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A Pan-STARRS + UKIDSS search for young, wide planetary-mass companions in Upper Sco

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Abstract. We have combined optical and NIR photometry from Pan-STARRS 1 and UKIDSS to search the young (5–10 Myr) star-forming region of Upper Sco for wide ($\approx$ 400–4000 AU) substellar companions down to $\sim 5\,M_{\rm Jup}$. Our search is $\approx$ 4 mag deeper than previous work based on 2MASS. We identified several candidates around known stellar members using a combination of color selection and spectral energy distribution fitting. Our followup spectroscopy has identified two new companions as well as confirmed two companions previously identified from photometry, with spectral types of M7.5–M9 and masses of $\sim$ 15–60 $M_{\rm Jup}$, indicating a frequency for such wide substellar companions of $\sim 0.6 \pm 0.3\%$. Both USco 1610−1913B and USco 1612−1800B are more luminous than expected for their spectral type compared with known members of Upper Sco. We have also confirmed a low-mass stellar companion, USco 1610−2502B (730 AU, M5.5).

1. Introduction

Recent advances in direct imaging techniques have led to the discovery of planets in moderately wide ($\sim$ 10–100 AU) orbits around other stars, such as HR 8799 (Marois et al. 2008). Direct imaging surveys have also discovered planetary-mass ($\lesssim 13\,M_{\rm Jup}$) companions with very large ($\sim$ 200–500 AU) orbital radii including 1RXS J1609−2105B ($8\,M_{\rm Jup}$, 330 AU; Lafrenière et al. 2008) and GSC 06214−00210B ($14\,M_{\rm Jup}$, 330 AU; Ireland et al. 2011). The most extreme of such wide companions is WD 0608-661B with a mass of $7\,M_{\rm Jup}$ and a projected separation of 2500 AU (Luhman et al. 2011). It is difficult to determine whether a planetary-mass companion at such a large distance formed from a protoplanetary disk (and thus should be considered a planet) or as a binary system (and should be called a brown dwarf). Regardless of their origins, detailed spectroscopic and photometric analysis of these directly imaged systems (e.g. Lafrenière et al. 2008) can yield insight into the properties (e.g. luminosity, temperature and mass) of gas-giant planets, and thereby shed light on the over 500 radial velocity and transiting exoplanets that lie within a few AU of their host stars and therefore cannot be directly studied.

Determining the separation distribution, and frequency of these wide planetary-mass companions will provide valuable clues about their formation. If wide substellar companions form like binary stars (e.g. Kratter et al.

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2010), we expect that they may reside at separations as large as ~1000 AU from their primary star, as stellar binaries are observed at such large separations. If instead such companions form like planets, we do not expect to find them beyond a few hundred AU, because protoplanetary disks should not form planets so far out (e.g. Dodson-Robinson et al. 2009). In addition, the typical sizes of circumstellar disks range from ~100–400 AU (Vicente & Alves 2005), making in situ formation by disk-instability at very wide separations, where there is no disk at all, unlikely.

2. Data and results

We have used the UKIDSS Galactic Cluster Survey (GCS) and the Pan-STARRS 1 (PS1) 3π Survey to search for wide ($\approx$ 400–4000 AU) planetary-mass companions in the Upper Sco association down to $\sim 5\,M_{\rm Jup}$. Combining both optical (PS1) and NIR (UKIDSS) data increases the wavelength coverage, significantly improving the ability to reject reddened background stars as potential planetary-mass companions. We use a selection method that combines traditional color-selection with SED fitting. Our method significantly decreases the number of reddened background stars that contaminate our sample compared with a solely color-selected sample.

We obtained followup low-resolution NIR spectroscopy of several candidates using SpeX (Rayner et al. 2003), a medium-resolution, near-IR spectrograph (0.8–2.5 μm) on the 3-meter NASA Infrared Telescope Facility (IRTF) on Mauna Kea. We discovered two new companions and confirmed three other companions. Figure 1 shows the UKIDSS K image and the reduced spectrum with the closest matching published spectrum for three of our companions. Four are very low mass substellar companions (spectral type M7.5-M9, mass $\approx 15\text{-}60\,M_{\rm Jup}$) and one is a low-mass star (spectral type M5, mass $\sim 0.1\,M_{\odot}$). The most extreme object is HIP 77900B because of its very wide projected separation (3200 ± 300 AU) and very small mass ratio ($q \approx 0.005$).

