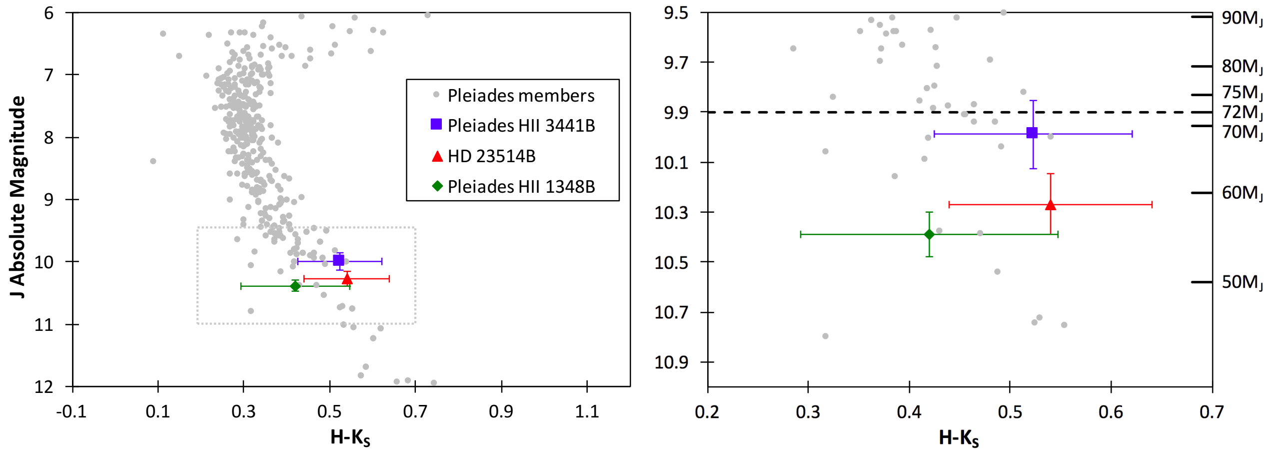

Fig. 3. Color-magnitude diagram of Pleiades substellar companions. Shown is absolute J-band magnitude over $H - K_S$ color. (Left) Pleiades member stars and three imaged substellar companions. (Right) expanded view of the three companions' color as marked by the grey box. Filled square, triangle, and diamond marks indicate Pleiades HII 3441B, HD 23514B (Rodriguez et al. 2012), and Pleiades HII 1348B (Geißler et al. 2012), respectively. Small gray circles are low-mass Pleiades members taken from Lodieu et al. (2007). The mass scale is shown on the right axis of the right panel. The BT-Settl model is used for a magnitude-to-mass conversion. The hydrogen-burning limit (72 M_J) is also shown as dashed line in the right panel.

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 1σ. There is no contradiction between Pleiades HII 3441B and a late M-dwarf spectrum.

[1] https://phoenix.ens-lyon.fr/simulator/index.faces

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)	α 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	$10.0^{+26.1}_{-8.8}$% (95% confidence interval)

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 ∼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 α Persei stars and 100 Praesepe stars, respectively (Patience et al. 2002). Our fraction is consistent 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 $0\farcs49 \pm 0\farcs02$ (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.

Acknowledgments

The authors recognize and acknowledge the significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. We thank the anonymous referee for careful reading our manuscript and for giving helpful comments. The authors are grateful for David Lafreniére for generously providing the source code for the LOCI algorithm. This publication makes use of VOSA to estimate the primary spectral type, developed under the Spanish Virtual Observatory project supported from the Spanish MICINN through grant AyA2011-24052. This work was partially supported by the Grant-in-Aid for JSPS fellows (Grant Number 25-8826). J.C. was supported by the U.S. National Science Foundation under Award No. 1009203.

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 χ^2 minimization using the VOSA web tool[2]. The fitted SED is shown in Figure 4. The effective temperature was estimated as 4550 ± 10 K using all data, and as 4850 ± 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 ± 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 ± 200 K, and corresponds to a spectral type of K3 $\pm$ 1 (Pecaut & Mamajek 2013).

