The SEEDS High-Contrast Imaging Survey of Exoplanets Around Young Stellar Objects

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Received 2016 April 15; revised 2016 November 23; accepted 2016 December 29; published 2017 February 9

Abstract

We present high-contrast observations of 68 young stellar objects (YSOs) that have been explored as part of the Strategic Exploration of Exoplanets and Disks with Subaru (SEEDS) survey on the Subaru telescope. Our targets are very young ((<10 Myr) stars, which often harbor protoplanetary disks where planets may be forming. We achieve a typical contrast of ∼10^−2−10^−5.5 at an angular distance of 1″ from the central star, corresponding to typical mass sensitivities (assuming hot-start evolutionary models) of ∼10 M_J at 70 au and ∼6 M_J at 140 au. We detected a new stellar companion to HIP 79462 and confirmed the substellar objects GQ Lup b and ROXs 42B b. An additional six companion candidates await follow-up observations to check for common proper motion. Our SEEDS YSO observations probe the population of planets and brown dwarfs at the very youngest ages; these may be compared to the results of surveys targeting somewhat older stars. Our sample and the associated observational results will help enable detailed statistical analyses of giant planet formation.

Key words: planetary systems – planet–disk interactions – planets and satellites: formation – stars: variables: T Tauri, Herbig Ae/Be
1. Introduction

Since the first convincing detection of an exoplanet around a main-sequence star (Mayor & Queloz 1995) in 1995, about 3500 exoplanets have been confirmed. Surprisingly, many exoplanets, such as hot Jupiters and high-eccentricity planets, are quite different from the planets in the solar system (e.g., Mayor & Queloz 1995; Holman et al. 1997). These unexpected exoplanets cannot necessarily be reproduced by conventional theories of planet formation, which were originally developed to explain the properties of the solar system (core accretion model; e.g., Hayashi et al. 1985). These planet formation models (e.g., Ida et al. 2013) have been updated to help explain the myriad exoplanets discovered to date. Ongoing observations and characterizations of various exoplanets help test the updated models. Most of the planet detections to date have resulted from radial velocity (e.g., Mayor & Queloz 1995) and transit surveys (e.g., Auvergne et al. 2009; Batalha et al. 2011). These indirect methods observe stars and measure periodic fluctuations caused by the existence of orbiting planets. They are particularly effective for detecting exoplanets with shorter orbital periods, such as periods shorter than 5 years.

Direct imaging is technically difficult because a large dynamic range is required to detect a planet that is $\sim 10^{-6}$ times fainter than the central star. However, with the development of adaptive optics (AO) on large ground-based telescopes, the method has begun to successfully open up the previously unexplored parameter space that is occupied by wide-separation gas giants ($\sim 5$–$75 M_J$ and $\sim 10$–$1000$ au). The number of exoplanets confirmed through direct imaging is still far smaller than those found through indirect methods, such as radial velocity or transit. However, direct imaging can reveal physical parameters (e.g., mass, temperature, and atmosphere information; Currie et al. 2011) and orbital parameters (e.g., semimajor axis, inclination, and eccentricity; Chauvin et al. 2012) of wide-orbit exoplanets that are poorly explored by indirect methods. As a result, direct imaging uniquely probes exoplanet populations that are effectively inaccessible by radial velocity and transit methods. The first directly imaged planets—e.g., HR 8799 bcde, κ And b, β Pic b, and Gl 504 b (Marois et al. 2008; Lagrange et al. 2010; Carson et al. 2013; Kuzuhara et al. 2013)—prove the extremes of planet formation. These planets, which orbit at $\sim 10$–$150$ au and have masses of $M \sim 3$–$15 M_J$, are difficult to form by either core accretion or disk instability (Dodson-Robinson et al. 2009; Kratter et al. 2010; Currie et al. 2011). However, constraining the frequency and semimajor axis distribution of these planets may clarify which planet formation mechanism is responsible for their existence (Brandt et al. 2014b). Estimating physical parameters of detected exoplanets requires accurate age estimations of the host stars. Young stellar objects (YSOs) make appealing target populations in part because most of them are associated with star-forming regions (SFRs) whose ages are relatively well established ($\sim 1$–$10$ Myr).

Here we observe YSOs with direct imaging in an effort to detect young exoplanets with ongoing formation and to improve our understanding of how planets form in protoplanetary disks. Previous direct imaging reported a few low-mass companions around YSOs such as GQ Lup b, ROXs 42B b, and possibly LkCa 15 bc (Neuhäuser et al. 2005; Currie et al. 2014b; Sallum et al. 2015). Strategic Exploration of Exoplanets and Disks with Subaru (SEEDS; Tamura 2009), a project exploring exoplanets and circumstellar disks with Subaru/HiCIAO (Suzuki et al. 2010) and AO188 (Hayano et al. 2008), has conducted a direct imaging survey of more than 400 targets between 2009 and 2015. A main goal of SEEDS is to constrain formation and evolution scenarios of planetary systems, including not only exoplanets, but also protoplanetary disks, from the point of view of direct imaging. To achieve this, SEEDS selected targets whose ages range from 1 Myr to a few Gyr for systematic analyses of systems at different stages. Comparing information on exoplanets with various ages can be useful for placing constraints on their formation and evolution mechanisms.

SEEDS has several target categories: YSOs, moving groups (Brandt et al. 2014a), open clusters (Yamamoto et al. 2013), debris disks (Janson et al. 2013), and nearby stars (M. Kuzuhara 2016, in preparation). We report here the observations and results from systematic explorations carried out in the YSO category. The sample selection of YSOs is described in Section 2. In Section 3, the observations and data reduction are presented for each target. Section 4 provides detection limit results and expanded information on individual targets. Preliminary statistical discussions are described in Section 5. Finally, we summarize our results in Section 6.

2. Sample Selection

2.1. Young Stellar Objects

We define YSOs to be young stars with average ages younger than $\sim 10$ Myr. Most of our targets show evidence of dusty circumstellar disks, ranging presumably from pre-planet building phases (optically thick gas-rich protoplanetary disks) to post-Jovian planet-building phases (optically thin gas-poor debris disks). Some spectral energy distribution (SED) data of YSOs show far-infrared (FIR) excess but little mid-infrared (MIR) excess (Strom et al. 1989). Disks showing such SED features are called “transitional disks” and have been predicted to have gaps, which may be a result of planet formation (Marsh & Mahoney 1992, 1993; Quanz et al. 2013a). Some such YSOs with transitional disks exhibit resolved gaps and accompanying structures (e.g., spiral arms) that may indicate hidden planets (Hashimoto et al. 2012; Muto et al. 2012; Grady et al. 2013; Currie et al. 2014c; Thalmann et al. 2014). In addition, a few young protoplanets have been imaged inside the gaps of transitional disks (Kraus & Ireland 2012; Currie et al. 2015). At near-infrared (NIR) wavelengths, young planets are brighter than their older counterparts, therefore YSOs may be particularly well suited for simultaneously probing lower mass planets and protoplanetary disks (see Section 3 for details).

SEEDS adopts two imaging modes. One mode is most effective for disk searches, while the other mode is more optimized for planet searches (see Section 3.1). The two methods can be combined to simultaneously study both planets and disks. The simultaneous study of disk and exoplanets is helpful for analyzing the relationship between disk structures and planet formation. However, we note that our SEEDS explorations are limited to exoplanets outside the gap region because of self-subtraction effects (details are described in Section 3.2). Neither are we able so far to conclude systematic relations between disk geometry and exoplanet frequency. Section 4.3 provides the available individual SED and disk information for each YSO. Most of our YSO targets are located at distances larger than 100 pc. This is because almost all SEEDS/YSO targets belong to SFRs, and active SFRs in the Milky Way are mainly located in Gould Belt (Dunham et al. 2015), which is farther than 140 pc. The targets of the...
YSO category are therefore fainter than those of other SEEDS categories, making the AO performance less effective. Moreover, the large distances make it more difficult to distinguish orbiting companions at a solar-system scale from the central star. However, as previously mentioned, our SEEDS data were optimized for studying disks, but can still place important constraints on giant planets.

2.2. SEEDS Target Selections

Table 2 lists all SEEDS/YSO data analyzed in this work, and Figure 8 summarizes spectral types of the YSO targets. Hereafter the targets are sorted by their RAs.

We explain here the procedures we employed to select our YSO targets. The guidelines and criteria are somewhat different for each SFR (see below for the details). However, we first describe the common target selection procedures used for all the SFRs.

First, we searched the literature for nearby SFRs that are observable from the summit of Maunakea. We aimed to select YSOs brighter than $R = 15$ to ensure high-quality AO performance and therefore a sufficient angular resolution. We deprioritized M-type YSOs because only a few gas giants are expected around M dwarfs (Kokubo & Ida 2002). Famous and relatively bright sources that have been observed in various methods such as AB Aur are prioritized. The YSOs whose disks had been resolved before SEEDS observations are also prioritized. The catalogs we used are described in the sections for each SFR. Our SEEDS/YSO observations were largely divided into two effective surveys: disk survey and planet survey. The YSOs whose SEDs suggested a large full disk were prioritized for disk study. Objects with transitional or debris disks were selected for both planet and disk explorations. Sources exhibiting little or weak IR excesses were slated for planet searches if they showed any youth indicators such as Hα emissions, X-ray emissions, or lithium absorptions. For each SFR, we adopted typical estimates for age and distance (see Table 1), which we later used to constrain potential exoplanet masses around the YSO. Most of our employed age estimations derived from isochrones of pre-main sequence evolutionary tracks (e.g., D’Antona & Mazzitelli 1994; Baraffe et al. 1998).

We describe the basic procedures of target selection for individual SFRs below. The majority of targets were selected before the SEEDS survey started, but we include in the subsequent summary information published since then.

Taurus-Auriga. At the first step, we selected YSOs with spectral types of B0–M1 (Strom et al. 1989; Beckwith et al. 1990; Kenyon & Hartmann 1995a; Andrews & Williams 2005; Furlan et al. 2006; McCabe et al. 2006; Najita et al. 2007). Subsequently, we removed close binaries that have separations between components smaller than 3″ (Beckwith et al. 1990; White & Ghez 2001; White & Hillenbrand 2004; Furlan et al. 2006; McCabe et al. 2006; Najita et al. 2007). The YSOs fainter than $R = 15$ were also removed by checking the USNO-B1.0 catalog (Monet et al. 2003). The $R$-band magnitudes of Taurus-Auriga (hereafter Taurus) YSOs measured by our previous Subaru-AO observations (e.g., Fukagawa et al. 2004; Ioh et al. 2005) were additionally used to support the USNO-B1.0 photometry. Next, we investigated SEDs of all selected YSOs using Spitzer data (Calvet et al. 2005; Hartmann et al. 2005; Furlan et al. 2006; Padgett et al. 2006; Najita et al. 2007; Lubman et al. 2010; Espaillat et al. 2011) and radio observations (Kitamura et al. 2002; Andrews & Williams 2005) in order to find circumstellar disks. We also assign the higher priorities to the YSOs with the observations of resolved disks (Kitamura et al. 2002; Andrews & Williams 2007; Isella et al. 2010a; Karr et al. 2010, and references in Section 4.3). In particular, the transitional disks are the highest-priority targets. The inner hole of a transitional disk can be caused by grain growth and/or photoevaporation, as well as the influence of planet formation (Williams & Cieza 2011). The large inner hole (>~100 au) serves to significantly decrease the infrared continuum (Williams & Cieza 2011). Hence, objects detected at only longer wavelength (e.g., >850 μm) have high priorities.

We examined CIAO (Subaru) and Hubble Space Telescope (HST) archival data to verify whether the targets have circumstellar structures such as nebular and companions. The stellar jets are closely related with the accretion disks (Blandford & Payne 1982), and we therefore include YSOs with jets in our disk survey targets.

Kenyon et al. (2008) summarized distance investigations of YSOs in Taurus with an optimum estimate of 140–145 pc as the distance of this SFR. On the other hand, distances of Taurus members estimated from their parallaxes are distributed within ~130–160 pc (Torres et al. 2007, 2009, 2012). We accordingly assume the distance to the Taurus SFR to be 140 pc. We calculated the median and the standard deviation of the Taurus age using the results of Bertout et al. (2007) in which member ages are estimated with evolutionary tracks of Siess et al. (2000), resulting in 1.3–13 Myr. Küçük & Akkaya (2010) carried out isochrone analyses with a large sample of YSOs in Taurus and found that the ages of these YSOs are best consistent to 1–3 Myr. Considering these studies, we adopt 1–13 Myr as the typical age of Taurus.

Upper Scorpius (Upper Sco). R-band magnitudes for the Upper Sco region were compiled from the USNO-B1.0 catalog (Monet et al. 2003). To identify YSOs, we first investigated the target Hα emission, lithium absorption, and X-ray emission from Walter et al. (1994), Preibisch et al. (1998), and Köhler et al. (2000), which were also used to obtain their spectral types and R magnitudes. To compile the subset suitable for disk and planet explorations, we selected those young targets whose SEDs showed infrared excesses and/or a gap around 24 μm, as

