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Low-mass companions to solar-type stars

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Abstract. We present preliminary results from a coronagraphic survey of young nearby Sun-like stars using the Palomar and Keck adaptive optics systems. We have targeted 251 solar analogs (F5–K5) at 20–160 pc from the Sun, spanning the 3–3000 Myr age range. The youngest (<500 Myr) ≈100 of these have been imaged with deeper exposures to search for sub-stellar companions. The deep survey is sensitive to brown-dwarf companions at separations >0.5″ from their host stars, with sensitivity extending to planetary-mass (5–15$M_{\rm Jup}$) objects at wider (>3″) separations. Based on the discovery of a number of new low-mass (<0.2$M_\odot$) stellar companions, we infer that their frequency at >20 AU separations (probed via direct imaging) may be greater (≈12%) than that found from radial velocity surveys probing <4 AU separations (≈6%; Mazeh et al. 2003). We also report the astrometric confirmation of the first sub-stellar companion from the survey — an L4 brown dwarf at a projected distance of 44 AU from the ≈500 Myr-old star HD 49197. Based on this detection, we estimate that frequency of sub-stellar companions to solar-type stars is at least 1%, and possibly of order a few per cent.

Key words. Stars: binary, low-mass, brown dwarfs

1. Introduction

High-contrast imaging searches for low-mass companions to nearby and/or young stars have increased dramatically in number since the first direct-imaging discovery of a brown dwarf around a main sequence star (Gl 229; Nakajima et al. 1995). Imaging with adaptive optics (AO) is a particularly powerful approach, as it provides the high angular resolution (≲0.1″) achievable at the diffraction limit of large ground-based telescopes. Young nearby stars are the most suitable targets for direct imaging of sub-stellar companions. At ages of 10–100 million years (Myr) the expected brightness ratio in the near-IR between an object near the deuterium-burning limit (≈0.013$M_\odot$ ≈ 13 Jupiter masses [$M_{\rm Jup}$]) and a solar-type star is 10^{-3}–10^{-4} (Burrows et al. 1997; Baraffe et al. 2003): within the dynamic range attainable by modern AO systems at 0.5″–1″ from bright stars. Therefore, AO surveys of young nearby stars allow the direct imaging of brown-dwarf and even potential planetary-mass (<13$M_{\rm Jup}$) companions at orbital separations comparable to the semi-major axis (40 AU) of Neptune's orbit in the Solar System.

The emergent picture from the first large-scale programs targeting nearby (<25 pc) stars (e.g., Oppenheimer et al. 2001; McCarthy & Zuckerman 2004) is that brown dwarfs are

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rare at separations 10–1000 AU from main sequence stars (frequency ∼1%). This has become known as the "brown dwarf desert at wide separations," following an analogy with the radial-velocity (RV) brown dwarf desert at <3 AU (Marcy & Butler 2000). However, recent results from more sensitive space- and ground-based imaging surveys, though not inconsistent with the initial estimates, all point to a somewhat higher (several per cent) frequency of sub-stellar companions over 20–200 AU separations (Potter et al. 2002; Lowrance et al. 2003; Neuhäuser & Guenther 2004). At even wider orbital semi-major axes (>1000 AU), Gizis et al. (2001) observe that the sub-stellar companion frequency (∼18%) is comparable to that of stellar companions. It is therefore possible that the brown dwarf desert at wide separations may at least partially be an artifact of the limited performance of ground-based surveys. To explore this possibility, we have conducted a large, sensitive survey for low-mass companions to young stars, using the Palomar and Keck AO systems.

2. Survey Sample and Observations

The core of the survey targets ≈100 young (<500 Myr; median age 100 Myr) solar-type (F5–K5) stars within 200 pc of the Sun (median distance 100 pc) using the high-order AO system and coronagraph at the Palomar 5-m telescope (Troy et al. 2000). A shallower non-coronagraphic survey, aimed at determining the low-mass stellar multiplicity of older solar analogs, encompasses an additional ≈150 stars. The total number of solar analogs surveyed with the Palomar AO system is 251, spanning the age range 3–3000 Myr. Follow-up astrometric and spectroscopic observations are obtained at Palomar and/or Keck.