References

Baraffe, I., Homeier, D., Allard, F., & Chabrier, G., 2015, A&A, 577, 42

Barrado y Navascués, D., Stauffer, J. R., & Jayawardhana, R., 2004, ApJ, 614, 386

Basri, G., Marcy, G. W., & Graham, J. R. 1996, ApJ, 458, 600

Belikov, A. N., Hirte, S., Meusinger, H., Piskunov, A. E., & Schilbach, E. 1998, A&A, 332, 575

Bell, C. P. M., Rees, J. M., Naylor, T., Mayne, N. J., Jeffries, R. D., et al. 2014, MNRAS, 445, 3496

Bianchi, L, & GALEX Team, 2000, Memorie della Società Astronomia Italiana, Vol. 71, p. 1123

Bihain, G., Rebolo, R., Béjar, V. J. S., et al. 2006, A&A, 458, 805

Bouvier, J., Rigaut, F., & Nadeau, D., 1997, A&A, 323, 139

Bouvier, J., Stauffer, J. R., Martin, E. L., et al. 1998, A&A, 336, 490

Brandt, T. D., McElwain, M. W., Turner, E. L., et al. 2014, ApJ, 794, 159

Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P., 2000, ApJ, 542, 464

Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, The IRSA 2MASS All-Sky Point Source Catalog, NASA/IPAC Infrared Science Archive