| Group               | Age (Myr) | Distance (pc) | Reference                      |
|---------------------|-----------|---------------|--------------------------------|
| Upper Scorpius      | 9–13      | 145           | de Zeeuw et al. (1999)         |
| (Upper Sco)         |           |               | Bertout et al. (1999)          |
|                     |           |               | Pecaut et al. (2012)           |
| Taurus-Auriga       | 1–13      | 140           | Bertout et al. (2007)          |
|                     |           |               | Kenyon et al. (2008)           |
|                     |           |               | Küçük & Akkaya (2010)          |
| Ophiuchus           | 0.3–3     | 120           | Greene & Meyer (1995)          |
|                     |           |               | Lombardi et al. (2008)         |
| Lupus               | 0.1–10    | 155           | Hughes et al. (1993)           |
|                     |           |               | Hughes et al. (1994)           |
|                     |           |               | Lombardi et al. (2008)         |
| Corona Australis (CrA) | 0.5–10    | 130           | Bertout et al. (1999)          |
|                     |           |               | de Zeeuw et al. (1999)         |
|                     |           |               | Neuhäuser et al. (2000)        |
| HD Name | Other Name | Group        | R.A.  | Decl. | R mag | Criteria |
|---------|------------|--------------|-------|-------|-------|----------|
| 21997   |            |              |       |       |       |          |
|         |            |              |       |       |       |          |
| 281934  | BP Tau     | Taurus-Auriga | 04 19 15.8357 | +29 06 26.8927 | 11.6 | full disk, CO depletion |
|         |            |              |       |       |       |          |
| 283571  | V819 Tau   | Taurus-Auriga | 04 19 26.260 | +28 26 14.30 | 11.2 | class III, FIR excess, Tr-disk |
|         |            |              |       |       |       |          |
| 284419  | T Tau      | Taurus-Auriga | 04 21 59.43445 | +19 32 06.4182 | 9.8 | IR excess |
|         |            |              |       |       |       |          |
| 285846  | UX Tau     | Taurus-Auriga | 04 27 04.698 | +26 06 16.31 | 12.3 | disk with jet |
|         |            |              |       |       |       |          |
| 28630   | LkCa 19    | Taurus-Auriga | 04 31 38.437 | +13 18 49.4355 | 9.8 | famous, Tr-disk |
|         |            |              |       |       |       |          |
| 30193   | AB Aur     | Taurus-Auriga | 04 33 42.732 | +18 02 56.33 | 11.6 | class III, Li |
|         |            |              |       |       |       |          |
| 302624  | SU Aur     | Taurus-Auriga | 04 34 52.005 | +22 50 30.18 | 12.0 | full disk, IR excess |
|         |            |              |       |       |       |          |
| 304646  | V397 Aur   | Taurus-Auriga | 04 35 27.375 | +24 14 58.93 | 11.8 | IR excess, diskless |
|         |            |              |       |       |       |          |
| 31648   | MWC 480    | Taurus-Auriga | 04 40 27.326 | +25 23 03.23 | 11.6 | Tr-disk |
|         |            |              |       |       |       |          |
| 34282   |            | ONC          | 04 55 30.978 | +30 21 59.54 | 11.7 | Tr-disk |
|         |            |              |       |       |       |          |
| 36010   | LkCa 14, V1115 Tau | Taurus-Auriga | 04 36 19.093 | +25 42 59.08 | 10.8 | class III, Tr-like disk |
|         |            |              |       |       |       |          |
| 36819   | LkCa 15, V1079 Tau | Taurus-Auriga | 04 39 17.796 | +22 21 03.48 | 11.6 | Tr-disk |
|         |            |              |       |       |       |          |
| 37105   | V1207 Tau, RX J0458.7+2046 | Taurus-Auriga | 04 40 27.326 | +25 23 03.23 | 11.6 | Tr-disk |
|         |            |              |       |       |       |          |
| 37106   |            | ONC          | 05 06 30.978 | +30 21 59.54 | 11.7 | Tr-disk |
|         |            |              |       |       |       |          |
| 37107   |            | ONC          | 05 30 27.52969 | +25 19 57.0823 | 8.3 | Tr-disk |
|         |            |              |       |       |       |          |
| 37108   |            | ONC          | 05 35 58.46690 | +24 44 54.0950 | 10.6 | Tr-like disk |
|         |            |              |       |       |       |          |
| 37109   |            | ONC          | 05 38 05.2497 | +01 15 21.670 | 9.9 | Tr-disk |
|         |            |              |       |       |       |          |
| 37110   |            | ONC          | 11 01 51.90867 | +34 42 17.0323 | 10.4 | famous, nearby, Tr-disk |
|         |            |              |       |       |       |          |
| 37111   |            | ONC          | 14 08 10.15 | +41 23 52.5 | 11.3 | Tr-disk |
|         |            |              |       |       |       |          |
| 37112   |            | ONC          | 15 15 48.39449 | +37 09 16.026 | 8.7 | Tr-disk, gap |
|         |            |              |       |       |       |          |
| 37113   |            | ONC          | 15 40 46.3816 | +42 29 53.548 | 8.2 | pre-Tr disk |
|         |            |              |       |       |       |          |
| 37114   |            | ONC          | 15 49 12.102 | +35 39 05.12 | 11.0 | companion |
|         |            |              |       |       |       |          |
| 37115   |            | ONC          | 15 54 41.59596 | -22 55 58.086 | 6.8 | debris disk |
|         |            |              |       |       |       |          |
| 37116   |            | ONC          | 15 56 09.17658 | -37 56 06.1193 | 13.4 | full disk |
|         |            |              |       |       |       |          |
| 37117   |            | ONC          | 15 56 41.88986 | -42 19 23.2746 | 8.3 | famous, asymmetric disk, gap |
|         |            |              |       |       |       |          |
| 37118   |            | ONC          | 15 03 57.677 | -20 31 05.51 | 11.7 | IR excess |
|         |            |              |       |       |       |          |
| 37119   |            | ONC          | 15 20 53.3509 | -23 19 45.7020 | 9.2 | debris disk |
|         |            |              |       |       |       |          |
| 37120   |            | ONC          | 15 38 27.6509 | -22 35 38.1585 | 9.0 | debris disk |
|         |            |              |       |       |       |          |
| 37121   |            | ONC          | 15 29 43.4849 | -26 13 54.08 | 10.8 | Tr-like disk |
|         |            |              |       |       |       |          |
| 37122   |            | ONC          | 15 37 23.6789 | -24 32 43.70 | 13.0 | companion |
|         |            |              |       |       |       |          |
| 37123   |            | ONC          | 15 31 33.46 | -24 27 37.3 | 11.7 | pre-Tr disk |
|         |            |              |       |       |       |          |
| 37124   |            | ONC          | 15 33 55.61 | -24 42 05.60 | 14.1 | Tr-disk |
|         |            |              |       |       |       |          |
| 37125   |            | isolated     | 18 24 29.7787 | -29 46 49.371 | 8.2 | gap, companion candidate |
identified via Spitzer infrared data (Chen et al. 2005; Carpenter et al. 2006, 2009; Dahm & Carpenter 2009; Dahm 2010). A gap around 24 μm indicates that the inner part of the disk is cleared (Strom et al. 1989; Espaillat et al. 2014).

We assume the age of the Upper Sco SFR to be 9–13 Myr based on Pecaut et al. (2012), who derived an age using a large sample of YSOs via not only isochrone, but also other indicators such as lithium absorptions or Hα emissions (Balachandran 1990; White & Basri 2003). de Zeeuw et al. (1999) and Bertout et al. (1999) measured individual distances of YSOs in Upper Sco with Hipparcos data and derived the typical value of 145 pc, which is used in this work.

ρ Ophiuchus. We first took stars of R < 15 in the ρ Ophiuchus area by investigating the literature (Bouvier & Appenzeller 1992; Wilking et al. 2005; Zacharias et al. 2005; Cieza et al. 2007). Next, in order to verify the youth of those stars, we attempted to collect the measurements of their Hα emissions summarized in Wilking et al. (2005), Bouvier & Appenzeller (1992), and Martin et al. (1998). The previous observations of speckle interferometry (Barsony et al. 2003; Ratzka et al. 2005), AO (Cieza et al. 2010), and HST/NICMOS (Allen et al. 2002) helped us rule out close binary systems.

We also checked whether the target candidates have circumstellar disks because they may have such disks if they are young. Infrared excesses in the SEDs and submillimeter emissions are indicators of circumstellar disk, therefore we examined whether these indicators have been observed for our target candidates using the Spitzer data (Cieza et al. 2007, 2010; Furlan et al. 2009; McClure et al. 2010) and submillimeter observations (Andre & Montmerle 1994; Andrews et al. 2009). In selecting disk-bearing YSOs, we prioritized transitional disks, which are useful for both planet searches and disk studies. We used optical spectroscopy (Bouvier & Appenzeller 1992; Martin et al. 1998; Wilking et al. 2005) and IR spectroscopy (Luhman & Rieke 1999) to check the strengths of lithium absorption, which is also a youth indicator, and the spectral types of our target candidates.

We cite the distance and the age of Ophiuchus from Lombardi et al. (2008) and Greene & Meyer (1995). Lombardi et al. (2008) obtained precise distance of Ophiuchus and Lupus by combining Hipparcos data with extinction maps from Two Micron All Sky Survey (2MASS) data. Greene & Meyer (1995) estimated ages of members in Ophiuchus with several evolutionary models. Greene & Meyer (1995) concluded that the age difference is comparable with observational uncertainties in determining stellar luminosities.

Lupus. Systematic sample selection in Lupus for SEEDS is not practical because of its low declination. We then include several intriguing objects based on millimeter/submillimeter observations (Hughes et al. 1994; Nuernberger et al. 1997; Wichmann et al. 1999; Joergens et al. 2001; Mele 2003; Merín et al. 2008; Comerón et al. 2009). They have strong emission at 1.3 mm that indicates the presence of a massive disk (e.g., Tsukagoshi et al. 2011).

As described above, Lombardi et al. (2008) estimated distances for Lupus. The estimated typical value of 155 pc is consistent with Hughes et al. (1993). Hughes et al. (1994) used a large number of stars in Lupus to estimate ages using isochrone. The mode value is 3.2 Myr, but the ages range from 0.1 to 10 Myr (Hughes et al. 1994). We adopt 0.1–10 Myr in order to cover this range.

Corona Australis. We selected bright stars (R < 15 mag) that show youth indicators (Wilking et al. 1997; Chini et al. 2003; Forbrich & Preibisch 2007), except for close binaries ( Köhler et al. 2008). We then evaluated priorities of each YSO and selected transitional disk targets (Hughes et al. 2010).

We adopt the age of Corona Australis (CrA) to be 0.1–10 Myr from Neuhäuser et al. (2000). Previous studies showed the age of CrA is between ~1 Myr (Kracke et al. 1973) and 6 Myr (Wilking et al. 1992). Neuhäuser et al. (2000) estimated the age of CrA members reported in Kracke et al. (1973) and Wilking et al. (1992) and the newly detected YSOs, using the evolutionary tracks from D’Antona & Mazzitelli (1994). For the distance, we used 130 pc as provided by de Zeeuw et al. (1999) and Bertout et al. (1999), who investigated the distance of CrA in addition to Upper Sco.

We also added some YSOs to our target list that are located in isolation or in other regions because they have intriguing features or they are located at nearer distance. Finally, we note that our target selections were verified by considering the observational efficiency of all SEEDS targets including YSO targets and their observability such as visibility in the allocated nights.

We adopt the age and distance of YSOs when individual observations have been conducted and use these parameters to estimate detection limit in mass unit (see Section 4.2 for details). For example, distances of YSOs in Upper Sco and CrA have been cataloged in Hipparcos (Bertout et al. 1999; de Zeeuw et al. 1999). Note that we assume and refer to the stellar parameters on Table 5 for the discussions of detection limits in Sections 4.3 and 4.2.

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Table 2
(Continued)

| HD Name | Other Name | Group   | R.A.  | Decl.  | R mag  | Criteria |
|---------|------------|---------|-------|--------|--------|----------|
| ...     | MWC 297    | Serpens-Aquila | 18 27 39.527 | –03 49 52.05 | 11.3   | Tr-disk  |
| ...     | RX J1842.9–3532 | CrA | 18 42 57.948 | –35 32 42.69 | 11.6   | Tr-disk  |
| ...     | RX J1852.3–3700 | CrA | 18 52 17.299 | –37 00 11.95 | 11.8   | Tr-disk  |
| 179218  | ...        | isolated | 19 11 25.032 | +15 47 15.6388 | 7.3     | IR excess, resolved disk |
| 200775  | HIP 103763 | Cepheus | 21 01 36.9164 | +68 09 47.7639 | 8.7     | flared disk |

Notes.

a Values of right ascension and declination taken from Hog et al. (1998), Hog et al. (2000), Cutri et al. (2003), Zacharias et al. (2003, 2005), and van Leeuwen (2007).

b R-band magnitudes taken from our photometric measurements, the UCAC 4 (Zacharias et al. 2012), and the USNO-B1.0 catalog (Monet et al. 2003).

c Motivations of target selections, whose details and references are described in Section 4.3.

d Orion Nebula Cluster.
3. Observations and Data Reduction

SEEDS observed about 70 YSOs (more than 100 data sets in total) from 2009 October to 2015 December. SEEDS has adopted the polarization differential imaging (PDI; Kuhn et al. 2001) technique together with angular differential imaging (ADI; Marois et al. 2006) in order to efficiently observe both exoplanets and circumstellar disks around these YSO targets. The PDI uses polarization and is useful to image circumstellar disks, since the scattered-light from disk surfaces tends to be polarized. Using PDI, SEEDS has mainly reported the results of disk observations for YSOs. However, this technique is not suitable for exoplanet detections because self-luminous exoplanets at wide orbits are basically unpolarized. Meanwhile, the ADI takes advantages of field rotation to remove stellar halo and speckles. This method is the most sensitive way to find such a self-luminous exoplanet, since it does not make use of polarization and can be applied to a detection of point source.

Our YSO observations were conducted using the ADI and PDI techniques simultaneously to search for planets and analyze disks with the identical data set. Ordinary and extraordinary rays are therefore simultaneously obtained by dividing one frame into two or four subframes. However, we note that our data reductions as detailed in Section 3.2.1 combine all subframes in each frame, so that the polarization information is not used in the point-spread function (PSF) subtractions and only the ADI PSF subtractions are applied to data reductions. We here explain the observations and data reductions we used to search for exoplanet around the SEEDS/YSO targets.

3.1. SEEDS Observations

Table 3 lists the filters, imaging modes, and observation dates we employed for each target. As shown in Table 3, we have observed some targets in multiple nights to follow-up detected companion candidates (CCs), characterize disks, and compensate for previous poor-quality observations. In order to test whether the CCs are physically associated with their primary stars, we need to confirm that the CCs share common proper motions (CPMs) with the primary stars.

Our direct imaging observations were conducted using the AO system AO188 (Hayano et al. 2008) on the Subaru Telescope. All but three YSOs have been observed using them as the natural guide stars (NGSs) for AO188. However, IRS 04125+2902, IRAS 16245-2423, and RX J1633.9-2422 are too faint to be observed with the NGS mode, and we accordingly chose the laser guide star mode for these faint targets.

The NIR camera HiCIAO (Suzuki et al. 2010) was used simultaneously with AO188. Then, multiple differential-imaging modes are available; we can use the “standard PDI” (sPDI) and “quad PDI” (qPDI) modes in addition to the standard ADI mode. We explain all of the modes below.

Subaru/HiCIAO adopts sPDI, from which we can obtain ordinary and extraordinary rays simultaneously with one Wollaston prism, and it offers qPDI, from which we can obtain two ordinary and extraordinary rays simultaneously with two Wollaston prisms. Therefore sPDI shows two images in one frame and qPDI shows four images in one frame (see Figures 1 and 2). HiCIAO PDI observations set an angular offset to decrease instrumental effects of polarization.

The fields of view (FOVs) are ~20RYPT to ~20RYPT, ~20RYPT to ~10RYPT (or ~10RYPT to ~20RYPT before 2014 April), and ~5RYPT to ~5RYPT for the ADI, sPDI, and qPDI modes, respectively (see Figures 1 and 2).

We found that the new FoV configuration of sPDI can improve the PSF subtractions. Our observations were basically performed using an $H$-band (~1.6 $\mu$m) filter, but a $K_s$-band (~2.2 $\mu$m) filter was used in the case of follow-up observations or poor seeing conditions.

We explore a faint companion around a YSO by acquiring deep long-integration images. While a part of our YSO targets is faint enough to be observable without saturating their images, the PSFs of bright targets were weakly saturated to increase the integration times. In addition, we observed some YSOs using occulting masks, helping us avoid excessive saturation and increase integration times. Table 3 lists the targets observed with occulting masks and the mask sizes.

In addition to the saturated frames, we took unsaturated and unmasked frames for a YSO target using neutral density (ND) filters with transmittance of 9.74% at $H$ (10.5% at $K_s$), 0.854% at $H$ (1.14% at $K_s$), or 0.063% at $H$ (0.14% at $K_s$). These are used to verify the centroid measurements for the masked or saturated images of central star (see Section 3.2). These frames are also used to measure the contrast between a detected companion and the primary star.

