Mem. S.A.It. Vol. 84, 992

Memorie della

Brown dwarfs and planets

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Abstract. The connection between brown-dwarfs and planets and the definition of giant planets themselves have been a matter of debate for more than a decade now. We summarize our current understanding of their respective formation mechanisms and associated physical properties. We then address the question of planetary formation around brown-dwarfs. Signs of disk evolution (accretion, outflows, grain growth) for young brown-dwarfs suggest that planetary formation may be on-going in the substellar regime. In this context, we report recent results of surveys targeting brown-dwarfs and very low mass stars to search for planetary mass companions and ultimately planets, using various observing techniques (imaging, radial velocity, microlensing, and astrometry). We also highlight the technical and observational challenges of observing such faint targets. Finally, we conclude with the perspectives offered by the new generation of telescopes and instruments in the coming years.

Key words. Brown-dwarfs, Planets: formation, detection, characterization.

1. Introduction

1.1. Planets versus brown-dwarfs

Brown-dwarfs (BDs) are "objects with true masses above the limiting mass for thermonuclear fusion of deuterium" ($M \sim 13M_{\rm Jup}$ for objects of solar metallicity), "no matter how they formed nor where they are located." Boss et al. (2003). Since the discovery of the first genuine brown-dwarfs (Rebolo et al. 1995; Nakajima et al. 1995), several hundreds of substellar objects have now been discovered free-floating, orbiting stars, or as part of multiple systems (binaries, hierarchical systems). Multiple formation pathways have been proposed for these objects: 1/ turbulent fragmentation of molecular clouds (Padoan & Nordlund 2004; Hennebelle & Chabrier 2008, 2009), 2/ premature ejection of protostellar embryos (Bate et al. 2002; Goodwin et al. 2004), 3/ photo-erosion of prestellar cores (Hester et al. 1996; Whitworth & Zinnecker 2004), 4/ and disk fragmentation (for example Stamatellos & Whitworth 2009). Recent discoveries of extremely light BDs by the WISE survey (Beichman et al. 2013) even confirmed that, in terms of masses, BDs and exoplanets overlap introducing difficulties to distinguish them.

Several criteria have been tentatively introduced to define BDs and exoplanets. The current drawing line, defined by the International Astronomical Union (Boss et al. 2003), is

Send offprint requests to: M. Bonnefoy based solely on the limiting mass for the ignition of deuterium. This limit originates from the obsolete stellar formation scenario of Shu et al. (1987). Twenty five year later, there are no doubts that stellar formation mechanisms can form isolated objects of a few Jupiter masses. Theoreticians rather tend to discriminate the two classes of objects based on their formation scenario (Chabrier et al. 2007). In this scheme, planets are mainly formed by nucleated instability within a disk (Pollack et al. 1996; Alibert et al. 2004, 2005). This mechanism involve the formation of core of solids, originating from the accretion of refractory material present in the disk. Once the core has reached a critical mass, a runaway phase starts where the planet acquires a gaseous envelope from the surrounding disk material. This mechanism is associated with longer timescales than the disk fragmentation scenario or other stellar mechanisms described earlier. Deuterium-burning phases have even been proposed for planets formed by nucleated instability (Mollière & Mordasini 2012; Bodenheimer et al. 2013).

However, from the observational point of view, it can be extremely difficult, even impossible, to access the history of formation of these astrophysical objects. Consequently, these definitions are still highly debated and differently interpreted in the community. Alternative definition as the ability for fusion have been proposed to distinguish planets from BDs (Basri & Brown 2006), but no clear consensus has emerged. In the following, and for clarity, we adopt the following wording: "planetary mass objects", or planetary mass companions (PMC), if bound to a star, for objects with *true or measured* masses, below 13.6 $M_{\rm Jup}$. More massive objects will be called BDs.