Duchêne, G., & Kraus, A. 2013, ARA&A, 51, 269

Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485

Geißler, K., Metchev, S. A., Pham, A. et al. 2012, ApJ, 746, 44

[2] http://svo2.cab.inta-csic.es/theory/vosa/

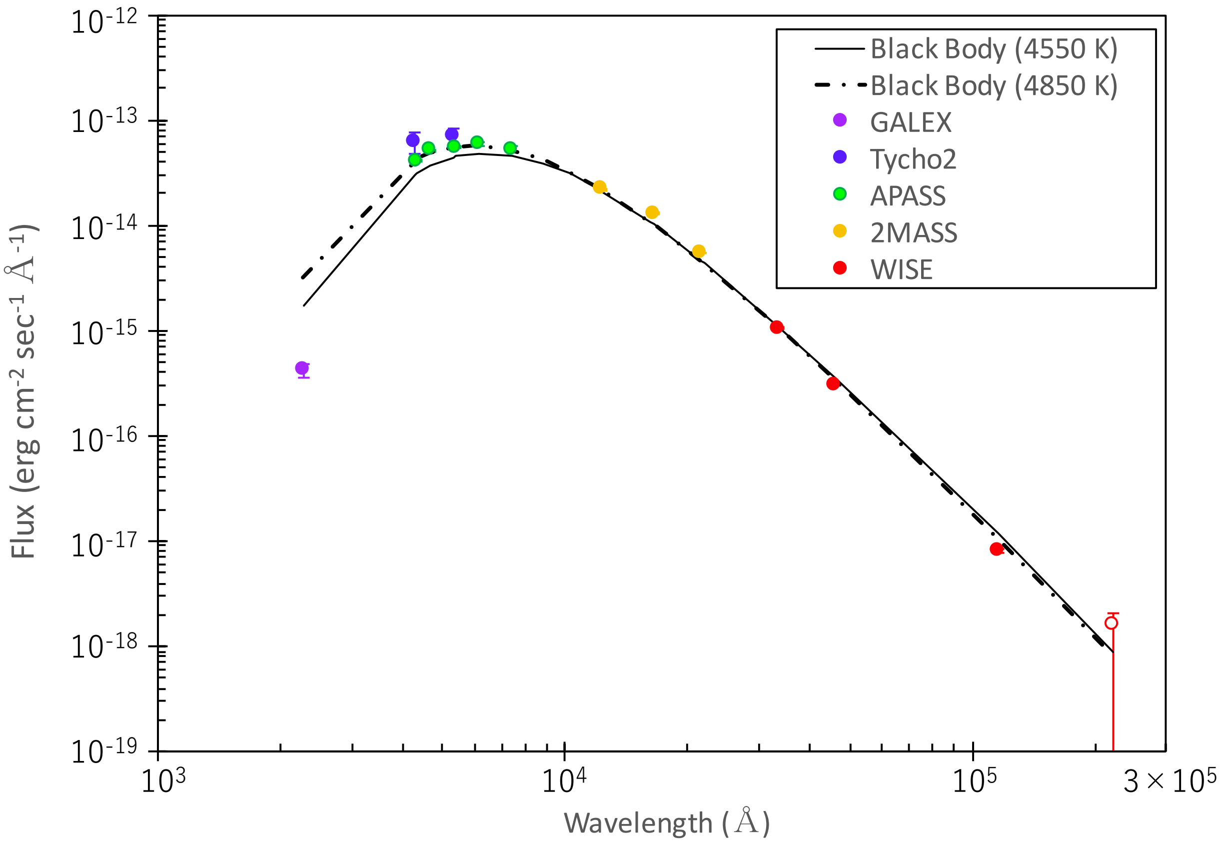

Fig. 4. SED of Pliades HII 3441 generated by VOSA. Black lines indicate the 4550 K and 4850 K black bodies that are most fitted model using the data with and without GALEX, respectively. Circles are published photometric results in the literature (Bianchi et al. 2000; Høg et al. 2000; Cutri et al. 2003;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

Hayano, Y., Takami, H., Guyon, O., et al., 2008, Proc. SPIE, 7015, 10

Henden, A. A., Welch, D. L., Terrell, D., & Levine, S. E., 2009, American Astronomical Society, AAS Meeting #214, id.407.02; Bulletin of the American Astronomical Society, Vol. 41, p.669

Høg, E., Fabricius, C., Makarov, V. V., Urban, S., Corbin, T., et al. 2000, A&A, 355, L27

Itoh, Y., Oasa, Y., Funayama, H., et al. 2011, Res. Astron. Astrophys., 11, 335

Jameson, R. F. & Skillen, I. 1989, MNRAS, 239, 247

Jameson, R. F., Dobbie, P. D., Hodgkin, S. T., & Pinfield, D. J., 2002, MNRAS, 335, 853

Janson, M., Brandt, T. D. Kuzuhara, M., et al. 2013, ApJL, 778, L4

King, I., 1962, AJ, 67, 471

Lafreniére, D., Marois, C., Doyon, R. Nadeau, D., & Artigau, È. 2007, ApJ, 660, 770

Lodieu, N., Dobbie, P. D., Deacon, N. R., et al. 2007, MNRAS, 380, 712

Marois, C., Lafreniére, D., Macintosh, B., & Doyon, R., 2006, ApJ, 647, 612

Melis, C., Reid, M. J., Mioduszewski, A. J., Stauffer, J. R., & Bower, G. C. 2014, Science, 345, 1029

Metchev, S. A., & Hillenbrand, L. A., 2009, ApJS, 181, 62

Moraux, E., Bouvier, J., Stauffer, J. R., & Cuillandre, J.-C., 2003, A&A, 400, 891

Patience, J., Ghez, A. M., Reid, I. N., & Matthews, K., 2002, AJ, 123, 1570

Pecaut, M. J., & Mamajek, E. E., 2013, ApJS, 208, 9

Richichi, A., Chen, W. P., Cusano, F., et al. 2012, A&A, 541, A96

Rodriguez, D. R., Marois, C., Zuckerman, B., et al. 2012, ApJ, 748, 30

Schilbach, E., Robichon, N., Souchay, J., & Guibert, J., 1995, A&A, 299, 696

Sharp, C. M., & Burrows, A., 2007, ApJS, 168, 140

Soderblom, D. R., Nelan, E., Benedict, G. F., et al. 2005, AJ, 129, 1616

Stauffer, J., Hamilton, D., Probst, R., Rieke, G., & Mateo, M. 1989, ApJL, 344, L21

Stauffer, J. R., Hamilton, D., & Probst, R. G. 1994, AJ, 108, 155

Stauffer, J. R., Schultz, G., & Kirkpatrick, J. D., 1998, ApJL, 499, L199

Stauffer, J. R., Schild, R., Barrado y Navascués, D., et al. 1998, 504, 805

Suzuki, R., Kudo, T., Hashimoto, J., et al. 2010, Proc. SPIE, 7735, 30

Tamura, M., Hodapp, K., Takami, H., et al. 2006, Proc. SPIE, 6269, 0V

Tamura, M., 2009, AIP Conference Proceedings, 1158, 11

van Leeuwen, F., 2009, A&A, 497, 209

Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., Ressler, M. E., Cutri, R. M., et al. 2010, AJ, 140, 1868