The images of globular cluster M5 or M15 were obtained in the HiCIAO runs and are compared with archival data from HST to measure the field distortion, including the plate scale and offset angle between the detector vertical axis and the celestial north direction.

We measured the HiCIAO plate scales, which depend on the optical configurations (Brandt et al. 2013) and range from ~9.46 to ~9.68 mas pixel$^{-1}$ along X axis and ~9.77 to ~10.02 mas pixel$^{-1}$ along Y axis. While the pixel scales vary along the X- and Y-axes, the aspect ratio has been extremely stable. Furthermore, the orientation angles between the HiCIAO vertical axis and celestial north have been reliably fixed to ~0.3°–0.2°. These measurements are suitable for the HiCIAO (ADI+)-sPDI or qPDI modes, although almost the same results have been obtained by analyzing the globular cluster data taken in the ADI mode alone (Brandt et al. 2013). After the distortion correction, the plate scale is corrected to be 9.5 mas pixel$^{-1}$ and the orientation angle is corrected to be zero.

3.2. Data Reduction

3.2.1. ADI Data Reductions

Our YSO targets have been observed using PDI+ADI mode. The data reduction pipelines previously used to search for exoplanets (e.g., Brandt et al. 2013; Kuzuhara et al. 2013) are dedicated to the data obtained with the ADI technique alone. To reduce the ADI+PDI data, we have customized an IDL pipeline for ADI reductions, and developed some auxiliary routines that are based on Python and PyRAF.

For sPDI+ADI or qPDI+ADI data, we first remove their correlated read noise (i.e., destriping), correct for hot pixels, and perform flat-fielding, similarly as for standard SEEDS ADI data (e.g., Brandt et al. 2013). After these processes, each frame is divided into two and four subframes in the case of sPDI and qPDI observations, respectively. In the sPDI+ADI mode, each subframe contains either ordinary ray or extraordinary ray for a YSO target. Meanwhile, in the qPDI+ADI mode, the four subframes contain two ordinary and extraordinary rays. The target centroids in each subframe are individually estimated and each image for the target is shifted to a common center after
Table 3
SEEDS/YSO Observing Logs

| HD Name                | Other Name                  | t_rot (minutes) | Rotation Angle (deg) | Band | Mode                     | Date (HST)   |
|------------------------|-----------------------------|----------------|----------------------|------|--------------------------|--------------|
| 21997                  | ...                         | 36             | 13.8                 | H    | sPDI+ADI                 | 2013 Jan 3   |
| ...                    | LkHo 330                    | 27             | 10.2                 | H    | sPDI+ADI+0°4mask         | 2011 Dec 22  |
| ...                    | IRAS 04028+2948             | 45             | 31.5                 | H    | qPDI+ADI                 | 2012 Dec 31  |
| ...                    | IRAS 04125+2902             | 24             | 15.4                 | H    | sPDI+ADI                 | 2013 Nov 24  |
| ...                    | LkCa 4, V1068 Tau           | 23             | 26.1                 | H    | qPDI+ADI                 | 2012 Nov 3   |
| ...                    | Elias I, V892 Tau           | 24             | 5.3                  | H    | sPDI+ADI+0°4mask         | 2013 Feb 26  |
| 281934                 | BP Tau                      | 32             | 15.5                 | H    | qPDI+ADI                 | 2012 Sep 13  |
| ...                    | V819 Tau                    | 33             | 12.8                 | H    | qPDI+ADI                 | 2012 Jan 1   |
| 283571                 | ...                         | 6              | 89.2                 | H    | sPDI+ADI+0°4mask         | 2011 Jan 27  |
| 284419                 | T Tau                       | 12             | 1.6                  | H    | qPDI+ADI                 | 2015 Jan 8   |
| ...                    | LkCa 8, IP Tau              | 31             | 29.2                 | H    | qPDI+ADI                 | 2011 Dec 30  |
| ...                    | DG Tau                      | 26             | 6.1                  | H    | qPDI+ADI                 | 2015 Jan 11  |
| 285846                 | UX Tau                      | 30             | 8.9                  | H    | qPDI+ADI                 | 2013 Nov 24  |
| ...                    | HL Tau                      | 40             | 3.6                  | K_i | qPDI+ADI                 | 2015 Jan 8   |
| ...                    | LkCa 4, V1075 Tau           | 26             | 1.8                  | H    | qPDI+ADI                 | 2012 Nov 4   |
| ...                    | GG Tau(A)                   | 33             | 0.9                  | H    | sPDI+ADI+0°6mask         | 2011 Sep 4   |
| ...                    | LkCa 14, V1115 Tau          | 28             | 27.0                 | H    | sPDI+ADI                 | 2011 Dec 29  |
| ...                    | LkCa 15, V1079 Tau          | 11             | 134.8                | H    | sPDI+ADI                 | 2009 Dec 25  |
| ...                    | LkCa 332/G1, V1000 Tau      | 28             | 4.0                  | H    | sPDI+ADI+0°4mask         | 2013 Jan 3   |
| ...                    | GO Tau                      | 40             | 16.7                 | H    | sPDI+ADI                 | 2009 Dec 24  |
| ...                    | GM Aur                      | 12             | 31.8                 | H    | qPDI+ADI                 | 2010 Dec 2   |
| ...                    | LkCa 19                     | 31             | 51.1                 | H    | sPDI+ADI                 | 2011 Dec 23  |
| ...                    | AB Aur                      | 8              | 50.1                 | K_i | sPDI+ADI                 | 2009 Dec 24  |
| 282624                 | SU Aur                      | 24             | 14.3                 | H    | qPDI+ADI                 | 2014 Jan 19  |
| ...                    | V397 Aur                    | 23             | 75.2                 | H    | sPDI+ADI                 | 2011 Dec 31  |
| ...                    | V1207 Tau, RX J0458.7+2046  | 17             | 125.0                | H    | qPDI+ADI                 | 2012 Nov 3   |
| ...                    | MWC 480                     | 52             | 69.9                 | H    | sPDI+ADI                 | 2015 Dec 28  |
| 31648                  | CQ Tau                      | 30             | 2.1                  | H    | sPDI+ADI                 | 2012 Jan 1   |
| 34282                  | ...                         | 28             | 4.0                  | H    | sPDI+ADI+0°3mask         | 2014 Oct 11  |
| 36112                  | MWC 758                     | 38             | 11.5                 | H    | sPDI+ADI+0°4mask         | 2011 Dec 29  |
| ...                    | TW Hya                      | 30             | 13.3                 | H    | qPDI+ADI                 | 2013 Jan 3   |
| ...                    | PDS 70                      | 23             | 24.1                 | H    | qPDI+ADI                 | 2012 Feb 27  |
| 135344B                | SAO 206462                  | 18             | 23.4                 | H    | sPDI+ADI+0°4mask         | 2011 May 20  |
| 139614                 | GQ Lup                      | 26             | 15.2                 | H    | sPDI+ADI+0°4mask         | 2014 Jun 6   |
| 141444                 | HIP 77545                   | 31             | 34.6                 | H    | sPDI+ADI                 | 2012 May 12  |
| ...                    | ...                         | 25             | 14.7                 | H    | ADI                      | 2014 Jun 7   |

Note: HD Name and Other Name denote different names for the same object. Rotation Angle and Band columns refer to the modes of observation. Dates are provided in HST format.
Table 3 (Continued)

| HD Name | Other Name | $I_{tot}$ (minutes) | Rotation Angle (deg) | Band | Mode | Date (HST) |
|---------|------------|---------------------|----------------------|------|------|------------|
| 142315  | HIP 77911  | 32                  | 28.2                 | $H$  | sPDI+ADI | 2012 May 10 |
| ...     | IM Lup     | 20                  | 10.5                 | $H$  | ADI   | 2014 Jun 8  |
| 142527  | HIP 78092  | 14                  | 19.3                 | $K_s$| sPDI+ADI+0''4mask | 2011 May 25 |
| ...     | RX J1603.9-2031A | 12              | 20.4                 | $H$  | sPDI+ADI | 2012 Apr 10 |
| ...     | RX J1604.3-2130A, USco J1604 | 25            | 10.3                 | $H$  | qPDI+ADI | 2012 Apr 11 |
| ...     | SZ 91      | 44                  | 42.7                 | $K_s$| sPDI+ADI | 2012 May 10 |
| 144587  | HIP 78996  | 34                  | 29.8                 | $H$  | sPDI+ADI+0''4mask | 2011 May 24 |
| ...     |           | 10                  | 3.9                  | $H$  | sPDI+ADI | 2013 May 17 |
| ...     | V1094 Sco, RX J1608.6-3922 | 36            | 21.2                 | $H$  | sPDI+ADI+0''4mask | 2011 May 20 |
| 145655  | HIP 79462  | 40                  | 12.8                 | $H$  | ADI   | 2012 Apr 11 |
| ...     |           | 27                  | 14.8                 | $H$  | ADI   | 2014 Apr 22 |
| ...     |           | 32                  | 25.3                 | $H$  | ADI   | 2015 Apr 29 |
| 147137  | HIP 80088  | 10                  | 5.7                  | $H$  | ADI   | 2012 Jul 5  |
| ...     | IRAS 16225-2607, V896 Sco | 29            | 32.0                 | $H$  | qPDI+ADI | 2012 May 11 |
| ...     | DoAr 25    | 33                  | 25.3                 | $H$  | qPDI+ADI | 2012 May 15 |
| ...     |           | 11                  | 7.2                  | $H$  | ADI   | 2014 Jun 9  |
| 148040  | HIP 80535  | 40                  | 36.6                 | $H$  | sPDI+ADI | 2012 May 13 |
| ...     | DoAr 28    | 10                  | 8.5                  | $H$  | ADI   | 2015 Apr 29 |
| ...     | SR 21      | 48                  | 30.5                 | $H$  | qPDI+ADI | 2012 Jul 8  |
| ...     | IRAS 16245-2423, Oph IRS 48 | 28            | 14.3                 | $H$  | qPDI+ADI | 2011 May 22 |
| ...     | ROXs 42B   | 30                  | 26.7                 | $H$  | qPDI+ADI | 2011 May 22 |
| ...     | DoAr 44, ROX 44 | 6              | 4.4                  | $K_s$| sPDI+ADI | 2012 May 12 |
| ...     | RX J1633.9-2442 | 46            | 22.8                 | $H$  | qPDI+ADI | 2014 Apr 23 |
| 169142  | ...        | 40                  | 23.1                 | $H$  | sPDI+ADI+0''4mask | 2011 May 23 |
| ...     | MWC 297    | 30                  | 13.2                 | $J$  | sPDI+ADI+0''4mask | 2013 May 19 |
| ...     | RX J1842.9-3532 | 20             | 36.2                 | $H$  | sPDI+ADI | 2012 Jul 7  |
| ...     | RX J1852.3-3700 | 34            | 13.8                 | $H$  | qPDI+ADI | 2012 Sep 13 |
| 179218  | ...        | 33                  | 29.2                 | $H$  | sPDI+ADI | 2011 Sep 5  |
| 200775  | HIP 103763 | 28                  | 26.5                 | $H$  | sPDI+ADI+0''4mask | 2011 Sep 4  |

Figure 1. Subaru/HiCIAO raw image taken in sPDI+ADI mode.

Figure 2. Subaru/HiCIAO raw image taken in qPDI+ADI mode.
correcting field distortion of all subframes; the distortion-corrected plate scale is 9.5 mas pixel\(^{-1}\). We subsequently integrate the subimages that were simultaneously acquired into a single image. Finally, the ADI reductions are applied to the sequence of images made by integrating each simultaneous image. When measuring the celestial coordinate of a detected object relative to its central star, we corrected the artificial angular offset in our observations (see Section 3.1).

In order to estimate the stellar centroids, we take into account the three different methods explained below. The first method is applied to a target observed with the long sequence of unsaturated data, for which we calculate the center of a PSF by fitting a two-dimension elliptical Gaussian function to the PSF on each image with IRAF. The second method is applied to saturated data. Then, we choose a reference frame from all saturated frames for a target, and calculate the relative centroids by comparing the reference frame with the rest of saturated frames. As in Section 3.1, we obtained unsaturated frames for a YSO target in the same night. The unsaturated frames are used to verify the centroid of reference frame.

For masked data, we adopt the third method, which estimates a position of star by fitting a Moffat function to its masked PSF. In the fit, we exclude the masked area of PSF. The Moffat function is given as

\[
I(r) = I_0 \left(1 + \left(2^\beta(x - x_c)^2 + (y - y_c)^2\right) / W\right)^{-\beta},
\]

where \(I_0\) is the peak value of PSF, \(x_c\) and \(y_c\) are the x and y center of the PSF, \(W\) is the FWHM, and \(\beta\) is the atmosphere scattering coefficient (Moffat 1969). Using a least-square fit, each parameter in Equation (1), including \(x_c\) and \(y_c\), is determined. This method based on the Moffat function fit should be the best way to determine a center of image whose PSF core is largely masked (0\(^{\prime}\)3–0\(^{\prime}\)4 in our observations; Walker et al. 1994).

The AO188 keeps the target centroids stable during observations. Furthermore, an atmospheric dispersion corrector (ADC; Egner et al. 2010) in AO188 is available to help mitigate the drift of centroids. Typically, centroid drifts are less than 1–2 pixels (\(\sim\)10–20 mas) over a long sequence of integrations for each target (Brandt et al. 2013). Even in observations at high airmass (Thalmann et al. 2011), the centroid drift is no more than a few tens of mas (Brandt et al. 2013). The image-registration algorithms explained above can remove the remaining centroid drifts that are not corrected by AO188; a drift is typically found to be less than \(\sim\)10 mas.

In order to improve the sensitivities of our observations, it is crucial to acquire integrations that are as long as possible. However, the PSF of a central star is usually made more saturated as the integration time of an individual frame increases. We note the balance between a PSF saturation and an integration time. After subtracting a radial profile from each intensity image, we perform ADI-LOCI data processing (Lafreniere et al. 2007) to attenuate starlight and speckles. LOCI requires tuning some parameters, which affects the performance of data reductions. At a radial distance (\(=R\)) from each central star, our LOCI processing requires a minimum field rotation of 0.75 (\(=N_0\) \(\times\) PSF’ FWHM/\(R\) radian between a PSF-subtracted image and the PSF-reference images. Our software masks the regions that do not have field rotations fast enough to pass this criterion. In addition, an optimization zone for reference-PSF modeling has an area of 300 (\(=N_0\)) \(\times\) \(\pi\) (FWHM/2\(^2\)) pixels. See Lafreniere et al. (2007) for details of LOCI parameters. All the LOCI-processed frames are median-combined into a final image with high SN.