1.2. Planets around brown-dwarfs

Low-mass stars and brown-dwarfs account for over 80 % of the stellar content of the Galaxy. While these stars might bear the "typical" planetary systems, little is known on the formation of planets around these objects. It is now established that young BDs, with masses down to the planetary mass regime, can be surrounded by circumstellar disks (Natta & Testi 2001; Natta et al. 2002; Testi et al. 2002; Scholz & Jayawardhana 2008; Luhman et al. 2005a,b, 2008, 2010). Brown dwarf can undergo a T Tauri-like phase during their early evolution, that involves accretion phases (Jayawardhana et al. 2003; Natta et al. 2004; Herczeg et al. 2009), and outflows (Whelan et al. 2007). Significant fundamental differences might however remain with respect to the early evolution of the star+disk system. Disks may have a lower mass than those surrounding stars (Klein et al. 2003; Scholz et al. 2006; Mohanty et al. 2013) and survive longer than around solar-mass stars (Carpenter et al. 2006; Dahm & Hillenbrand 2007; Scholz et al. 2007). Although Pinilla et al. (2013) showed that rapid inward drift is more significant for particles in BD disks than in T-Tauri disks, thus making planet formation by core-accretion more challenging. Observations of BD disks at millimeter-wavelengths have nevertheless evidenced fast ($<$ 1 Myr) grain growth processes, up to millimeter sizes in the outer portion of the disks (Bouy et al. 2008; Ricci et al. 2012, 2013). There is therefore no current reason to think that planetary formation is not on-going around BDs.

In this context, we review in the next section the results obtained by various observing techniques to search for the presence of companions to BDs.

2. Observational search

BD companions and exoplanets have been actively studied using indirect techniques (radial velocities, microlensing, transit search and astrometry) sensitive to the close circumstellar environment ($\leq$ 5–10 AU), and more recently direct imaging, unique to probe larger separations ($\geq$ 5–10 AU). Initially targeting solar-type stars, these surveys have recently extended to the lower end of the stellar mass function to study the environment of very low-mass stars (VLMS) and BDs. The existence of PMCs have been revealed around BDs by radial velocity, microlensing and direct imaging surveys, setting new constraints for the models of stellar and planetary formation. Specific transit searches for planets orbiting BDs or VLMS (Martín et al. 2013) have been conducted. They however remain very challenging owing to the host faintness at optical wavelengths. The observations, even if conducted in the near-infrared (Blake et al. 2007, 2008), e.g. at wavelengths where the sources are brighter, can still be biased by the Earth atmospheric extinction (Bailer-Jones & Lamm 2003), the brown dwarf intrinsic variability due to heterogeneous cloud coverage and magnetic activity (Lane et al. 2007; Berger et al. 2009; Koen et al. 2005; Radigan et al. 2013), and uncertainties in the predicted radii for brown-dwarfs (Mathieu et al. 2007). In this review, we will summarize the main results obtained so far to search for low-mass companions to BDs in the context of classical multiplicity study or specific search for exoplanets around BDs. In Section 2.1, we describe the results of RV surveys, in Section 2.2 obtained during microlensing campaigns, in Section 2.3 with astrometry and in Section 2.4 with direct imaging.