Yamamoto, K., Matsuo, T., Shibai, H. et al. 2013, PASJ, 64, 90

Zapatero Osorio, M. R., Rebolo, R., & Martin, E. L. 1997, A&A, 317, 164

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, $\sim$25 pc; King et al. 2003), Octans-Near association ($<$100 Myr, $\sim$90 pc; Zuckerman et al. 2013), and AB Doradus MG ($\sim$50 Myr, 30 pc; López-Santiago et al. 2006). One target (GJ 212) is considered to belong to either Hercules-Lyra association ($\sim$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.

References

Ammler-von Eiff, M., Bedalov, A., Kranhold, C., Mugrauer, M., Schmidt, T. O. B., et al. 2016, A&A, 591, 84

Brandt, T. D., Kuzuhara, M., McElwain, M. W., et al., 2014b, ApJ, 786, 1

Goldin, A., & Makarov, V. V., 2007, ApJS, 173, 137

Janson, M., Brandt, T. D., Moro-Martín, A.,et al. 2013b, ApJ, 773, 73

King, J. R., Villarreal, A. R., Soderblom, D. R., Gulliver, A. F., & Adelman, S. J., 2003, AJ, 125, 1980

López-Santiago, J., Montes, D., Crespo-Chacón, I., & Fernández-Figueroa, M. J., 2006, ApJ, 643, 1160

Montes, D., López-Santiago, J., Gálvez, M. C., Fernández-Figueroa, M. J., De Castro, E., & Cornide, M., 2001, MNRAS, 328, 45

Uyama, T., Hashimoto, J., Kuzuhara, M., et al. 2016, submitted to AAS Journals (arXiv:1604.04697)

Zacharias, N., Monet, D. G., Levine, S. E., Urban, S. E., Gaume, R., & Wycoff, G. L., 2005, VizieR On-line Data Catalog: I/297

Zuckerman, B., Vican, L., Song, I., & Schneider, A., 2013, ApJ, 778, 5

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 43.9	+25 29 57.1	K	Pleiades	135	11.41	10.39	9.86	9.74
HII 636†	-	03 45 22.2	+23 28 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	+24 25 53.5	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	8.81	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_S
		(h m s)	(d m s)			(pc)	(mag)	(mag)	(mag)	(mag)
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_S magnitudes: 2MASS (Cutri et al. 2003)

Other properties are taken from the above group citations.

Supplementary Table 2. Observing Logs Taken after September 2012

Name	Date (UT)	Mode	Filter	Sub Exposure (s)	Coadd	Total Exposure (minutes)
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
ome 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

Supplementary Table 2. (Continued)

Name	Date (UT)	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 (UT)	Separation (arcsec)	PA (degree)	*H* (mag)
Chi Cet B	CC1	C (known)	2013 Jan. 3	0.278	349.7	8.68
	CC2	maybe C$^{\diamond}$	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
			2012 Dec. 31	8.94	125.4	-
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	*	*	*

Supplementary Table 3. (Continued)

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
ome Tau	CC1	BG	2014 Jan. 20	7.47	305.3	17.5
			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	-
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	$\star$	$\star$	$\star$
	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$^\sharp$	-	-	-	-	-
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

Supplementary Table 3. (Continued)

Primary Name	CC Number	Status	Date (UT)	Separation (arcsec)	PA (degree)	*H* (mag)
			2014 Apr. 24	9.010	139.8	-
BD-00 4333	CC1	BG	2012 Nov. 5	7.098	16.9	19.0
			2013 Oct. 16	∗	∗	∗
			2014 Jun. 7	7.172	16.9	-
	CC2	BG	2012 Nov. 5	8.959	14.8	17.5
			2013 Oct. 16	∗	∗	∗
			2014 Jun. 7	9.033	14.8	-

Note: Status column abbreviations

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

Typical uncertainties of separation, PA, and photometric results are $0\farcs01$–$0\farcs03$, 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 CC was not detected in the second epoch.

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