LOCI partially decreases the flux of a point source by self-subtracting its PSFs. This flux loss is more significant at smaller separations (Lafreniere et al. 2007). We estimate the artificial flux loss by applying LOCI to the data with injected fake companions. We initially inject the fake sources with SN ratios of \(\sim\)15 from \(\sim\)0\(^{\prime}\)2 to the edge of the FOV. This procedure is repeated 15 times, changing the initial position angle to cover the full range of \((r, \theta)\) in the field to avoid overlap of the PSFs. Finally, we measure the flux loss at each position of more than 1000 fake companions and plot the radial profile of self-subtraction. As to SEEDS data, the typical flux loss is \(\sim\)50% at 0\(^{\prime}\)3, \(\sim\)20% at 0\(^{\prime}\)8, and under 10% at larger distances than 1\('.\) In addition, we correct the flux loss to derive the photometry of the detected companion and contrast limit on each target (see Section 3.2.2).

### 3.2.2. Producing Contrast Curves

A discussion of the exoplanet frequency based on statistical analysis requires detection limits for each target. We calculate the detection limit by defining a noise distribution. First, the final reduced image for each target is normalized by dividing the image by its integration time. Next, the normalized map is convolved with an aperture whose radius is equal to half of the FWHM of the central star PSF. An aperture of the same size was used for the photometry of the central star in unsaturated frames. Finally, we define the rings at intervals of \(\sim\)0\(^{\prime}\)06 from the central stars and measure the standard deviation of counts at each ring in the convolved map. The standard deviations are determined to be the noises as a function of angular separations from the central star. To produce a contrast curve, the noise function is divided by the unsaturated PSF flux of the central star. Some SEEDS/YSO observations in the early part took reference frames with occulting masks or did not take unsaturated frames. These observations have disadvantages in that we have to use other observations for photometric reference, which increases the uncertainty of the contrasts. The partial flux losses in the contrast curves have been corrected. Finally, we adopt a 5\(\sigma\) detection threshold in this paper.

Sensitivity and contrast depend on weather condition, AO performance (seeing), and integration time. Some data were taken in bad conditions whose detection limit was low, and they are not meaningful for the exoplanet survey because of their low contrast. We note that accurately estimating the flux loss by self-subtraction at small angular separations is a difficult task.

### 4. Results

A few of our observations were conducted with only PDI, which cannot be used for exoplanet search. Excluding these, we finally reduced the data taken for the 68 YSO targets (99 data sets in total) to explore planetary-mass companion candidates. Note that some data have rotation angles that are too small to explore the inner region (\(<\)100 au). We do not include sources with S/N lower than 5 in the list of CCs. As a result, we found 15 new CCs within 400 au from their central stars. We detected a new stellar companion that is physically associated with HIP 79462 (see Section 4.3.52). We also
detected an unreported bright source around TYC 4496-780-1 (see Section 4.3.1) that either is a stellar companion or a background star. In addition, we confirmed 2 convincing low-mass companions. These companions have been reported previously; GQ Lup b (see Section 4.3.42) and ROXs 42B b (see Section 4.3.60).

Although our observations detected more point sources, it is impossible to statistically explore the objects at the projected separations larger than 400 au because many targets have been observed with pPdI, which has a FOV corresponding to 400 au. Moreover, we assume that planet formation at such large separations from primary stars is relatively challenging since the standard disks around pre-main sequence stars should not be so large (cf. Andrews & Williams 2007), therefore we did not prioritize the follow-up observations of these wide-separation companions. Note that substellar companions exist at very large distances from their primary stars (e.g., Bailey et al. 2014; Naud et al. 2014). With the caveat that such substellar companions with very wide separations cannot be ruled out as the companions formed from the circumstellar disks, we do not discuss CCs at separations larger than 400 au based on the above reasons. Seven point sources out of 15 candidates within 400 au from their central stars are identified to be background stars by conducting common proper motion test.

We present the detailed frameworks of detection limits and luminosity–mass conversion in Sections 4.1 and 4.2. We also summarize our observed results for individual targets.

4.1. Contrast

Our results of detection limit are listed in Table 4. Note that SEEDS observations are basically carried out in $H$ band, but some YSOs are observed only in $K_s$ band. For the YSOs observed at multiple epochs, we adopt the deepest detection limits of all detection epochs from multiple observations. Figures 9 and 10 show our final results of $5\sigma$ detection limit with bright ($<8$ mag in $H$ or $K_s$ band) and faint ($>8$ mag) stars. Sources brighter than the contrast curves can be detected by HiCIAO observations with more than $5\sigma$ significance. Comparing Figures 9 with 10, we find that typical detection limits are better in observing bright YSOs by a factor of $\sim 2$–10 than faint YSOs. We calculated the typical limiting magnitudes by adding the brightness of central stars to the contrast curves, in order to investigate whether this difference arises from the difference of AO efficiency. As a result, the limiting magnitudes around bright and faint targets are almost the same: $\sim 14$–15 mag at 0″/3, $\sim 15.5$–17 mag at 0″/5, $\sim 18$–19 mag at 1″/0, and $\sim 19$–20 mag beyond 2″/0.

As already described in Section 3.2.2, some of early observations did not take unsaturated frames, thus we need to use the data of the other targets as photometric reference, making it more uncertain to estimate the contrast limits. A bundle of contrast curves in Figures 9 and 10 looks wider than those of moving group targets (Brandt et al. 2014b, 2014a) to some extent. In CQ Tau, GQ Lup, HIP 103763, HIP 79462, IRAS 16225-2607, MWC 297, PDS 70, ROX 44, TYC 4496-780-1, and UX Tau data, bright point sources affect the contrast curves. We masked these bright sources when deriving contrast curves. We masked these bright sources when deriving the detection limits, but we cannot completely remove their influence on the detection. IRAS 04125+2902 and LkHa 332 G1 also have bright sources in the FOV, but the companions are outside of our explored separation range. We typically achieve a contrast of $\sim 10^{-3.5}$ at 0″5, $10^{-4}$–$10^{-5}$ at 1″, and $10^{-4.5}$–$10^{-6}$ beyond 2″. This detection limit is similar to that of other SEEDS categories (Brandt et al. 2014a) and one of the highest contrasts of YSO imaging surveys conducted so far (see Section 5.3.2). There are many bad pixels at the edges of the detector, which can effect the contrast curves, and some contrast curves even become shallower at the wider separations.

Figure 11 compares the detection limits of this work with some of previous high-contrast surveys. Note that some previous works set detection significances different from $5\sigma$ and adopted different filters in imaging observations. In comparison with the results of other high-contrast imaging surveys for young moving groups (see Section 5.3.1), our median contrast limits appear to be lower at 1″. YSOs are basically located at farther distances and thus are fainter than young moving group members, which affects the AO performance. Nevertheless, although our contrast results appear shallow in terms of contrast, the central stars are generally faint, which means that our data may be as deep as those of previous studies in terms of limiting magnitude. Planets around YSOs may also be younger and brighter than those in the young moving groups, enabling us to constrain up to a mass a few times higher than Jovian. On the other hand, our survey achieved the strongest constraints compared to other YSO imaging surveys (see Section 5.3.2).

4.2. Luminosity–mass Conversion and Detectable-mass Limit

We reveal a detected companion’s mass and how massive planets can be detected in our YSO observations. To do this, we need to convert our $5\sigma$ contrast limit into the mass detection limit and the detected companion’s luminosity into its mass. The relationships between age, luminosity, and mass of giant planets and brown dwarfs have been theoretically modeled (e.g., Baraffe et al. 2003; Allard et al. 2011). The relations should vary depending on how planets form from circumstellar disks (Marley et al. 2007).

We adopt the age–luminosity–mass relation of the COND03 model (Baraffe et al. 2003), one of the hot-start models. Cold-start models have been also proposed to model the luminosity and temperature evolution of a giant planet, which depends on the planet formation scenarios (e.g., Marley et al. 2007). Observational results disagree with a very cold-start model (Marleau & Cumming 2014). As described in Section 1, although the controversy about the formation scenario has not been settled, the mass estimates based on the evolution models are probably uncertain particularly for young exoplanets because the initial conditions are very uncertain (Marleau & Cumming 2014). To calibrate these models requires comparing parameters between those estimated by direct imaging and by other methods such as radial velocity or transit. However, there are no exoplanets detected by both direct imaging and indirect methods so far.

The luminosity–mass conversions also require the age and distance of the target, so that the stellar parameters of our observed YSOs need to be known in our analysis. As discussed in Section 2.2, most YSOs are located in SFRs, thus age and distance of YSOs can be approximately estimated from their group membership. Table 1 shows typical age and distance of SFRs targeted in this study. Table 5 shows the stellar parameters of each YSO. Note that we use the stellar parameters to estimate detection limits in Section 4.3 and
| HD Name        | Other Name | Magnitude (band) | $\Delta$ mag (5$\sigma$ contrast) |
|----------------|------------|------------------|----------------------------------|
| ...            | TYC 4496-780-1 | 7.76±0.02 (H) | 0.025 0.05 0.075 1.0 1.5 2.0 3.0 |
| 21997          | ...         | 6.12±0.03 (H)  | ...                              |
| ...            | LkHα 330   | 7.92±0.03 (H)  | ...                              |
| ...            | IRAS 04028+2948 | 9.47±0.03 (H) | ...                              |
| ...            | IRAS 04125+2902 | 9.76±0.03 (H) | ...                              |
| ...            | LkCa 4, V1068 Tau | 8.52±0.02 (H) | ...                              |
| ...            | Elias 1, V929 Tau | 7.02±0.03 (H) | ...                              |
| 281934         | BP Tau     | 8.22±0.02 (H)  | ...                              |
| ...            | V819 Tau   | 8.65±0.02 (H)  | ...                              |
| 283571         | TY Tau     | 6.13±0.06 (H)  | ...                              |
| 284419         | T Tau      | 6.24±0.02 (H)  | ...                              |
| ...            | LkCa 8, IP Tau | 8.89±0.02 (H) | ...                              |
| ...            | DG Tau     | 7.72±0.03 (H)  | ...                              |
| 285846         | UX Tau     | 7.96±0.02 (H)  | ...                              |
| ...            | HL Tau     | 7.41±0.02 (K$_{s}$) | ... |
| ...            | L1551-51, V1075 Tau | 9.06±0.02 (H) | ...                              |
| ...            | L1551-53, V1076 Tau | 9.46±0.03 (H) | ...                              |
| ...            | DL Tau     | 7.96±0.02 (K$_{s}$) | 8.1 9.6 10.2 10.9 11.0 11.0 9.1 |
| ...            | DM Tau     | 9.76±0.02 (K$_{s}$) | 6.9 8.9 9.6 10.1 10.7 10.8 9.2 |
| ...            | CI Tau     | 8.43±0.04 (H)  | ...                              |
| ...            | DN Tau     | 8.54±0.03 (H)  | ...                              |
| ...            | LkCa 14, V1115 Tau | 8.71±0.03 (H) | ...                              |
| ...            | LkCa 15, V1079 Tau | 8.60±0.02 (H) | ...                              |
| ...            | LkHα 332/G1, V1000 Tau | 8.40±0.02 (H) | ...                              |
| ...            | GO Tau     | 9.78±0.02 (H)  | ...                              |
| ...            | GM Aur     | 8.60±0.02 (H)  | ...                              |
| 282630         | LkCa 19    | 8.32±0.02 (H)  | ...                              |
| 31293          | AB Aur     | 4.23±0.02 (K$_{s}$) | 6.7 8.6 9.3 9.4 10.0 10.3 10.4 |
| 282624         | SU Aur     | 6.56±0.02 (H)  | ...                              |
| ...            | V397 Aur   | 8.32±0.02 (H)  | ...                              |
| ...            | V1207 Tau, RX J0458.7+2046 | 8.96±0.02 (H) | ...                              |
| 31648          | MWC 480    | 6.26±0.03 (H)  | ...                              |
| 34282          | ...        | 8.48±0.03 (H)  | ...                              |
| 36112          | MWC 758    | 6.56±0.02 (H)  | ...                              |
| 36910          | CQ Tau     | 7.06±0.02 (H)  | ...                              |
| 290764         | V1247 Ori  | 8.20±0.25 (H)  | ...                              |
| ...            | TW Hya     | 7.56±0.04 (H)  | ...                              |
| ...            | PDS 70     | 8.82±0.04 (H)  | ...                              |
| 135344B        | SAO 206462 | 6.59±0.03 (H)  | ...                              |
| 139614         | ...        | 7.33±0.04 (H)  | ...                              |
| ...            | GO Lup     | 7.70±0.03 (H)  | ...                              |
| 141441         | HIP 77545  | 8.00±0.03 (H)  | ...                              |
| 142315         | HIP 77911  | 6.67±0.03 (H)  | ...                              |
| ...            | IM Lup     | 8.09±0.04 (H)  | ...                              |
| 142527         | HIP 78092  | 5.72±0.03 (H)  | ...                              |
| ...            | RX J1603.9-2031A | 8.77±0.03 (H) | ...                              |
| ...            | RX J1604.3-2130A, USco J1604 | 9.10±0.02 (H) | ...                              |
| ...            | SZ 91      | 9.85±0.02 (K$_{s}$) | 8.5 9.3 9.6 9.6 9.8 9.8 9.8 |
| 144587         | HIP 78996  | 7.36±0.06 (H)  | ...                              |
| ...            | V1094 Sco, RX J1608.6-3922 | 9.04±0.02 (H) | ...                              |
| 145655         | HIP 79462  | 7.43±0.07 (H)  | ...                              |
| 147137         | HIP 80088  | 7.90±0.04 (H)  | ...                              |
| ...            | IRAS 16225-2607, V896 Sco | 7.95±0.06 (H) | ...                              |
| ...            | DoAr 25    | 8.40±0.05 (H)  | ...                              |
| ...            | HIP 80535  | 7.31±0.05 (H)  | ...                              |
| ...            | DoAr 28    | 8.99±0.02 (H)  | ...                              |
| ...            | SR 21      | 7.51±0.04 (H)  | ...                              |
| ...            | IRAS 16245-2423, Oph IRS 48 | 8.82±0.07 (H) | ...                              |
| ...            | DoAr 44, RX 44 | 8.25±0.06 (H) | ...                              |
| ...            | RX J1633.9-2442 | 9.36±0.02 (H) | ...                              |
| 169142         | ...        | 6.91±0.04 (H)  | ...                              |
| ...            | MWC 297    | 4.39±0.21 (H)  | ...                              |
Section 5. The individually adopted parameters are usually consistent with those of the groups they belong to. CQ Tau, IM Lup, and Sz 91 have somewhat different distances from the those of Taurus and Lupus. V1094 Sco, HIP 79462, USco J1604, and LkHα 332/G1 have different ages from the typical value of Upper Sco and Taurus. In this calculation, we only used 10 Myr for YSOs in Upper Sco instead of 11 Myr so as to avoid extrapolating the planet luminosity at 11 Myr from the luminosity models in 1–10 Myr. For HIP 103763 we used 1 Myr instead of the adopted age because our adopted luminosity model does not publish the calculations for the objects with such a very young age.