2.1. Radial velocities

The search for companions to VLMS and BDs has been originally initiated to study the frequency of multiple systems in VLM binaries, a fundamental property to characterize their mechanisms of formation. Following the first identification of a brown-dwarf binary (Martín et al. 1999), a large number of surveys were performed in imaging and showed that VLM binaries are rarer (f_{Bin} ~10–30%), more closely separated (distribution peaked at 3–10 AU) and more frequently in near-equal mass configuration than their higher mass stellar counterparts (Reid et al. 2001; Bouy et al. 2003; Burgasser et al. 2003, 2007; Allen 2007). These surveys were however not sensitive to physical separations closer than 3 AU in the field or 10 AU in open clusters. They were also typically limited to mass ratio higher than $q > 0.5$, i.e not capable of exploring the presence of planetary mass companions. Separations of less than 3 AU were scrutinized with dedicated RV observations. The first spectroscopic BD/VLM binary PPl 15, member of the Pleiades open cluster, was discovered by Basri & Martín (1999). Several spectroscopic surveys followed in young clusters (Joergens & Guenther 2001; Kenyon et al. 2005; Kurosawa et al. 2006; Prato 2007; Maxted et al. 2008) and in the field (Reid et al. 2002; Guenther & Wurchtel 2003; Basri & Reiners 2006; Burgasser et al. 2009; Blake et al. 2010; Rodler et al. 2012), but with a limited number of detection (Zapatero Osorio et al. 2004; Stassun et al. 2006; Joergens & Müller 2007). The lowest mass companion was found around the BD candidate Cha Hα 8 of the nearby Chamaeleon I star forming region (SFR) (Joergens & Müller 2007; Joergens et al. 2010). With a predicted mass of 16-20 $M_{\rm Jup}$, the mass ratio drops to $q \sim 0.2$ and a separation of $\sim$ 1 AU. More generally, the determination of the binary frequency of very young BDs at less than 3 AU in the same SFR showed that it does not differ from the rate at larger separations observed in the field and open clusters. It remains consistent with an overall frequency of 10–30% (Joergens 2008). Despite the progress of high-resolution spectrographs, the faintness of these targets forbids the sensitivity of current RV survey to reach low-mass ratio binaries ($q < 0.1$), i.e to access PMCs around BDs. Current RV surveys of M dwarfs find a very low frequency of giant planets ($f < 2\%$) compared to telluric planets ($f \sim 35\%$) (Bonfils et al. 2013). The putative population of planets around BDs is likely out of reach of current instrumentation. Future high resolution spectrographs working in near-infrared wavelengths like CARMENES/Cal. Alto (Quirrenbach et al. 2012) or SPIROU/CFHT (Micheau et al. 2012) will help extending current searches to study the signs of planetary formation around BDs.

2.2. Microlensing

The microlensing technique relies on the magnification of the light caused by the gravity of a lens object, located between a background star and an observer. Microlensing is suitable to detect faint objects such as (cold and faint) brown-dwarfs (Paczyński et al. 1986) down to planetary mass objects (Sumi et al. 2011), since the magnification effect occurs regardless of the lens intrinsic brightness. It is also able to detect low mass systems, with separations (< 1 AU), e.g. midway between those of system detected by radial velocity surveys and of planetary mass companions detected by direct imaging. Microlensing provide a measurements of the component masses and of the distance of the components. Mass measurements do not require a proper modeling of the evolution of the main properties of the detected objects, like it is the case for direct imaging detections (see section 2.4).

Recently, Choi et al. (2013) and Han et al. (2013) reported the first, and so far the only, detections of three tight pairs, composed of a low mass brown-dwarf and of a planetary mass object OGLE-2009-BLG-151/MOA-2009-BLG-232, OGLE-2011-BLG-0420, and OGLE-2012-BLG-0358Lb. These systems have remarkable properties: their total mass is extremely low (0.024-0.031 $M_{\odot}$) – and can fall in the same range as some of directly imaged systems (2MASS J04414489+2301513, 2M1207 b) – while they remain very tight (0.2-0.9 AU). As a consequence, they occupy a peculiar location with respect to pairs of field dwarfs in diagrams representing the gravitational binding energy versus the total system mass (see Figure 5 of Choi et al. 2013). Their binding energy is also one to three order of magnitudes higher than those of widely separated systems with similar total masses discovered by direct imaging. The mass ratio of OGLE-2009-BLG-151/MOA-2009-BLG-232 and OGLE-2011-BLG-0420 suggest that they might have formed via classical formation mechanisms of stellar binaries (Bate et al. 2012). The lower mass ratio of the system component of OGLE-2012-BLG-0358Lb indicate that the lower component of this system might have been formed by instability of the primordial disk surrounding the most massive component of the system.