Although faint primary stars, such as M dwarfs or white dwarfs, offer more favorable contrast for imaging sub-stellar companions, the sample was limited to solar analogs only, since young F–G stars have remained relatively unexplored by previous surveys because of their comparatively small numbers in the solar neighborhood. The source list is largely a sub-sample of the Sun-like stars targeted by the Formation and Evolution of Planetary Systems (FEPS; Meyer et al. 2004) *Spitzer* Legacy program. We note that the FEPS sample is biased against equal-brightness binaries ($\Delta K_S < 3$ mag and separation <15″ in 2MASS), because they would complicate the analysis of *Spitzer* data (PSF FWHM of 7″ at 70μm). Nevertheless, a number of close binaries were found in the course of our survey (Section 3) because of the higher spatial resolution (0.10″ at K_S band) allowed by AO compared to seeing-limited observations.

A detailed description of the observing procedure is provided in Metchev & Hillenbrand (2004). Here we only state that imaging is conducted at K_S band (2.15μm) with total exposure times of 24 min per star in the (deep) coronagraphic survey, and 10–50 s per star in the (shallow) non-coronagraphic survey. Figure 1 shows the distribution of the deep survey sample on an age vs. heliocentric distance diagram, with empirically-derived companion mass detection limits (using sub-stellar cooling models from Burrows et al. 1997) for 1″ (*left* panel) and 3″ (*right* panel) separations. Given the dynamic range achievable with the Palomar AO system at K_S (≈8.5 mag at 1″; ≈13.5 mag at 3″), we are sensitive to brown dwarfs above the deuterium-burning limit (∼13 $M_{\rm Jup}$) around approximately half of the sample stars at 1″ separations, and around nearly all of the stars at 3″ separations. Massive (≥3$M_{\rm Jup}$) outer planets are also detectable around the youngest and the nearest of the solar analogs.

3. Multiplicity

First-epoch imaging ended in 2003, and the second-epoch astrometric and spectroscopic follow-up is nearly (≈90%) complete. The first-epoch observations uncovered 207 candidate companions within 15″ from 116 of the 251 stars in our overall sample (Figure 2). At the median age (100 Myr) and median K-band absolute magnitude ($M_K = 3.5$ mag) of the stars in the deep sample, any candidate companion fainter than $\Delta K_S = 6$ mag with respect to its primary is a possible brown dwarf, and any candidate fainter than $\Delta K_S =$

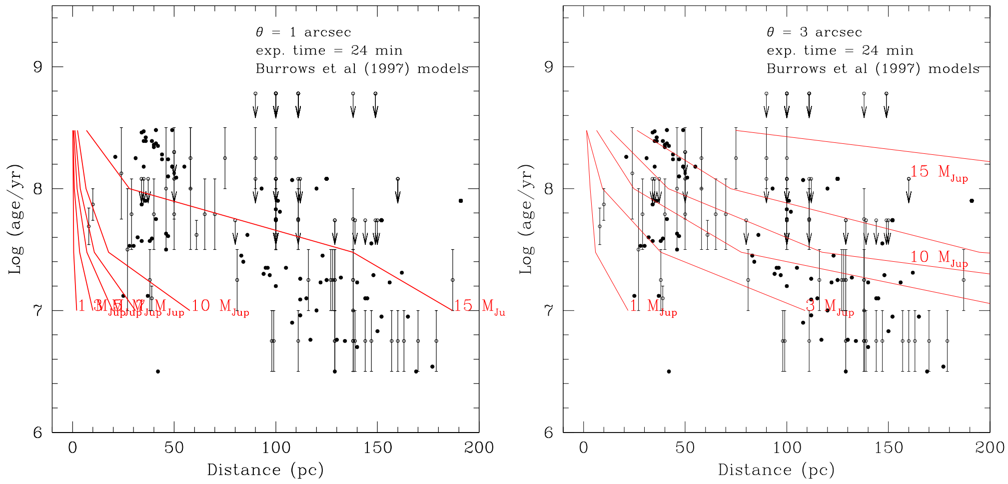

Fig. 1. The sample of ≈100 solar analogs in the deep survey on an age vs. distance diagram. Over-plotted (solid lines) are the limiting survey sensitivities to brown dwarf companions of a range of masses at angular separations of 1″ (*left* panel) and 3″ (*right* panel) from their respective primaries. That is, if a star residing below the $XM_{\rm Jup}$ line in either of the panels had a $\geq XM_{\rm Jup}$ companion at the corresponding angular separation (1″ or 3″), the companion should have been detectable.