Using the extinction law of Cardelli et al. (1989), we first corrected the interstellar extinctions, which only weakly influence most of our YSO targets (<~0.5 mag; see Table 5), however. Adopted parameters of distance and age in Table 5 are used to calculate the mass in units of Jovian mass and the central stars are fainter. This figure shows that we can set a typical upper limit of 5–10 MJ at a few tens of au. In this case, our observations could be sensitive to smaller exoplanets around the fainter YSOs than brighter YSOs because the central stars are fainter. This section discusses exoplanets outside 100 au and brown dwarfs in the solar-system scale. Because Orion Nebula Cluster, Serpens-Aquila, and Perseus are located farther than the other SFRs (see Tables 1, 5), it is not possible to constrain planetary-mass companions within 100 au in these SFRs. Some contrast curves are influenced by the bright companions (see Section 4.1), which produces the biases in the contrast determinations.

4.3. Results of the Individual Companion Survey

4.3.1. TYC 4496-780-1

This isolated T Tauri star in front of the Cepheus complex has strong NIR and FIR excess and a Hα accretion signature (Guillot et al. 2010).

SEEDS observed this system in 2012 July with qPDI+ADI mode. We detected a bright source at ∼1″5. Guillot et al. (2010) suggested that this system is a spectroscopic binary system; we find that our detected object is possibly a stellar component of the pair. Since we have no follow-up observations of this target and this detected source is very bright, we do not consider this object to be a planetary-mass CC.

4.3.2. HD 21997

This A3 star is a member of the Columba moving group (Moor et al. 2006, 2013), which is as old as ∼30 Myr (Torres et al. 2008). However, its SED shows a transitional-like disk rather than a debris disk (Moor et al. 2013). SEEDS therefore observed HD 21997 in the YSO category.

We reduced the data taken in 2013 January with sPDI+ADI and the 0″4 mask, and detected no CCs.

4.3.3. LkHα 330

LkHα 330 is a T Tauri star in the Perseus SFR. This star has an SED of a transitional disk, and a gap and asymmetric structure was observed in the disk (e.g., Brown et al. 2008, 2009; Isella et al. 2013). SEEDS observed LkHα 330 three times in 2011 December using sPDI+ADI with the 0″4 mask, and in 2014 October and 2015 January using the qPDI+ADI mode without a mask. Our data reductions for all data detected no CC. We constrained the potentially existing exoplanets to be smaller than 60 MJ at 50 au, or 16.5 MJ at 100 au.

4.3.4. IRAS 04028+2948

This Herbig Ae/Be star in the Taurus SFR has an SED with an IR excess and concavity in the MIR range (Kenyon et al. 1990; Rebull et al. 2011).

We reduced the data observed in 2012 December with the qPDI+ADI mode and detected no CCs in its FOV. We set a detection limit of 20 MJ at 50 au.

4.3.5. IRAS 04125+2902

This T Tauri star is a 4″0 binary system in the Taurus SFR and has a transitional disk (Kim et al. 2013; Espaillat et al. 2015).

We reduced the data taken in 2013 November and in 2014 January with the sPDI+ADI mode and confirmed this system to be a binary system. We did not detect any other CCs in its FOV.

4.3.6. LkCa 4

LkCa 4 is a T Tauri star in the Taurus star association and has an SED indicative of a class III object (Furlan et al. 2006; Howard et al. 2013). The spectroscopic study derived the Li abundance of this system (Sestito et al. 2008).

SEEDS observations were carried out in 2012 November with qPDI+ADI, resulting in no detection of CCs in its FOV.

4.3.7. Elias 1

Elias 1 (=V892 Tau) is a Herbig Ae/Be star in a 4″0 binary system, which is a member of the Taurus association, and it possesses a circumbinary disk (Monnier et al. 2008), which is interesting for studying the disk property.

### Table 4

(Continued)

| HD Name | Other Name | Magnitude (band)^a | Δ mag (5σ contrast) |
|---------|------------|-------------------|-------------------|
|         |            |                   | 0″25 0″5 0″75 1″0 1″5 2″0 3″0 |
| ...     | RX J1842.9-3532 | 8.71±0.04 (H)     | ... 8.0 8.8 9.6 10.9 11.2 8.3 |
| ...     | RX J1852.3-3700 | 9.14±0.02 (H)     | ... 9.5 10.6 11.1 11.8 11.9 11.7 |
| 179218  |            | 6.65±0.03 (H)     | ... ... ... ... ... ... 14.1 |
| 200775  | HIP 103763 | 5.47±0.03 (H)     | ... 9.4 11.2 12.5 13.8 12.1 11.9 |

Note.
^a H-band magnitudes taken from 2MASS (Cutri et al. 2003; Skrutskie et al. 2006).
| HD Name    | Other Name | Sp type | Av | Age (Myr) | Distance (pc) | Reference |
|-----------|------------|---------|----|-----------|---------------|-----------|
| TYC 4967-780-1 | G*        | ...    | 15 | 150       | 56            |
| 21997     | ...        | A7     | 30 | 72        | 27, 29, 44, 66, 69 |
| LkHα 330 | G3        | 1.8    | 3  | 250       | 22, 25, 65, 78 |
| IRAS 04028+2948 | A1     | ...    | 6  | 140       | 64            |
| IRAS 04125+2902 | M1.25   | 2.39   | 6  | 140       | 12, 37, 79    |
| LkCa 4, V1068 Tau | K7     | 1.21   | 2.5| 140       | 1, 13, 18     |
| Elias 1, V892 Tau | A6     | 5.93   | 2  | 140       | 1, 18, 63     |
| 281934 BP Tau | K7       | 0.49   | 2.2| 140       | 1, 18, 45     |
| 283571 T Tau | K0       | 1.39   | 1.8| 140       | 1, 5, 68      |
| LkCa 8, IP Tau | M0      | 0.24   | 4.0| 140       | 1, 11, 40, 80 |
| DG Tau | K6       | 1.29   | 9.0| 140       | 12, 68, 79    |
| UX Tau | G8       | 0.21   | 1  | 152       | 1, 5, 6, 45   |
| HL Tau | K7       | 7.4    | 0.9| 140       | 1, 41, 83     |
| L1551-51, V1075 Tau | K7    | 0.0    | 6  | 140       | 1            |
| GG Tau(A) | K7      | 0.76   | 1.5| 140       | 1, 36         |
| L1551-55, V1076 Tau | K7    | 0.69   | 6  | 140       | 1            |
| DL Tau | K7       | 1.21   | 1  | 140       | 3, 12, 17, 43 |
| DM Tau | M1       | 0.00   | 3.6| 140       | 1, 3         |
| CI Tau | K7       | 1.77   | 1.7| 140       | 1, 3, 17     |
| DN Tau | M0       | 0.49   | 2.6| 140       | 1, 43        |
| LkCa 14, V1115 Tau | M0    | 0.00   | 8.9| 140       | 1, 43        |
| LkCa 15, V1079 Tau | K5     | 0.62   | 1.4| 140       | 1, 43        |
| LkHo 332/G1, V1000 Tau | M1–M2.5 | 4.6  | 0.2| 140       | 26, 42, 71   |
| GO Tau | M0       | 1.18   | 4.8| 140       | 1, 3        |
| GM Aur | K3–K5.5  | 1.2    | 7.2| 140       | 3, 20, 84    |
| LkCa 19 | K0       | 0.00   | 6  | 140       | 1            |
| AB Aur | A0–A1   | 0.50   | 3  | 144       | 2, 4, 45     |
| SU Aur | G2       | 0.90   | 2.2| 140       | 1, 3, 45     |
| V397 Aur | K7     | 0.00   | 4.4| 140       | 1, 55, 68, 80, 86 |
| V1207 Tau, RX J058.7+2046 | K7    | 0.3    | 2.7| 140       | 52, 81       |
| MWC 480 | A5      | 0.096  | 6.7| 146       | 2, 31        |
| MWC 758 | A5      | 0.0    | 3.5| 279       | 47, 49, 50, 66 |
| CQ Tau | F3       | 2.0    | 13 | 100       | 4, 5       |
| V1247 Ori | A0/A5/F2 | 0.64  | 7.4| 385       | 62, 89       |
| TW Hya | M2       | 0.0    | 8  | 54        | 57, 58, 66, 77 |
| PDS 70 | K5       | 0.81   | 10 | 140       | 48, 67, 90, 91 |
| SAO 206462 | F4    | 0.3    | 8  | 142       | 8, 23, 50, 55, 82 |
| GQ Lup | A7       | 0.09   | 7.0| 140       | 8, 82, 85, 92 |
| HIP 77545 | A2–A3  | 1.25   | 11 | 119       | 14, 66, 93   |
| HIP 77911 | B9     | 0.34   | 11 | 148       | 34, 66       |
| IM Lup | M0       | 0.5    | 1  | 190       | 19, 94       |
| HIP 78092 | F6     | 0.37   | 2  | 140       | 2, 85, 87    |
| RX J1603.9-2031A | K5    | 0.7    | 11 | 145       | 73          |
| RX J1604.3-2130A, USco J1604 | K2   | 1.0    | 3.7| 145       | 35, 59, 88   |
| IRAS 16225-2030, V896 Sco | K6    | 3.0    | 3  | 155       | 60, 61       |
| HIP 78996 | A9     | 0.47   | 11 | 108       | 14, 66, 93   |
| HIP 79462 | G2     | 0.45   | 6  | 142       | 14, 66, 93   |
| HIP 80088 | A9     | 0.61   | 11 | 139       | 14, 66, 93   |
| IRAS 16225-2030, V896 Sco | K7    | 1.3    | 0.8| 120       | 38, 39       |
| DoAr 25 | K5       | 2.7    | 3.8| 145       | 20, 30, 97, 98 |
| HIP 80535 | G0     | 0.00   | 8  | 120       | 14, 66, 74   |
| DoAr 28 | K5       | 2.3    | 5  | 139       | 38, 75       |
| SR 21 | G3       | 9.0    | 4.7| 120       | 20, 76       |
| IRAS 16245-2423, Oph IRS 48 | A0    | 12.9   | 1.5| 120       | 24, 38       |
| RXs 42B | M0      | 1.9    | 2.5| 120       | 33, 51       |
| DoAr 44, ROX 44 | K3    | 2.2    | 1.5| 120       | 6, 38, 50    |
| RX J1633.9-2442 | K7    | 5.0    | 2.0| 120       | 54, 79       |
| 169142 | A5       | 0.31   | 8  | 145       | 2, 8, 74     |
This object was observed in 2013 February with the sPDI + ADI + 0.′4 mask. We confirmed the stellar companion, but did not detect any other CCs.

4.3.8. BP Tau

This T Tauri star in the Taurus SFR was observed by resolving the disk, in which CO appears to begin to be depleted (Dutrey et al. 2003).

SEEDS observations were carried out in 2012 September with the qPDI+ADI mode. We detected a point source at ∼3″1 near the edge of FOV. In order to discuss the proper motion of the CC, we used HST/NICMOS and Subaru/CIAO data. Our CPM test showed that this source is most likely a background star. We used the proper motions reported in Zacharias et al. (2012) (μα = 7.4 ± 1.2, μδ = −28.4 ± 0.7 [mas yr−1]). However, NICMOS data are saturated and CIAO data are masked, which means these data have a large astrometric uncertainty. Judging whether this object is a companion or a background star requires follow-up observations. We do not conclude that this object is a background star.

4.3.9. V819 Tau

V819 Tau is a class III object in the Taurus association and has an excess at 24 μm and FIR (Furlan et al. 2006; Luhman et al. 2009), which may arise from a transitional disk.

HiCIAO images taken in 2012 January with qPDI+ADI detected no CCs in its FOV.

4.3.10. RY Tau

RY Tau is a T Tauri star in the Taurus SFR. Isella et al. (2010a) resolved this disk and reported an inner gap, which suggests that a planet with a mass lower than 5 M_J exists between 10 and 50 au from the primary star.

HiCIAO images taken in 2011 January with the sPDI+ADI + 0.′4 mask and in 2014 October with sPDI+ADI detected a faint source at 5″. We do not include this object as a CC.

4.3.11. T Tau

T Tau was the first selected protostar as a new type of variable star (Joy 1945). This YSO is a well-studied triple system in the Taurus-Auriga SFR. T Tau is now called T Tau Sa and T Tau Sb. These components of the system have IR excesses and the companions are called T Tau Sa and T Tau Sb.

The SEEDS observation carried out in 2015 January had only a few rotation angles and we cannot discuss exoplanets located within 2″3.

4.3.12. IP Tau

This T Tauri star in the Taurus SFR has a pre-transitional disk (Espaillat et al. 2011). A SEEDS observation was carried out in 2011 December with the qPDI+ADI mode. We reduced the data and detected no CCs. Calculation of detection limit excludes possible companions more massive than 14 M_J at 50 au.

4.3.13. DG Tau

This T Tauri star is a binary system with a separation of ∼1″ (e.g., Rodmann et al. 2006) in the Taurus SFR and has a resolved image of its circumstellar disk (Isella et al. 2010a), accompanied by the radio jet (Lynch et al. 2013).

We did not detect any point sources in the FOV of the qPDI+ADI data taken in 2015 January.

Note.

4. Inferred from its T_eff and the spectral type versus T_eff relation of Pecaut & Mamajek (2013).

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4.3.14. UX Tau

UX Tau A is a T Tauri binary in the Taurus SFR. Espaillat et al. (2007) reported a transitional disk around UX Tau A. SEEDS reported that the polarization degrees strongly vary over the disk, indicating a thin disk with dust grains (Tanii et al. 2012).

We reduced the HiCIAO data taken in 2013 November with the qPDI+ADI mode and confirmed the stellar companion at a separation of $\sim 2''7$. We did not detect any other CCs. Because of the detection limit, we cannot discuss the inner part of 400 au, which was automatically masked by LOCI.

4.3.15. HL Tau

HL Tau is a T Tauri star associated with the Taurus SFR. Previous studies using Subaru/CIAO (Tamura et al. 2000) have reported an asymmetric (C-shaped) feature and different color pattern on its disk (Murakawa et al. 2008). Recently, a multi-ring feature in the mid-plane of the disk was reported by ALMA observations (ALMA Partnership et al. 2015), with which Akiyama et al. (2016) discussed planet formation in this system. Testi et al. (2015), using the Large Binocular Telescope Interferometer MIR camera (LBTI/LMIRcam), tried to find companions of HL Tau, but this resulted in a non-detection and an upper limit on the exoplanets of $\sim 10-15M_j$ at 70 au.

SEEDS observations were conducted in 2015 January after the ALMA press release. At the observations, the PSF of HL Tau varied strongly, possibly due to bad weather condition. In the final image made through our data reductions, there were residuals of a stellar halo, preventing us from detecting any CCs.

4.3.16. L1551-51

L1551-51 is a T Tauri star in the Taurus association. Its SED classifies the star as a class III object (Luhman et al. 2010; Howard et al. 2013). Martin et al. (1994) derived Li abundances of this YSO from spectroscopic observations.

We reduced the data taken in 2012 November with qPDI+ADI and detected no CCs.

4.3.17. GG Tau

GG Tau is a T-Tauri star associated with the Taurus SFR. This star is one of a quadruple system (Aa, Ab, Ba, Bb White et al. 1999) and is surrounded by the circumstellar disk (e.g., Krist et al. 2005). SEEDS reported a gap and asymmetric features in its disk (Itoh et al. 2014; Yang et al. 2016).