A large number of similar systems are expected to be detected in the coming years with a new generation of instruments (upgrades for the OGLE camera; KMTNet, EUCLID, WFIRST).

2.3. Astrometric surveys

The astrometric technique aims at detecting the gravitational influence of planetary mass companions on the star or brown dwarf motion in the plane of the sky. The method is limited by the faintness of the target, the gravitational potential of the companion and the number of reference stars used to measure the relative motion. For the detection of companions to BDs, astrometric measurements with a 50-100 micro-arcseconds (μas) precision are mandatory and were recently demonstrated using ground-based optical imaging with an 8m class telescope (Lazorenko et al. 2011; Sahlmann et al. 2013). This technique opens a new window to the parameter space of low mass ratios and small-to-intermediate separations (0.1-10 AU) explored around ultracool binaries. Contrary to microlensing observations, the repeatability of the observations offers the possibility to measure the eccentricity and orbital period of the detected systems.

In this context, the Planets Around M and L dwarfs with Astrometry (PALTA) survey, conducted on the FORS2 camera at VLT aim to look for planetary mass companions around twenty late-M and early-L dwarfs (Shalmann et al., in preparation). This 15 nights program was initiated in 2010. The parallax and proper motions of the sources can be inferred from the observations with an average epoch uncertainty of 110 μas, and residual dispersion of 140 μas. These sensitivities are comparable to those expected for the GAIA satellite (Mignard et al. 2011). As a result, PALTA is able to probe for companions at 10 pc as light as 0.6 $M_{\rm Neptune}$ placed on 2000 days orbits). It should enable to exclude planets more massive than Jupiter in intermediate periods (~50-400 days) for several targets.

Very recently, Sahlmann et al. (2013) announced the first detection of the PALTA survey. The brown-dwarf companion identified around the L1.5 dwarf DENIS-P J082303.1-491201 (Phan Bao et al. 2008) forms a high mass ratio system (q~ 0.36), which can be seen as a scaled up version in mass of the two brown-dwarf binaries identified so far by microlensing (OGLE-2009-BLG-151/MOA-

2009-BLG-232, OGLE-2011-BLG-0420). Its properties (binding energy∼ 10^{44} erg, total mass∼100 $M_{\rm Jup}$, separation=0.35 AU) are similar to those of some low mass binaries in the field and in young associations (Faherty et al. 2011; Basri & Martín 1999; Burgasser et al. 2008, 2012; Lane et al. 2001), although it falls in a scarcely populated parameter space (see Figure 4 and 5 of Choi et al. 2013).

2.4. Direct imaging

Direct imaging offers the possibility to detect self-luminous companions placed on wide-orbits (>1 AU), to characterize their atmosphere (Patience et al. 2010; Barman et al. 2011; Bonnefoy et al. 2013a,b; Konopacky et al. 2013) and, for some cases, constrain their orbital parameters (Neuhäuser et al. 2011; Chauvin et al. 2012; Mugrauer et al. 2012).

Nearby (d< 100pc) and young (age < 150 Myr) brown-dwarfs represent observational niches for the direct imaging search of planetary mass companions. At these ages, companions are still hot and large (Baraffe et al. 2003). They can therefore be detected at favorable contrasts in the near-infrared. Adaptive optics systems equipped with efficient wavefront sensors (NaCo at VLT, LMIRCam at LBT) or laser guide stars (Keck LGS, Gemini/ALTAIR, Subaru) can restore partially the angular resolution of ground-based telescopes on these faint hosts. The intrinsic faintness of the target enable to detect fainter (then lower mass) companions for a given reachable contrast.