12 mag is potentially below the deuterium-burning limit. However, contamination from background sources is high, with the faintest and most widely separated companions being most probably unrelated background stars. Figure 2 shows the loci of likely companions and likely background stars, where they are separated by the dotted line delineating the empirically determined (Brandner et al. 2000) background contamination rate for a Galactic latitude of $b \sim 15°$ (toward the Scorpius-Centaurus OB association). Given that the majority of the stars in our sample reside at higher Galactic latitudes, the line gives a conservative estimate (by 1–2 mag at moderate latitudes) of the background contamination.

The astrometric analysis of the follow-up observations is currently ∼20% done, and an estimate of the overall survey completeness has not been performed yet. Therefore, at this stage we can only present preliminary multiplicity results for the sample. Nevertheless, for *stellar* companions, these are not likely to differ significantly from the final results, since the observed fraction of stellar companions is less affected by background contamination and incompleteness compared to that of sub-stellar companions. There are 78 candidate stellar binary systems in the locus of "likely companions" in Figure 2, where we have excluded the companions discovered at separations smaller than the K_S-band diffraction limit (0.10″) of the Palomar AO system. One out of 78 is (spectroscopically) confirmed to be sub-stellar (Section 4), while the majority are expected to be stellar. For 47 of these systems the K_S-band flux ratio is $\Delta K_S < 3.0$, and for 31 it is $\Delta K_S \geq 3.0$. Whereas the statistics of the $\Delta K_S < 3.0$ bin are affected by the inherent sample bias against such binaries, the statistics of the higher flux ratio bin are not. At the median spectral type of the sample (G5 V), a flux ratio of $\Delta K_S \geq 3.0$ corresponds approximately to a mass ratio of $q = M_2/M_1 \leq 0.2$ on the main sequence. Thus, we find that 12.4±2.2% (assuming Poisson errors) of wide (≥20 AU) binaries have mass ratios $q \leq 0.2$. On the other hand, based on one confirmed brown dwarf companion among the 100 stars in the deep sample, we find that the sub-stellar companion

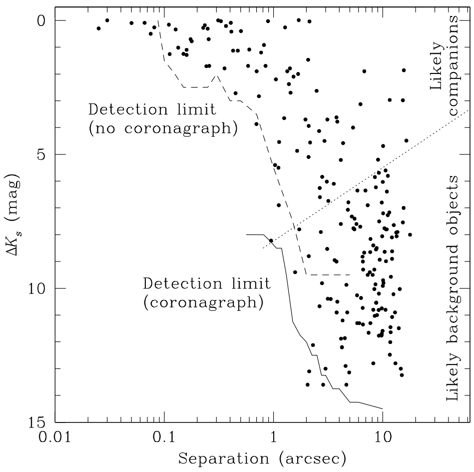

Fig. 2. Candidate companions from the first-epoch survey. K_S-band detection limits of the deep coronagraphic (solid line) and shallow non-coronagraphic (dashed line) parts of the survey are also shown. Companions residing to the left of the lines (beyond the K_S sensitivity limits of the Palomar AO survey) were discovered either at J band (where the PSF is only 0.05″ [FWHM], vs. 0.10″ at K_S) or during follow-up observations at Keck (where the higher dynamic range at >0.8″ is 1–1.5 mag greater). The dotted line marks the empirically determined (Brandner et al. 2000) contamination rate from background objects at a Galactic latitude of $b \sim 15°$. At this latitude, objects residing below the line are more likely to be unrelated background stars.

frequency at wide orbital separations is likely of order 1%. However, neither of these estimates is corrected for completeness, which, in the case of the sub-stellar companion frequency, may boost the estimate by a factor of several.

We put these numbers in the context of sensitive multiplicity surveys targeting smaller orbital separations. From a near-IR RV survey of 0.6–0.85$M_\odot$ primaries, Mazeh et al. (2003) find that 6.3 ± 4.7% of short-period (<3000-day) binaries have mass ratios $q \leq 0.2$. For the range of primary masses in their sample, the 3000-day period limit translates into a separation limit of <4 AU. On the other hand, Marcy & Butler (2000) estimate that <0.5% of Sun-like primaries have brown-dwarf companions orbiting within 3 AU. Both estimates are somewhat lower than the low-mass stellar and sub-stellar companion fractions found for the widely-separated systems in our survey. We interpret this as evidence that the fraction of low-mass stellar companions at wide (>20 AU) separations may be higher than that at small (<4 AU) separations. The tendency is also in agreement with the observed trend for an increasing frequency of sub-stellar companions at larger orbital semi-major axes (Section 1). However, a robust conclusion will be possible only after the completion of the common proper motion and completeness analyses of our entire sample.