HiCIAO observed GG Tau twice, once for short exposure time, and LOCI cannot be applied. We therefore use only the same data as presented by Itoh et al. (2014), which were taken in 2011 September using the sPDI+ADI mode and the 0''6 occulting mask. The occulting mask is large, and this observation did not obtain a fast enough field rotation to examine the inner region of the planetary system. As a result, the inner part within 300 au is masked after the LOCI data reduction, and we detect no CC.

4.3.18. L1551-55

This T Tauri member of the Taurus SFR is classified as class III (Luhman et al. 2010; Howard et al. 2013). Magazzu et al. (1992) observed this YSO and estimated the Li abundance.

A SEEDS observation was carried out in 2012 November with the qPDI+ADI mode. We did not detect any CCs in its FOV.

4.3.19. DL Tau

DL Tau is a T Tauri member of the Taurus association and has an infrared excess (Hartmann et al. 2005; Andrews & Williams 2007). Andrews & Williams (2007) resolved the disk around DL Tau.

HiCIAO images observed in 2014 October with qPDI+ADI did not detect any CCs.

4.3.20. DM Tau

This T Tauri star belongs to Taurus SFR. Previous studies reported that this system has a transitional disk (Calvet et al. 2005; Andrews & Williams 2007). Andrews et al. (2011) reported a gap at $\sim 20$ au from the central star.

A SEEDS observation was carried out in 2009 December with the sPDI+ADI mode. Our data reduction detected no CCs.

4.3.21. CI Tau

CI Tau is a T Tauri star in the Taurus SFR, has an infrared excess in its SED, and its disk was resolved (Andrews & Williams 2007).

This system was observed in 2012 September with the qPDI+ADI mode. We did not detect any CCs in its FOV.

4.3.22. DN Tau

DN Tau, a T Tauri member of the Taurus association, has an IR excess from MIR to FIR in its SED (Andrews & Williams 2007; Najita et al. 2007), and its disk was resolved by submillimeter observations (Andrews & Williams 2007).

We reduce HiCIAO data taken in 2009 December with sPDI+ADI and do not detect any point sources.

4.3.23. LkCa 14

LkCa 14 is a T Tauri star in the Taurus association. This system is classified as a class III object and has an IR excess (Hartmann et al. 2005; Dent et al. 2013), which may imply a transitional disk.

HiCIAO images taken in 2011 December with sPDI+ADI detected no CCs in the FOV.

4.3.24. LkCa 15

LkCa 15 is a T Tauri star in the constellation of Taurus and has a transitional disk (Espaillat et al. 2007; Najita et al. 2007), which has a gap structure revealed by imaging observations in various wavelengths (e.g., Piétu et al. 2006; Thalmann et al. 2010, 2014, 2015). Furthermore, the CCs have been reported and investigated by Keck/NIRC2 observations (Kraus & Ireland 2012). The Large Binocular Telescope (LBT) confirmed the CCs, and MagAO observation discovered the H$\alpha$ emission that implies mass accretion (Sallum et al. 2015).

Thalmann et al. (2010) used the SEEDS data taken in 2009 December with the sPDI+ADI mode. In addition to this observation, LkCa 15 was observed in 2010 January with ADI, in 2010 December with sPDI+ADI, in 2011 January with sPDI+ADI, and in 2013 November with qPDI+ADI mode. We
analyzed all of these data and detected no point sources. The inner exoplanets detected by Sallum et al. (2015) are located in the strong self-subtraction region, and LOCI automatically masked this. In the first and fourth epoch, however, we recognized a similar signal pattern in the final maps as in Gemini/NIRI images (Thalmann et al. 2014), although these patterns have a low S/N ratio of \( \sim 2 \). These signals probably are from protoplanetary disks, but we do not discuss the disk feature. We finally estimated an upper limit of 5 \( M_J \) at 30 au, of 4.5 \( M_J \) at 50 au, and of 3.5 \( M_J \) at 70 au.

4.3.25. LkHs 332 G1

This T Tauri star is a \( \sim 0.23 \) binary system in the Taurus association (Leinert et al. 1993). Previous studies reported accretion signatures (e.g., McCabe et al. 2006). The SED has an IR excess that may stem from a transitional disk (Hartmann et al. 2005).

We observed this system in 2013 January with spPDI+ADI and the 0"/4 mask. The occluding mask prevented us from confirming the stellar companion. HiCIAO image detected a bright point source at the edge (\( \sim 10'' \)) of the FOV, and this object probably is a stellar companion or background star because of its wide separation.

4.3.26. GO Tau

This T Tauri star is a member of the Taurus SFR. Its SED is appeared to be that of a transition disk (Najita et al. 2007). The disk was imaged at submillimeter wavelengths (Andrews & Williams 2007).

SEEDS observed GO Tau in 2009 December with the spPDI+ADI mode. We detect a point source at 4"/9, but did not reobserve this system. We exclude this object as an exoplanet candidate because its separation is too large. We did not detect any other CCs.

4.3.27. GM Aur

GM Aur is a T-Tauri star of the Taurus association. HST/NICMOS resolved the protoplanetary disk (Schneider et al. 2003). The SED of GM Aur represents a transitional disk (Calvet et al. 2005; Najita et al. 2007; Espaillat et al. 2010), whose cavity was detected by sub-mm observations (e.g., Hughes et al. 2009; Andrews et al. 2011). Spectroscopy from FUV to NIR range has been executed (Ingleby et al. 2015) and theoretical simulation suggests a gap in the disk (e.g., Espaillat et al. 2010).

This object was observed in 2010 December with the qPDI+ADI mode and 2011 December with the spPDI+ADI mode. We reduced these data, but detected no signal. We calculated the contrast of both data sets and show the data with the higher contrast in Table 4. Finally, we estimated the upper limit to be 2.5 \( M_J \) at 50 au and 1.5 \( M_J \) at 100 au.

4.3.28. LkCa 19

This class III YSO is a T Tauri star in the Taurus SFR (Hartmann et al. 2005; Howard et al. 2013). This system has an IR excess at \( \lambda = 24 \) \( \mu \)m and can be thought to have a transitional disk (Hartmann et al. 2005; Luhman et al. 2010).

We reduced the data observed in 2011 December with spPDI+ADI and detected a point source at \( \sim 4''/4 \) separation. We do not include this object as a CC because of its very wide separation.

4.3.29. AB Aur

AB Aur is a Herbig Ae/Be star in the Taurus association. This relatively bright star has a protoplanetary disk resolved by various instruments (e.g., Oppenheimer et al. 2008; Perrin et al. 2009). The CIAO and HiCIAO observations revealed an asymmetric feature at \( \sim 50-500 \) au (Fukagawa et al. 2004; Hashimoto et al. 2011).

We reduced the data taken in 2009 December with the spPDI+ADI mode, which is different from Hashimoto et al. (2011), who reported HiCIAO data taken in 2009 October with only the PDI mode. We did not detect any point sources. We then calculated the upper limit of the mass of potential exoplanets to be 13 \( M_J \) at 100 au.

4.3.30. SU Aur

SU Aur is a T Tauri star associated with the Taurus association. This system had been reported to have an IR excess (e.g., Hartmann et al. 2005) and a nebula (Nakajima & Golimowski 1995). SEEDS revealed the asymmetric and tail structures in this system (de Leon et al. 2015).

SU Aur was observed in 2014 January and in 2014 October with the qPDI+ADI mode. We reduced these data and did not detect any CC. The detection limit is estimated to be 10 \( M_J \) at 50 au.

4.3.31. V597 Aur

This class III YSO in the Taurus SFR has an IR excess (Hartmann et al. 2005; Furlan et al. 2006), which is indicative of a transitional disk.

A SEEDS observation was carried out in 2011 December with the spPDI+ADI mode and detected a point source at \( \sim 6'' \). We do not include it as a CC because of the very wide separation.

4.3.32. RX J0458.7+2046

RX J0458.7+2046 (V1207 Tau) is a T Tauri star in the Taurus SFR. Wichmann et al. (2000) estimated the Li abundance of this system, and Wahhaj et al. (2010) reported that this system has a diskless SED.

A HiCIAO observation was conducted in 2012 November with the qPDI+ADI mode and in 2015 December with spPDI+ADI. We detected a point-like source at the edge of FOV. The follow-up observation in 2015 showed that the source was a false positive, and we did not detect any CCs within 400 au.

4.3.33. MWC 480

MWC 480 is a relatively bright Herbig Ae/Be star in the Taurus association and has a full disk that has so far been imaged at multiple wavelengths (Piétu et al. 2006; Grady et al. 2010; Kusakabe et al. 2012), and CO emission from the disk has been observed (Akaiyama et al. 2013).

We reduced the data observed in 2010 January with the spPDI+ADI mode and detected two sources at \( \sim 4'' \) and two sources at \( \sim 6'' \), which are not included in planetary-mass CCs because of their large separations.

4.3.34. HD 34282

HD 34282 is a Herbig Ae/Be star associated with the Orion Nebula Cluster. It has a large disk (Merín et al. 2004) with CO
emissions (Dent et al. 2005), whose image was previously resolved (Piétu et al. 2003). A recent study, published after our SEEDS observations for HD 34282, suggested that the disk is a transition disk (Khalfaiejad et al. 2016).

SEEDS observation was carried out in 2011 December with the sPDI+ADI and 0\".4 mask. We detected no companions within its FOV.

4.3.35. MWC 758

MWC 758 is a Herbig Ae/Be star in the Taurus SFR. This system has been known to have a transitional disk (Isella et al. 2010b) and CO emission in its disk (Dent et al. 2005). Grady et al. (2013) and Benisty et al. (2015) reported obvious asymmetric features and spiral arms, which can be caused by giant planets. Dong et al. (2015) discussed the potential exoplanets that may cause the asymmetric and arm features.

SEEDS observed MWC 758 in 2011 December with the sPDI+ADI plus 0\".4 mask and qPDI+ADI, and 2013 October with the qPDI+ADI mode. We analyzed these data and detected a point source at ~2\".5, which was concluded to be a background star by Grady et al. (2013). We did not detect any other CCs and finally exclude the possibility that there is an exoplanet with a mass higher than 16MJ outside 150 au.

4.3.36. CQ Tau

This Herbig Ae star in the Taurus association has a disk in which CO emission was reported (Dent et al. 2005). By investigating carbon chemistry of the disk, Chapillon et al. (2010) suggested that the disk of CQ Tau is most likely a transitional disk. Previous studies discussed the radial profile of the disk (e.g., Doucet et al. 2006; Trotta et al. 2013).

SEEDS observation were carried out in 2012 January with qPDI+ADI, in 2014 October with the sPDI+ADI+0\".3 mask, and in 2015 December with sPDI+ADI. We detected a point source at ~2\".2, and our CPM test revealed that this object is most likely a background star. We adopted the proper motions reported in Zacharias et al. (2012) (\(\mu\alpha = 2.2 \pm 0, 6,\mu\delta = -25.5 \pm 0.7 \text{ mas yr}^{-1}\)).

4.3.37. V1247 Ori

Previous spectral classifications of V1247 Ori range from F2 to A0 (e.g., Vieira et al. 2003; Kraus et al. 2013). V1247 Ori is a member of the Orion SFR and shows a dip around ~15\(\mu\)m in the SED, suggesting the presence of a transitional disk (Caballero 2010; Kraus et al. 2013). Kraus et al. (2013) discovered an asymmetric feature in the disk using the Very Large Telescope Interferometer, the Keck Interferometer, Keck-II, Gemini South, and IRTF.

SEEDS observations were conducted three times in 2013 November with the sPDI+ADI plus 0\".3 occulting mask, in 2014 January with qPDI+ADI, and in 2015 January with the ADI mode. We reduced these data and did not detect any CC. Since this object is located at 385 pc, our constraints do not allow us to discuss exoplanets within 100 au; our observations can constrain the mass of potentially existing objects of 33MJ at 100 au and 12MJ at 200 au.

4.3.38. TW Hya

TW Hya is the nearest system from the Earth of our whole targets. This T Tauri star is in the TW Hydrae moving group (e.g., Webb et al. 1999; Zuckerman et al. 2001; Brandt et al. 2014a), which is located at about 50 pc and is about 10 Myr old. The declination is very low (\(\delta < -30^\circ\)), making it relatively difficult to observe this moving group in high airmass. TW Hya has a transitional disk with active accretion reported by its SED (e.g., Calvet et al. 2002; Goto et al. 2012; Menu et al. 2014), and its disk has been resolved in various wavelengths (Krist et al. 2000; Weinberger et al. 2002; Qi et al. 2004). Detailed information of selection criteria is described in Akiyama et al. (2015). SEEDS also observed this system and revealed a multi-gap feature at 20 and 80 au (Akiyama et al. 2015).

We analyzed the same data as reported in Akiyama et al. (2015), which were taken in 2011 March and 2013 January with the qPDI+ADI mode. We did not detect any signal and set constraints on the detectable mass of the exoplanet of 16 and 3MJ at the inner and outer gaps. Akiyama et al. (2015) analyzed the HiCIAO polarized intensity images and estimated a mass of the potential planet that creates a gap structure to be lower than 0.7MJ according to the theoretical calculations of Jang-Condell & Turner (2012). Our results are consistent with the predictions of Jang-Condell & Turner (2012), but cannot set stronger constraints.

4.3.39. PDS 70

PDS 70 is a T Tauri star in the Centaurus group. The SED of this system implies a transitional disk (Metichev et al. 2004; Riaud et al. 2006), and Riaud et al. (2006) resolved a scattered-light disk around PDS 70 (detailed information is described in Hashimoto et al. 2012).

SEEDS observed this object in 2012 February with the qPDI+ADI mode and detected a gap feature (Hashimoto et al. 2012). This gap is ~70 au wide, and Hashimoto et al. (2012) discussed the possibility of multi-planet systems. We reduced the same data as mentioned above, detecting a point source at ~2\".2. Hashimoto et al. (2012) concluded that this source is a background star by combining their results of observations and those in Riaud et al. (2006). Thus we did not detect any CC. We estimated the detection limit of 16MJ at 70 au.

4.3.40. SAO 206462

SAO 206462 is a T Tauri star, sometimes called a Herbig F star, and a ~20\" virtual binary system (HD 153534; Augereau et al. 2001). The secondary star is outside the FOV of SEEDS observation. This object is in the constellation of Lupus. SAO 206462 has been predicted to have a gap from its SED feature (Brown et al. 2007), which was later confirmed by submillimeter imaging (Brown et al. 2009).

Muto et al. (2012) revealed spiral arms and an asymmetric feature using the SEEDS data, and also discussed potential planets by examining the disk geometry. The Submillimeter Array (SMA) and ALMA observations also revealed the inner gap (Brown et al. 2009; van der Marel et al. 2016). Dong et al. (2015) discussed the potential exoplanets that may cause the asymmetric features around SAO 206462, as well as MWC 758.