Consequently, seven PMCs have been found around low-mass stars ($M \leq 0.5 M_\odot$) and six were found orbiting brown-dwarfs, among the sample ∼30 PMCs detected by direct imaging. The technique has unearthed a great diversity of system configurations (around single hosts, binaries; see Figure 1). Planetary mass companions around brown-dwarfs are found with projected separations between 2.6 AU (Liu et al. 2011) and 800 AU (Luhman et al. 2009). The discovery of companions in 1 Myr old clusters, with separations between 15 AU (2MASS J04414489+2301513) (Todorov et al. 2010) and 800 AU (FU Tau) (Luhman et al. 2009), put upper limits on timescales for formation, plus eventual dynamical ejection. These timescales are consistent with gravitational instability in disks and fragmentation of cloud cores. Recent evidence for ongoing accretion and/or (detached?) disks in companion orbiting low-mass stars (e.g., GQ Lup b, CT Cha b, GSC 06214-00210 b; FU Tau B) (Seifahrt et al. 2007; Schmidt et al. 2008; Bowler et al. 2010; Luhman et al. 2009) supports these formation scenarios.

The moderate contrast between the components of these low mass systems do not require the use of complex observation and analysis techniques to extract the companion spectrum (Vigan et al. 2008, 2012, 2013). Hence, most of bright (and young) directly imaged planetary mass companions orbiting brown-dwarfs have now been characterized spectroscopically in the near-infrared (Patience et al. 2010; Bonnefoy et al. 2013b; Bowler et al. 2013). Spectra revealed peculiar features that can be associated to the reduced surface gravity of the objects. These features are retrieved in the spectra of young isolated objects identified in star forming regions (Lucas et al. 2001; Lodieu et al. 2008; Alves de Oliveira et al. 2012) and in the field (Faherty et al. 2013; Allers et al. 2013).

The use of novel techniques (angular differential imaging, sparse aperture masking) and observation strategies (imaging at 3.8 μm, lucky imaging) on 8-m class telescopes, and the identification of young late-type dwarfs in the solar neighborhood (Schlieder et al. 2010, 2012a,b; Malo et al. 2013) offers the opportunity to detect companion with sub-Jovian masses. This has motivated new ongoing surveys on Keck (Bowler et al. 2012a,b, 2013), and NaCo (Delorme et al. 2012), whose target sample extend in the substellar mass regime. These surveys are sensitive to Jovian companions. The statistics inferred from the observations could be compared to multiplicity studies in star forming region (Ahmic et al. 2007; Biller et al. 2011; Kraus et al. 2012) – sensitive to high-mass ratio systems – which showed that binary frequency and binary separations decline smoothly between masses of 0.5 $M_\odot$ and 0.02 $M_\odot$, and that mass ratio distribution