4. HD 49197B - a Young Ultra-Cool Brown Dwarf

From the deep coronagraphic survey we have confirmed physical association between the components of one young stellar/sub-stellar binary: HD 49197A/B (Fig. 3). Because the primary does not belong to a known young moving group, its age can be constrained only approximately, based on chromospheric activity indicators and on its photospheric lithium abundance. From the strength of the Ca H & K core emission measured in Keck/HIRES spectra, Wright et al. (2004) assign an age of 525 Myr for HD 49197. From our own high-resolution optical spectra, we measure a lithium equivalent width of 80 mÅ (Hillenbrand et al., in prep.), consistent with a Pleiades-like (120 Myr; Stauffer et al. 1998) or older age. Assuming that the Ca H & K age is accurate to 50%, given the variation in chromospheric activity of solar-type stars (Henry et al. 1996), we adopt an age range of 260–790 Myr for HD 49197A. If the binary components are co-eval, the mass of HD 49197B is $0.060^{+0.012}_{-0.025} M_\odot$, i.e., sub-stellar.

Given its association with a young main sequence star, HD 49197B (L4±1 V) is a member of a very short list (5–6) of confirmed *young* ultra-cool (L or T) dwarfs. Although the existence of ultra-cool dwarfs has also

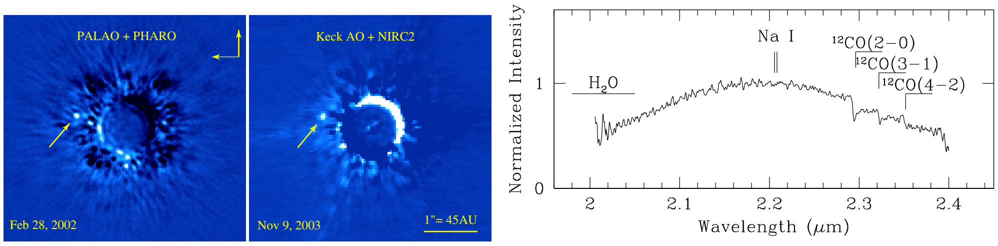

Fig. 3. A brown dwarf companion to the F5 V 260–790 Myr old star HD 49197 (45 pc, K_S=8.2 mag). *Left* panel: first- and second-epoch PSF-subtracted images confirming its proper motion association with the primary. HD 49197B is 8.2 mag fainter than the primary at K_S, and at a projected separation of 44 AU (0.95″). *Right* panel: K-band spectrum of HD 49197B, showing H_2O and CO_2 absorption characteristic of cool dwarfs, and lack of Na I absorption (not expected in mid-L dwarfs). The spectral type is determined to be L4±1, and the inferred mass is 35–72$M_{\rm Jup}$.

been reported toward young open clusters (e.g., Zapatero Osorio et al. 1999; Lucas et al. 2001; López Martí et al. 2004), their physical association with the corresponding cluster, or their spectral classification based on near-IR steam absorption indices, is still the subject of dispute (e.g., McGovern et al. 2004; Burgasser et al. 2004; Luhman et al. 2003). Therefore, because of its rarity, the physical properties of HD 49197 are of interest for constraining brown-dwarf cooling models, and for projecting the spectroscopic characteristics of even cooler objects of similar age — potential planets.

5. Conclusion

We have nearly completed a sensitive AO survey for low-mass companions to young solar analogs. Preliminary results indicate that low-mass stellar and sub-stellar ($M_2 < 0.2 M_\odot$) companions are more common at wide (>20 AU) than at small (<4 AU) orbital separations. The frequency of wide sub-stellar companions is found to be ≥1%. We also report the astrometric and spectroscopic confirmation of the first brown dwarf companion to emerge from the survey: HD 49197B. Because of its youth, HD 49197B is a member of a short list of known young ultra-cool dwarfs and is thus of interest as a benchmark for the spectral classification and theoretical modeling of similar objects in the future. When completed, this survey will provide factors of several better statistics on stellar multiplicity across two dex of binary mass ratios, from 0.01–1.0, and over 10–1000 AU separations, compared to previous surveys. The result will be a much more definitive estimate of the depth and extent of the brown dwarf desert.

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