SEEDS observed this system in 2011 May with the sPDI+ADI and 0\".4 occulting mask. After the LOCI data reduction, we detected two point sources. Our identified sources are exterior to 400 au from SAO 206462. Furthermore, our observations are unable to detect a CC in the gap of disk because of the strong self-subtraction of LOCI-ADI reductions. Finally, we set an upper limit. Muto et al. (2012) predicted the positions of two potential exoplanets, one of which is in the software mask of LOCI.
however, and cannot be detected even if this planet truly exists. At 0\arcsec.9, ~130 au, where another potential planet could be located, the HiCIAO detection limit excludes the probability of planets larger than 3 $M_J$. This constraint agrees with the theoretical prediction of the planet mass (Muto et al. 2012).

4.3.41. HD 139614

This star is a Herbig Ae/Be star associated with the Lupus-Ophiuchus complex, with dust emissions in the SED (Meeus et al. 1998; Matter et al. 2014) that can be interpreted as a pre-transitional disk (Matter et al. 2014).

We reduced the data acquired in 2014 January with the sPDI +ADI and 0\arcsec.4 mask and detected two point sources at ~3\arcsec.5 separations. We also detected relatively low SN (~4–4.5) objects within 1\arcsec and need follow-up observation. Therefore we did not detect convincing CCs within 400 au.

4.3.42. GQ Lup

GQ Lup is a T-Tauri star in the Lupus SFR and has infrared excess with a MIR concavity (Dai et al. 2010). In this system, a companion (GQ Lup b) has been discovered by direct imaging (Neuhäuser et al. 2005). The mass estimate of GQ Lup b ranges from 1 to 60 $M_J$ (e.g., Neuhäuser et al. 2005; Seifahrt et al. 2007; Lavigne et al. 2009).

SEEDS observed this planetary system in 2013 May with both the qPDI+ADI mode and the sPDI+ADI mode plus a 0\arcsec.4 occulting mask. We confirmed the companion (see Figure 3 and Table 6). Our qPDI+ADI data reductions derived the separation and position angles of GQ Lup b to be $(\rho, \theta) = (0\arcsec.723 \pm 0\arcsec.012, 277\arcsec.38 \pm 1\arcsec.40)$. Our results did not deviate from the measurements in Neuhäuser et al. (2008), but had larger errors of position angle because the seeing was poor and the central star of the science frames is masked or strongly saturated. Neuhäuser et al. (2008) found that the separation between the companion and central star decreases by ~2–3 mas yr$^{-1}$ due to its orbital motion (Figure 2 (a) of Neuhäuser et al. 2008)). The extrapolation of the separation decrease calculated by Neuhäuser et al. (2008) is consistent with our data, which can help to constrain the companion’s orbital motion.

Our photometric estimation resulted in deriving the mass of GQ Lup b to be ~15–20 $M_J$. We also detected one more point source at 6\arcsec, but this object has been concluded as a background star (e.g., Neuhäuser et al. 2008). We also excluded the possibility of exoplanets more massive than 16 $M_J$ at 70 au.

4.3.43. HIP 77545

This Herbig Ae/Be star is a member of Upper Sco. Carpenter et al. (2009) detected an infrared excess at 24 \micron, but did not detect the excesses at 8 and 16 \micron.

SEEDS observations were made in 2012 May with sPDI +ADI and in 2014 January with ADI. We detected a point source at 3\arcsec.8 and two additional sources at the wider separations in the second data set. On the other hand, the first data set showed no point sources with significant SN ratios, and we need more follow-up observations. Given that this system is located at about 120 pc, we do not include these sources among CCs.

4.3.44. HIP 77911

HIP 77911 is a Herbig Ae/Be star in the Upper Sco association. Previous study has reported a debris disk (Carpenter et al. 2009; Mathews et al. 2013). This system was observed in 2012 May with the sPDI+ADI and in 2014 January with the ADI mode. We reduced the data and detected some point sources at separations larger than 4\arcsec (~600 au). We do not count them as CCs.

4.3.45. IM Lup

IM Lup is a T Tauri star in the Lupus association. The protoplanetary disk of IM Lup has been imaged from optical to radio wavelengths (Pinte et al. 2008; Panić et al. 2009). The surface density of the disk greatly changes at ~400 au (Panić et al. 2009).

IM Lup was observed in 2014 June with the qPDI+ADI mode. After the data reduction, we detected two companions at 2\arcsec and 2\arcsec.5. Mawet et al. (2012) has reported the point source closer to the central star as a background star by calculating its proper motion with VLT/NACO and HST/NICMOS data, but the more distant source has not been reported before, requiring more follow-up observations to clarify the parameters of this object.

4.3.46. HD 142527

HD 142527 is a relatively bright Herbig Ae/Be star in the constellation of the Lupus association. Some studies have reported the gap and asymmetric structure of the disk in this system (e.g., Fukagawa et al. 2006; Verhoeff et al. 2011; Fukagawa et al. 2013; Avenhaus et al. 2014). The possibility of companion existences was examined by Biller et al. (2012).

SEEDS observed HD 142527 in 2011 May with the sPDI+ADI combined with the 0\arcsec.4 mask and in 2012 April with the sPDI+ADI mode. We detected two high-S/N point sources and one marginally detected source in each data set, which are located at distances larger than 550 au. Therefore we exclude them from the list of CCs. Furthermore, we estimated the upper limit of the detectable companion mass to be 20 $M_J$ at 50 au.

4.3.47. RX J1603.9-2031A

This T Tauri star is one of a ~4\arcsec binary system in the Upper Sco association (Köhler et al. 2000) and shows an infrared excess (Carpenter et al. 2009; Mathews et al. 2013).
SEEDS images taken in 2012 July with qPDI+ADI detected no CCs and set an upper limit of the potential exoplanet of 5 $M_J$ at 50 au from the central star.

4.3.48. RX J1604.3-2130A

RX J1604.3-2130A (USco J1604) is a T Tauri star of the Upper Sco association and has an SED indicative of transition disk (Dahm & Carpenter 2009). This transition disk shows a gap feature revealed by SMA and Subaru (SEEDS) (Mathews et al. 2012; Mayama et al. 2012). Mayama et al. (2012) reported an arc-like structure inside the ring of RX J1604, at the west side of the star. This structure is now suspected to be an artifact.

We reduced HiCIAO data observed in 2012 April with the qPDI+ADI mode; they have been used by Mayama et al. (2012). We did not detect any CC and set the detection limit of the mass of potentially existing exoplanet as 5.5 $M_J$ at 50 au.

4.3.49. SZ 91

This T Tauri star is a member of the Lupus molecular cloud (Hughes et al. 1994) with a transitional disk (e.g., Merín et al. 2008; Romero et al. 2012). Tsukagoshi et al. (2014) also used the HiCIAO data and spatially resolved the inner ($r \sim 65$ au) and outer ($r \sim 170$ au) disks.

We used the same data as reported by Tsukagoshi et al. (2014), which were taken in 2012 May with the sPDI+ADI mode. As a result, we detected two point sources at $\sim 4''2$ and $\sim 9''$. We do not count them in our CC list and set an upper limit of 6.5 $M_J$ at 70 au.

4.3.50. HIP 78996

This Herbig Ae/Be star associated with the Upper Sco association has a debris disk (Carpenter et al. 2009; Mathews et al. 2013).

SEEDS observations were carried out in 2011 May with the sPDI+ADI+$0''4$ mask and in 2013 May with sPDI+ADI. We detected a point source at $3''5$ from the primary star. Our CPM test indicates that this object is most likely a background star. For the proper motion test, we used the proper motions reported in Zacharias et al. (2012) ($\mu_{\alpha} = -11.8 \pm 0.9$, $\mu_{\delta} = -23.2 \pm 0.9$ [mas yr$^{-1}$]).

4.3.51. V1094 Sco

This T Tauri star in the Lupus association has a full disk (Tsukagoshi et al. 2011; Bustamante et al. 2015).

We reduced the data taken in 2011 May with the sPDI+ADI+$0''4$ mask and detected five point sources at $5''5$–$9''$ ($\sim 850$–$1400$ au). The outer radius of the disk was estimated to be $320$ au (Tsukagoshi et al. 2011); we therefore do not discuss the possibility of a companion for these sources.

4.3.52. HIP 79462

HIP 79462 is a T Tauri star in the Upper Sco association. This system has a debris disk (Carpenter et al. 2009; Dahm et al. 2012).

SEEDS observed HIP 79462 three times with only the ADI mode in 2012 April, 2014 April, and 2015 April. We detected a companion, HIP 79462B (see Figure 4 and Table 6) at $(\rho, \theta) = (0''648 \pm 0''013, 3''35 \pm 1''07)$; these values are derived from 2012 April data. The $H$-band contrast is $4.2 \pm 0.3$ magnitudes; this gives an absolute $H$-band magnitude of $5.9 \pm 0.3$ assuming a distance of $142$ pc and an $H$-band magnitude of $7.43 \pm 0.07$ for the primary (Cutri et al. 2003; Skrutskie et al. 2006). We have no measurements of the companion’s color. The COND03 and solar-metallicity BT-Settl models at an age of 10 Myr (Baraffe et al. 2003; Allard et al. 2011) give an effective temperature of $\sim 3200$ K and a mass of $0.2 M_\odot$, well above the minimum mass for hydrogen ignition. Pecaut & Mamajek (2013) list a spectral type of M4 at $T_{\text{eff}} = 3200$ K.

4.3.53. HIP 80088

HIP 80088 is a Herbig Ae/Be star in the Upper Sco association. Its SED indicates the presence of a debris disk (Carpenter et al. 2009; Mathews et al. 2013).

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**Table 6**

Detected Companions in This Study

| HD Name | Other Name | $\Delta H$ (mag) | Separation | Position Angle | Date (HST) and Method |
|---------|------------|-----------------|------------|----------------|-----------------------|
| ...     | GQ Lup     | $6.7 \pm 0.3$   | $0''723 \pm 0''012$ | $277''38 \pm 1''40$ | 2013 May 17, qPDI+ADI |
| 145655  | HIP 79462  | $4.2 \pm 0.3$   | $0''648 \pm 0''013$ | $3''35 \pm 1''07$ | 2012 Apr 11, ADI      |
| ...     | ROXs 42B   | ...            | $1''14 \pm 0''004$ | $269''7 \pm 0''17$ | 2014 June 8, ADI      |

**Notes.**

* This system was observed in $Y$ band.

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**Figure 4.** Subaru/HiCIAO $H$-band image of a companion around HIP 79462 taken in 2014 April. The central star is masked. North is up and east is left.
This object was observed twice in 2012 July using ADI-only and the sPDI+ADI mode. We detected two point sources at ~8″ and 10″, but do not include them in our CC list because of their wide separations.

4.3.54. IRAS 16225-2607

This T Tauri star is a member of the Ophiuchus SFR. The previous study reported an SED that appears to be a transitional disk SED (Furlan et al. 2009). Furlan et al. (2009) did not report a stellar companion in this system, but Elliott et al. (2015) and Ansdell et al. (2016) reported a stellar companion at ~0″9.

The SEEDS observation was made in 2012 November with the qPDI+ADI mode. We detected the same source at ~1″0 separation as reported by Elliott et al. (2015). Photometric result showed that this object is more massive than a brown dwarf (∆H ~ 1 mag). Another point source was detected, which is located at 1′′5 from the central star and near the bright stellar companion, and was therefore possibly affected by the companion. We need follow-up observations for this source.

4.3.55. DoAr 25

DoAr 25 is a T-Tauri star in the constellation of Ophiuchus, and its SED indicates that it is a less evolved version of a transitional disk (Andrews et al. 2008).

We reduced the two data sets taken in 2012 May with the qPDI+ADI mode and in 2014 January with the ADI mode. We did not detect any signal in the first data, but detected a CC in the second data set. This object is separated by 4′′5 from the central star, and we thus assume that this is not a substellar companion. Our calculated contrast excludes the possibility of exoplanets more massive than 11MJ at 70 au.

4.3.56. HD 148040

This T Tauri star is a member of the Upper Sco association. This system has a 24 μm excess but lacks a 70 μm excess (Chen et al. 2005, 2011).

HiCIAO images were taken in 2012 May with the sPDI +ADI and in 2015 April with the ADI mode. We detected a point source at ~3′9, but the CPM test revealed that this object is a background star. We used the proper motions reported in Zacharias et al. (2012) (μα sin i = −11.4 ± 1.4, μδ = −22.0 ± 1.0 [mas yr⁻¹]).

4.3.57. DoAr 28

DoAr 28 is a T Tauri star associated with the ρ Ophiuchus association. This system has a transitional disk with an asymmetric and a hook feature (McClure et al. 2010; Rich et al. 2015). A CC discovered at ~1″ was concluded to be a background star using the SEEDS data (Rich et al. 2015).

We reduced the same data as Rich et al. (2015) taken in 2012 May and 2014 January with the qPDI+ADI mode. We detected the CC and conducted the CPM test, confirming this object to be a background star.

4.3.58. SR 21

SR 21 is a T Tauri star of the Ophiuchus SFR and is classified as one of a ~6′′4 binary system (Prato et al. 2003). This disk has a transitional disk feature and a cavity identified by the SED data and submillimeter observations (Andrews et al. 2009; Brown et al. 2009; Furlan et al. 2009; Pérez et al. 2014; van der Marel et al. 2016). Nevertheless, Follette et al. (2013) reported no cavity in the NIR scattered-light image.

For SEEDS observation, SR 21 was observed in 2011 May with the qPDI+ADI mode. We reduced this data set and detected a feature like a point source, which has an SN ratio of 4.5. However, there are the remnants of spiders in the final image, and this source is detected near these remnants. Therefore we assume that this signal is very likely effected by the spiders. We also ruled out possible exoplanets smaller than 11MJ at 70 au.

4.3.59. Oph IRS 48

Oph IRS 48 is a Herbig Ae/Be star associated with the Ophiuchus SFR. The disk of its system shows a gap feature (Brown et al. 2012), which may originate from a companion (van der Marel et al. 2013, 2014).

We reduced the SEEDS data taken in 2013 March with the qPDI+ADI mode and did not detect any signal. We then set upper limit of 30MJ at 50 au.

4.3.60. ROXs 42B

ROXs 42B is a T Tauri star in the ρ Ophiuchus SFR. This system has a companion ROXs 42B b and a CC “c” (Currie et al. 2014b). We follow the expression of “c” in Currie et al. (2014b) because Kraus et al. (2014) and Currie et al. (2014a) independently argued that this object is very likely a background star.

SEEDS observed ROXs 42B in 2014 June with the ADI mode. We reduced the data and confirmed companions b and “c” (see Figure 5 and Table 6). They are located at (ρ, θ) = (1814 ± 0.004, 269.7 ± 0.17) and (0°55 ± 0°006, 228°7 ± 0°64), respectively. Our results will help discuss the orbital motion of the companion. However, there were no reference frames in this observation, and these errors may be underestimated. This follow-up observation after Currie et al. (2014b, 2014a) was conducted in Y band (~0.97–1.07 μm), which is different from the typical HiCIAO imaging band. Therefore we use this data set as confirmation of the companion and do not discuss the detection limit.

Figure 5. Subaru/HiCIAO Y-band image of a companion around ROXs 42B taken in 2014 June. The central star is masked. North is up and east is left.
ROX 44 is a T Tauri star associated with the Ophiuchus SFR. This system has a (pre-)transitional disk (Andrews et al. 2009; Espaillat et al. 2010).