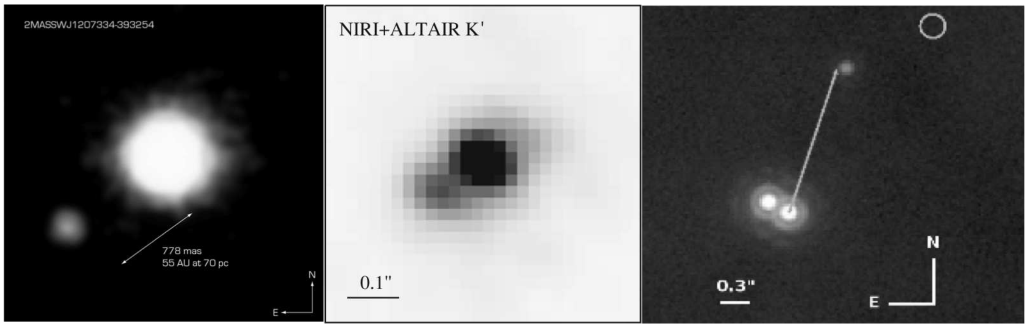

Fig. 1. Examples of the variety of systems with planetary mass companions imaged around brown-dwarfs of very low mass stars. Left: the planetary mass companion discovered at a projected separation of 55 AU around the 8 Myr old brown-dwarf 2MASS J12073347-3932540. Middle: The tight (15 AU) pair 2MASS J04414489+2301513 composed of a planetary mass companion orbiting a brown dwarf. Right: A 12-14 $M_{\rm Jup}$ companion (upper-right) identified at a projected separation of 84 AU around a pair of low mass stars. Credits: Left: Figure 1, Chauvin et al., A&A, 425, 29, 2004, reproduced with permission © ESO. Middle: from Figure 1, Todorov et al., ApJ, 714, 84, 2010. Reproduced by permission of the AAS. Right: from Figure 1, Delorme et al., A&A, 553, 5, 2013, reproduced by permission ©ESO.

becomes progressively more concentrated toward equal-mass systems for declining system masses. Here again, the population of companion probed have likely formed via classical stellar mechanisms of formation (gravo-turbulent fragmentation or disk instability).

3. Conclusions

In this review, we first recalled that a way to define planets and brown dwarfs has not reached a consensus in the community. Whereas a mass-based definition has no physical ground anymore, a formation-based one is extremely difficult to apply for observers. We highlighted the fact that various observational clues indicate that planetary formation is likely to be on-going around BDs. We then summarized the state-of-the-art of observational searches to study the multiplicity and the diversity of substellar systems using different techniques like radial velocities, microlensing, astrometry and direct imaging. Multiplicity studies indicate that binary frequency and binary separations decline smoothly between masses of $0.5\,M_{\odot}$ and $0.02\,M_{\odot}$, pointing toward similar formation mechanisms between stars and BDs. The discovery of low-mass ratio BD binaries by direct imaging or microlensing techniques show possible companions formed in the disk of the primary. Despite the instrumental progress in the past years, current performances are not sensitive enough to bring any meaningful constraints on the putative existence of a population of planets (Jovian planets or telluric planets), which might have formed by core-accretion, around BDs. This population is probably marginally explored. In the incoming years, new radial velocity surveys in the near-infrared (100 stars with $M < 0.25\,M_{\odot}$ targeted with CARMENES (2014), and SPirou at CFHT (2017), new and more sensitive microlensing surveys (upgrades for the OGLE camera; KMTNet, EUCLID, WFIRST), high-precision astrometric survey conducted from space (GAIA) and from the ground (PALTA), finally new high-resolution imagers in the nIR and mIR on the VLT (ERIS), the E-ELTs (ELT-MIR), and JWST, should help exploring this *terra incognita*, and possibly reveal the diversity and the extent of planetary formation in our Universe.

Acknowledgements. We are grateful to the conference organizers for offering the opportunity to review these discoveries. We thank J. Sahlmann for providing additional informations on the PALTA survey. We acknowledge contributions from P. Delorme, B. Biller, A-M. Lagrange.