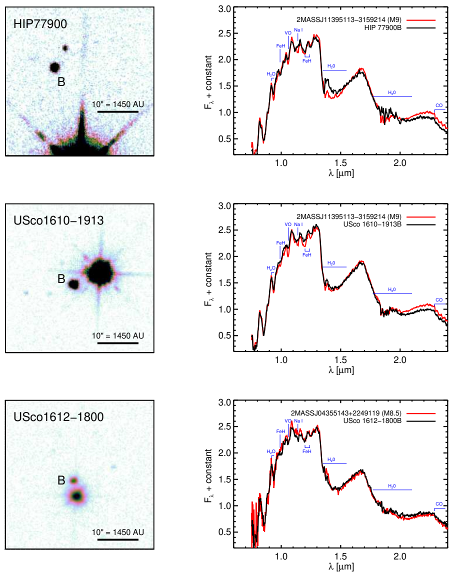

Fig. 1. *LEFT Column* – The finder chart (UKIDSS K and width of 30″) with the letter B identifying the companion. North is *up* and East is *left*. *RIGHT Column* – IRTF SpeX spectrum of our companions compared to the young (8–12 Myr) M9 in TW Hydrae (Looper et al. 2007, 2MASS J11395113−3159214;) for HIP 77900B and USco 1610-1913B. We compare USco 1612–1800B with the young (1–2 Myr) M8.5 in Taurus (2MASS J04355143+2249119; Muench et al. 2007).

3. Conclusions

We have spectroscopically confirmed 4 wide substellar companions out of our search around 673 Upper Sco members. Our results indicate a frequency for wide (400-4000 AU) substellar companions down to $5\,M_{\rm Jup}$ of $\sim 0.6 \pm 0.3\%$. The wide projected separations for all of our companions are difficult to explain as either the massive-end of planetary formation or the low-mass tail of binary-star formation.

Altogether, our companions suggest that young substellar companions, but not necessarily their respective primary stars, are overluminous compared to the models and the observed cluster sequence (Figure 2). As a result, our new companions do not all appear

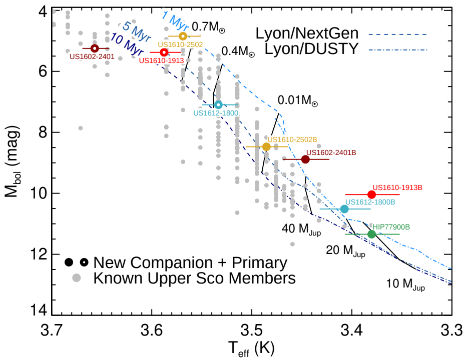

Fig. 2. The bolometric magnitude and temperature of our new companions and their primaries compared to the model grids are the *solid* and *open circles* for the companions and the primaries, respectively (Chabrier et al. 2000; Baraffe et al. 1998). Each system is a different shade. The *gray circles* are the Upper Sco free-floating members from Kraus & Hillenbrand (2007). The three *dashed* lines are isochrones for 1 Myr, 5 Myr, and 10 Myr. The *solid lines* trace out the evolution for an object with a given mass.

coeval with their primary stars on an HR diagram, in contrast to results for young higher mass binary systems (Kraus & Hillenbrand 2009). In addition, two of our companions (USco 1610−1913B and HIP 77900B) present another puzzle, because they have the same spectral type but luminosities that differ by 1.5 mag. One possible reason for the overluminosity of young companions compared to the models could be different accretion histories (Baraffe et al. 2012). Young stars may have strong episodic accretion which will increase the star's radius and thus the luminosity.

Regardless of the formation scenario of these companions, we can use them as young spectral benchmarks to constrain evolutionary models. These new companions provide us with a unique glimpse into the early life of brown dwarfs. Further discoveries will improve our constraints on models and our understanding of planet/brown dwarf formation, the typical properties of these young systems, and their likely evolution.

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