We analyzed SEEDS data taken in 2011 May with the qPDI+ADI and 2012 May with the sPDI+ADI mode. We detected a point source at ∼2那儿 in the first-epoch data. In the second-epoch data, this CC is located at the inner region where self-subtraction is significant. We conducted the classical ADI data reduction (Marois et al. 2006) with the second data to avoid self-subtraction, but did not detect the candidate. We also have trouble creating the fits header at the first-epoch data, in which the angular offset was mistakenly recorded. Thus we had to assume the offset from the other parameters in the header. We used HST/WFC3 data taken in 2014 October to check the proper motion. We subtracted the 180那儿 rotated image from the original image and confirmed a point source at a similar position. The PSF of the central star is heavily saturated, making the centroid measurements uncertain. Because of the large uncertainties and the trouble in our fits header, we still include this object in our CCS, and we need the more follow-up observations. We finally set the lower limit for the detectable mass of potential companions to be 3 $M_J$ at 70 au.

4.3.62. RX J1633.9-2442

This T Tauri star is a member of the Ophiuchus molecular cloud and has a transitional disk (Cieza et al. 2010, 2012; Orellana et al. 2012).

SEEDS observed this object in 2014 April with the qPDI+ADI mode and detected no CCS in its FOV. We then estimated the detection limit to be 9 $M_J$ at 50 au.

4.3.63. HD 169142

HD 169142 is a Herbig Ae/Be-type relatively bright star isolated from SFRs (Dent et al. 2006). We therefore adopt the stellar parameters that have been individually estimated for HD 161492 itself (see Table 5). The disk of HD 169142 has a gap (Grady et al. 2007; Quanz et al. 2013b) and an asymmetric feature (Quanz et al. 2013b), as well as a CC (Reggiani et al. 2014).

### Table 7

| HD Name | Other Name | Separation | Position Angle | Date (HST) |
|---------|------------|------------|----------------|------------|
| 36910   | CQ Tau     | 2那儿 ± 0那儿 | 53那儿 ± 0那儿 | 2012 Jan   |
| 144587  | HIP 78996  | 3那儿 ± 0那儿 | 21那儿 ± 0那儿 | 2013 May   |
| 148040  | HIP 80535  | 3那儿 ± 0那儿 | 17那儿 ± 0那儿 | 2015 Apr   |
| 169142  |            | 2那儿 ± 0那儿 | 3那儿 ± 0那儿 | 2011 May   |

### Figure 7

Vertical and horizontal axes are the $\Delta \alpha$ and $\Delta \delta$ of the companion candidates relative to their first-epoch positions. The number represents objects 1, 2, 3, and 4 as labeled in Figure 6. The red square plots correspond to the predicted positions of background stars at the second epoch. If the companion candidates are background stars, then their $\Delta \alpha$ and $\Delta \delta$ changes along with the blue curves, on which the green triangle plots indicate the predicted positions of background stars at the second epoch.

SEEDS observations were conducted in 2011 May and 2013 May with the sPDI+ADI plus a 0那儿 mask. The PDI data reduction detected a gap and an asymmetric feature in its disk (Momose et al. 2015). On the other hand, SEEDS images cannot discuss the reported CC, which is located within the occulting mask. Other than this CC, we detected many other CCSs (see Figure 6). HD 169142 is located within the Sagittarius constellation, and there are many background stars. We then select signals within 400 au from all detected sources, which resulted in six CCSs in the data from 2011 May. However, only four candidates of these objects were detected in the follow-up observation in 2013 May. Then we executed a CPM test for the four CCSs; their separations and position angles are listed in Table 7. Figure 7 shows the results of the CPM test. The first observation did not take a position reference frame, and we may underestimate errors. We consider them to be background stars because they move so fast and similarly. The difference can be explained by their proper motion and parallax. We assumed a proper motion of $(\mu_\alpha, \mu_\delta) = (-3那儿 ± 1那儿, -3那儿 ± 1那儿)$ [mas yr$^{-1}$] (Zacharias et al. 2012). The two objects remaining without the proper motion tests will be investigated with the next follow-up observations. For the
detection limit, we constrained the mass of potential companions to 16.5 \,M_J at 50 \,au.

4.3.6. MWC 297

This Herbig Ae/Be star belonging to the Serpens-Aquila SFR has a (pre-)transitional disk (Malbet et al. 2007; Rumble et al. 2015). We adopted the distance and age of this YSO from the typical value of the SFR (see Table 5; Kaas et al. 2004).

HiCIAO images taken in 2012 July with the sPDI+ADI mode detected two CCs at the separations of \(\sim 3''\) and \(\sim 3''\,4\) (>750 au). We do not include them in exoplanet candidates because of their large separations. We achieved a contrast of \(10^{-5}\) at 1'', but we were not able to attain good enough detection limits to detect a planetary-mass companion within 400 au because the central star is too bright.

...
3.6. RX J1842.9-3532
RX J1842.9-3532 is a T Tauri star associated with the CrA molecular cloud complex and has a transitional disk (Hughes et al. 2010).

We used the HiCIAO data observed in 2012 September with qPDI+ADI and detected no CCs in its FOV. We then constrain the mass of possible exoplanets to 11.5 $M_J$ at 50 au.

3.6.6. RX J1852.3-3700
RX J1852.3-3700 is a T Tauri star in CrA and has a transitional disk (Hughes et al. 2010).

A SEEDS observation was conducted in 2011 September with the sPDI+ADI mode. We detected six CCs; only one of them is within 3" (~400 au), and we exclude that the other five point sources are CCs. This CC also needs follow-up observation to determine whether it is a companion or background object. For the detection limit, we set the mass limit of substellar companions to be 6.5 $M_J$ at 50 au.

4.3.7. HD 179218
HD 179218 is an isolated Herbig Ae/Be star and located at 240 pc from the Sun. The SED has an IR excess that seems to have a disk with an inner polar cavity (Elia et al. 2004; van der Plas et al. 2008). Liu et al. (2007) resolved its disk and suggested that the disk has an inner hole.

The HiCIAO data of this object were taken in 2012 September with the sPDI+ADI mode. The disk is detected within 550 au. We assume that these point sources are background stars or stellar companions. The inner part of 2″/3 (~550 au) is masked because of the insufficient rotation angle, and thus we cannot derive the detection limit within 400 au.

4.3.8. HIP 103763
HIP 103763 is a triple system in the Cepheus complex. The primary and secondary stars constitute the spectroscopic binary, and the separation between each component is 15 mas (e.g., Millan-Gabet et al. 2001; Okamoto et al. 2009). In addition, the third component is separated by ~6″ from the primary (Li et al. 1994). The primary star has a flare disk that extends to ~1000 au (Okamoto et al. 2009).

A HiCIAO observation was conducted in 2011 September with the sPDI+ADI+0′′.4 mask. We confirmed the bright star at ~3″, which can be a background object or the third companion.

5. Results and Discussion of Total Data

5.1. Companion Candidates

We confirmed two convincing low-mass companions at ~100–150 au out of 68 YSOs. The frequency is computed to be 2/68, corresponding to a probability of ~2.9% for the substellar companions with masses between 1 and 70 $M_J$ and projected separations between 50 and 400 au.

We note that the estimate of the detection frequency of substellar companions is very preliminary, since our calculation ignored several factors that are needed in the statistical discussion, such as the differences of detection sensitivities and the orbital parameters of companions. To statistically improve these problems in the analysis of the frequency of substellar companions, a Bayesian analysis should be useful (e.g., Lafrenière et al. 2007; Biller et al. 2013; Brandt et al. 2014b). We will describe the statistical framework of Bayesian analysis in a forthcoming paper.

5.3. Comparison with Previous Surveys

5.3.1. Surveys for Nearby Young Stars

In addition to SEEDS, there are some planet-finding programs that targeted more nearby and relatively older targets than are found in SFRs, such as stars in young moving groups. The Gemini Deep Planet Survey (Lafrenière et al. 2007) observed 85 nearby stars with ages <6700 Myr and distances <100 pc. This survey obtained 5σ H-band detection limits of 9.5 mag at 0″/5, 12.9 at 1″, 15.0 at 2″, and 16.5 at 5″, which are deep enough to detect companions more massive than 2 $M_J$ with projected separations ranging from 40 to 200 au. The Gemini NICI Planet Finding survey (Biller et al. 2013) carried out high-contrast imaging of 80 nearby stars with ages younger than several hundreds of Myr. They achieved 5σ completeness detection limits of 10.7, 13.5, and 15.4 mag at 0″/5, 1″, and 2″, which are estimated from detection limits with a 95% threshold reported in Biller et al. (2013) by using Equation (1) in Brandt et al. (2014b). The VLT/Naco Large Program (Chauvin et al. 2015) observed solar-type targets with distances smaller...
than 100 pc and ages younger than 200 Myr, leading to typical contrasts of \( \sim 10 \), 12, and 13 mag at 0\(^{\prime}\)5, 1\(^{\prime}\), and 15\(^{\prime}\), respectively. Other direct imaging surveys for stars older than YSOs (\( \sim 10–5000 \) Myr) are also summarized in Chauvin et al. (2015). Our observations targeted YSOs, not nearby young stars, and our results are useful for comparisons with those older than YSOs.

The International Deep Planet Survey (Galicher et al. 2016) explored 292 young nearby stars with a median age of 100 Myr and a median distance of 37 pc. This research achieved typical 5\(\sigma\) detection limits of \( \sim 12.5 \pm 2.5 \) mag at 1\(^{\prime}\) in H, CH4, K, and \( L_p \) bands.

The roughly estimated probability of substellar companions derived in Section 5.2 can be compared with the probability of previous surveys around older stars. Brandt et al. (2014b) performed a statistical analysis for the high-contrast data taken by the SEEDS and other teams. The statistical analysis for the sample of \( \sim 250 \) nearby stars including many young stars in moving groups suggests that 1.0\%–3.1\% (68\% confidence) or 0.92\%–11\% (95\% confidence) of the stars host substellar companions with masses of 5–70\( M_J \) between 10 and 100 au (Brandt et al. 2014b). Our tentative results apparently agree with this conclusion. The main difference between our study and the study of Brandt et al. (2014b) is the age range and separation range; this difference can be useful for discussing a formation rate of substellar companions and their possible orbital evolutions. If the statistical analysis for YSOs were to disagree with those of older stars such as reported by Brandt et al. (2014b), this disagreement would arise from different conditions in the planet formation or evolution mechanism.

5.3.2. YSO Surveys

Thomas et al. (2007) observed 72 Herbig Ae/Be stars with Gemini/Altair-NIRI and VLT/NACO. Thomas et al. (2007) detected some companions, including brown dwarfs, but gas giant exoplanets were not detected. They achieved K-band detection contrasts of \( 10^{-2.4} \) at 0\(^{\prime}\)5 and \( 10^{-7} \) at farther than 2\(^{\prime}\); our obtained contrasts are much higher than theirs. The number of our targets is comparable with those of Thomas et al. (2007). Metchev & Hillenbrand (2009) conducted a Paloma/Keck AO survey around 266 F5–K5 stars between 3 Myr and 3 Gyr and between 10 and 190 pc, \( \sim 30 \) targets of which are YSOs. They statistically derived the frequency of brown dwarfs (0.012–0.072\( M_J \)) to be 3.2\( \pm 0.3\% \) (2\(\sigma\) confidence). Fukagawa et al. (2010) observed 16 Herbig Ae/Be stars with Subaru/ CIAO and obtained a 2\(\sigma\) H-band contrast of \( \sim 9.5 \) mag at 2\(^{\prime}\) and \( \sim 12 \) mag beyond 4\(^{\prime}\). SEEDS provides better contrast limits and more YSO (including T Tauri stars) observations than in Fukagawa et al. (2010). Kraus et al. (2008, 2011) have conducted AO-aided high-resolution imaging surveys at Taurus and Upper Sco with the Keck/NIRC2 and Paloma/PHARO observatories to reveal the brown dwarf frequency. The typical detection limit of these studies are above the deuterium-burning limit, except that the detection limits for some YSOs can constrain an exoplanet with a mass of a few\( M_J \).

As described above, detecting planetary-mass objects near YSOs was very difficult because of the inadequate contrasts at small separations. Although the targets of Kraus et al. (2008, 2011) overlap with ours, this study is the first large-scale and systematic exploration of exoplanets around YSOs. Although our detection limits still need to be updated, their youth enables us to constrain the mass of detectable exoplanets up to a few Jovian masses.

6. Summary

The SEEDS project completed the main survey of exoplanets and disks around more than 400 targets. Of these targets, we reduced and analyzed 99 SEEDS/YSO data sets for exoplanet exploration. Our exploration provides the first large-scale and systematical analysis that achieves a high enough contrast to detect young exoplanets, and it uses the largest sample of any YSO exoplanet survey to date. YSOs often have protoplanetary disks in which planets are being formed. The SEEDS project adopts the PDI technique combined with the ADI technique, which are effective for detecting both disks and exoplanets around YSOs.

We discovered 15 new point sources within 400 au around 68 YSOs; 7 of these are identified to be background stars, 1 is identified to be a stellar companion, and 1 is either a stellar companion or a background star. We will aim at follow-up observations of the remaining 6 CCs to conduct their CPM tests. We also confirmed 2 companions that have been reported previously: GQ Lup b and ROXs 42B b. LKCa 15 b, c and HD 169142 b are not detected in this research. We estimated 5\(\sigma\) detection limits of contrast as a function of separation angle, which are transformed into detection limits in mass based on the properties of the observed YSOs (see Table 5) and the COND03 models. As a result, we typically achieved contrasts of \( 10^{-3.3} \) at 0\(^{\prime}\)5, \( 10^{-4.6} \) to 5\(^{\prime}\) at 1\(^{\prime}\), and 0\(^{\prime}\)4–3\(^{\prime}\)6 beyond 2\(^{\prime}\). We can also determine the typical upper limits of potentially existing exoplanets to be \( \sim 10 M_J \) at 0\(^{\prime}\)5 and \( \sim 6 M_J \) at 1\(^{\prime}\).

Since previous studies calculated the frequency for older exoplanets than we did (e.g., Brandt et al. 2014b; Chauvin et al. 2015), our study will help compare the results of imaging surveys that targeted different ages.

Furthermore, we expect the next “extreme” AO system such as Gemini/GPI (Macintosh et al. 2006), VLT/SPHERE (Beuzit et al. 2006), and SCExAO (Guyon et al. 2010) to reveal the relationship between giant exoplanets and disk features by exploring the gap region in protoplanetary disks.

The authors thank David Lafrenière for generously providing the source code for the LOCI algorithm. The authors would like to thank the anonymous referees for their constructive comments and suggestions that improved the quality of the paper. This research is based on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatories of Japan. Based in part on data collected at Subaru telescope and obtained from the SMOKA, which is operated by the Astronomy Data Center, National Astronomical Observatory of Japan. We also acknowledge the SDPS project for our use of the CIAO archival data. Some/all of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts. Data analysis were carried out on common use data analysis computer system at the Astronomy Data Center, ADC, of the National Astronomical Observatory of Japan. This research has made use of NASA’s Astrophysics Data System.