References

Ahmic, M., et al. 2007, ApJ, 671, 2074
Alibert, Y., et al. 2004, A&A, 417, 25
Alibert, Y., et al. 2005, A&A, 434, 343
Allers, K. N., et al. 2013, ApJ, 772, 79
Allen, P. 2007, ApJ, 668, 492
Alves de Oliveira, C., et al. 2012, A&A, 539, 151
Bailer-Jones, C. A., & Lamm, M. 2003, MNRAS, 339, 477
Baraffe, I., et al. 2003, A&A, 402, 701
Barman, T. S., et al. 2011, ApJ, 733, 65
Basri, G., & Brown, M. E. 2006, AREPS, 34, 193
Basri, G., & Martín, E. L. 1999, AJ, 118, 2460
Basri, G., & Reiners, A. 2006, AJ, 132, 663
Bate, M. R., et al. 2002, MNRAS, 332, 65
Bate, M. R., et al. 2012, MNRAS, 419, 3115
Boss, A. P., et al. 2003, IAUS, 211, 529
Rebolo, R., et al. 1995, Nature, 337, 129
Beichman, C., et al. 2013, ApJ, 764, 101
Berger, E., et al. 2009, ApJ, 695, 310
Biller, B., et al. 2011, ApJ, 730, 39
Blake, C. H., et al. 2007, ASPC, 366, 87
Blake, C. H., et al. 2008, PASP, 120, 860
Blake, C. H., et al. 2010, ApJ, 723, 684
Bodenheimer, P., et al. 2013, ApJ, 770, 120
Bonfils, X., et al. 2013, A&A, 549, 109
Bonnefoy, M., et al. 2013a, A&A, 555, 107
Bonnefoy, M., et al. 2013b, accepted for publication in A&A, astro-ph: 1306.3709
Bouy, H., et al. 2003, AJ, 126, 1526
Bouy, H., et al. 2008, A&A, 486, 877
Bowler, B., et al. 2010, ApJ, 723, 850
Bowler, B., et al. 2012a, ApJ, 753, 142
Bowler, B., et al. 2012b, ApJ, 756, 69
Bowler, B., et al. 2013, ApJ, 774, 55
Burgasser, A. J., et al. 2003, ApJ, 586, 512
Burgasser, A. J., et al. 2007, ApJ, 658, 557
Burgasser, A. J., et al. 2008, ApJ, 689, 53
Burgasser, A. J., et al. 2009, AJ, 138, 1563
Burgasser, A. J., et al. 2012, ApJ, 757, 110
Carpenter, J. M., et al. 2006, ApJ, 651, 49
Chabrier, G., et al. 2007, in Protostars and Planets V, B. Reipurth, D. Jewitt, and K. Keil eds., (University of Arizona Press, Tucson), 623
Chauvin, G., et al. 2004, A&A, 425, 29
Chauvin, G., et al. 2005, A&A, 438, 25
Chauvin, G., et al. 2012, A&A, 542, 41
Choi, Y. J., et al. 2013, ApJ, 768, 129
Dahm, S. E., & Hillenbrand, L. A. 2007, AJ, 133, 2072
Delorme, P., et al. 2012, A&A, 539, 72
Delorme, P., et al. 2013, A&A, 553, 5
Faherty, J. K., et al. 2011, AJ, 141, 71
Faherty, J. K., et al. 2013, AJ, 145, 2
Goodwin, S. P., et al. 2004, A&A, 414, 633
Guenther, E. W., & Wurchtel, G., 2003, A&A, 401, 677
Han, C., et al. 2013, submitted to ApJ, astro-ph: 1307.6335
Hennebelle, P., & Chabrier, G. 2008, ApJ, 684, 395
Hennebelle, P., & Chabrier, G. 2009, 702, 1428
Herczeg, G. J., et al. 2009, ApJ, 696, 1589
Hester, J. J., et al. 1996, AJ, 111, 2349
Jayawardhana, R., et al. 2003, ApJ, 592, 282
Joergens, V. 2008, A&A, 492, 545
Joergens, V., & Guenther, E. 2001, A&A, 379, 9
Joergens, V., & Müller, A. 2007, ApJ, 666, 113
Joergens, V., et al. 2010, A&A, 521, 24
Kenyon, M. J., et al. 2005, MNRAS, 356, 89
Klein, R., et al. 2003, ApJ, 593, 57
Koen, C., et al. 2005, MNRAS, 362, 727
Konopacky, Q. M., et al. 2013, Science, 339, 1398
Kraus, A. L., et al. 2012, ApJ, 757, 141
Kurosawa, R., et al. 2006, MNRAS, 372, 1879
Lane, B. F., et al. 2001, ApJ, 560, 390
Lane, B. F., et al. 2007, ApJ, 668, 163
Lazorenko, P. F., et al. 2011, A&A, 527, 25
Liu, M. C., et al. 2011, ApJ, 740, 108
Lodieu, N., et al. 2008, MNRAS, 383, 1385
Lucas, P. W., et al. 2001, MNRAS, 326, 695
Luhman, K. L., et al. 2005a, ApJ, 635, 93
Luhman, K. L., et al. 2005b, ApJ,620, 51
Luhman, K. L., et al. 2008, ApJ, 688, 362
Luhman, K. L., et al. 2009, ApJ, 691, 1265
Luhman, K. L., et al. 2010, ApJ, 186, 111
Malo, L., et al. 2013, ApJ, 762, 88
Martín, E. L., et al. 1999, Science, 283, 1718
Martín, E. L., et al. 2013, A&A, 555, 108
Mathieu, R. D., et al. 2007, in Protostars and Planets V, B. Reipurth, D. Jewitt, and K. Keil eds., (University of Arizona Press, Tucson), 411
Maxted, P. F., et al., 2008, MNRAS, 385, 2210

Micheau, Y., et al. 2012, Proc. SPIE, 8446, 84462R
Mignard, F., et al. 2011, Advances in Space Research, Volume 47, Issue 2, p. 356-364
Mollière, P., & Mordasini, C. 2012, A&A, 547, 105
Mohanty, S., et al. 2013, ApJ, 773, 168
Mugrauer, M., et al. 2012, MNRAS, 424, 1714
Nakajima, T., et al. 1995, Nature, 378, 463
Natta, A., & Testi, L. 2001, A&A, 376, 22
Natta, A., et al. 2002, A&A, 393, 597
Natta, A., et al. 2004, A&A, 424, 603
Neuhäuser, R., et al. 2011, MNRAS, 416, 1430
Paczyński, B., et al. 1986, ApJ, 304, 1
Padoan, P., & Nordlund, Å. 2004, ApJ, 617, 559
Patience, J., et al. 2010, A&A, 517, 76
Phan Bao, N., et al. 2008, MNRAS, 383, 831
Pinilla, P., et al. 2013, A&A, 554, 95
Pollack, J. B., et al. 1996, Icarus, 124, 62
Prato, L. 2007, ApJ, 657, 338
Quirrenbach, A., et al. 2012, Proc. SPIE, 8446, 84460R
Radigan, J. et al. 2013, ApJ, 750, 105
Reid, N., et al. 2001, AJ, 121, 489
Reid, N., et al. 2002, AJ, 124, 519
Ricci, L., et al. 2012, ApJ, 761, 20
Ricci, L., et al. 2013, ApJ, 764, 27
Rodler, F., et al. 2012, A&A, 538, 141
Sahlmann, J., et al. 2013, A&A, 556, 133
Schlieder, J. E., et al. 2010, AJ, 140, 119
Schlieder, J. E., et al. 2012a, AJ, 143, 80
Schlieder, J. E., et al. 2012b, AJ, 144, 109
Schmidt, T. O. B., et al. 2008, A&A, 491, 311
Scholz, A., et al. 2006, ApJ, 645, 1498
Scholz, A., et al. 2007, ApJ, 660, 1517
Scholz, A., & Jayawardhana, R. 2008, ApJ, 672, 49
Seifahrt, A., et al. 2007, A&A, 463, 309
Shu, F. H., et al. 1987, ARA&A, 25, 23
Stamatellos, D., & Whitworth, A. P. 2009, MNRAS, 392, 413
Stassun, K., et al. 2006, Nature, 440, 311
Sumi, T., et al. 2011, Nature, 473, 349
Testi, L., et al. 2002, ApJ, 571, 155
Todorov, K., et al. 2010, ApJ, 714, 84
Vigan, A., et al. 2008, A&A, 489, 1345
Vigan, A., et al. 2012, A&A, 540, 131
Vigan, A., et al. 2013, A&A, 555, 49
Whelan. E. T., et al. 2007, ApJ, 659, 45
Whitworth, A. P., & Zinnecker, H. 2004, A&A, 427, 299
Zapatero Osorio, M. R., et al. 2004, ApJ, 615, 958