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Direct imaging and spectroscopy of planets and brown dwarfs in wide orbits†

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Abstract. Recent direct imaging discoveries of exoplanets have raised new questions about the formation of very low-mass objects in very wide orbits. Several explanations have been proposed, but all of them run into some difficulties, trying to explain all the properties of these objects at once. Here we present the results of a deep adaptive optics imaging survey of 85 stars in the Upper Scorpius young association with Gemini, reaching contrasts of up to 10 magnitudes. In addition to identifying numerous stellar binaries and a few triples, we also found several interesting sub-stellar companions. We discuss the implications of these discoveries, including the possibility of a second pathway to giant planet formation.

Keywords. brown dwarfs, planetary systems, stars: low-mass, stars: pre-main-sequence

1. Introduction

The detection and characterization of low-mass sub-stellar companions on large orbits (over several tens of AU) around stars is of great importance for our understanding of planet, brown dwarf, and star formation, as well as for our understanding of the dynamical evolution of such companions in multiple systems or in circumstellar disks. Currently, most formation models of planets or low-mass brown dwarf companions - core accretion (e.g., Pollack *et al.* 1996), gravitational instability (e.g., Boss 1997), and fragmentation of a pre-stellar core (e.g., Padoan & Nordlund 2002; Bate *et al.* 2003) - cannot easily explain the existence of companions at large orbital separations, like those recently discovered via direct imaging (see e.g. Marois *et al.* 2008; Lafrenière 2008, 2010). Those companions have separations of tens to several hundreds of AU and mass ratios of the order of 0.01 relative to their primaries. In this context a good determination of the semi-major axis, mass, and mass ratio distributions of far out giant planets will provide a powerful tool to understand the formation mechanisms at play and distinguish between star-like and planet-like origins. In addition to this, wide sub-stellar companions are good benchmark objects for the study of brown dwarf/planetary atmospheres and evolution models. They have in general the same age and metallicity of the host star, their distance can often be easily inferred, and their high separation from their star in the sky makes them the easiest companions to study.

† Talk was delivered by R. Jayawardhana (rayjay@astro.utoronto.ca)

2. AO imaging survey in Upper Scorpius

Here we present the outcomes of our survey of 85 young stars belonging to the 5 Myr old Upper Sco association. The observations were taken using the NIRI camera (Hodapp *et al.* 2003) and the ALTAIR adaptive optic system at the Gemini North Telescope, the sensitivity being such to allow us to reach the planetary domain at separations higher than $\sim$ 60 AU (See Figs. 1), leading to the discovery/confirmation of 4 new sub-stellar companions. The characteristics of the companions are summarized in Table 1, whether Figs. 2 and 3 show the AO images of each target.

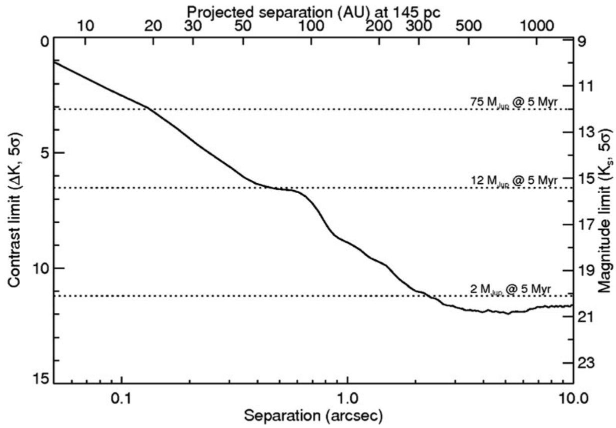


Figure 1. Detection limits of our observations, as a function of the separation. The dotted lines indicate the expected contrast for various planetary masses.

Table 1. Principal characteristics of the new companions and their host stars

ID	M_{Star} ($M_{\odot}$)	M_{Comp} (M_{Jup})	Separation (AU)	Reference
1RXS 1609	0.85	~ 8	330	Lafrenière *et al.* (2008, 2010)
HIP 78530	2.50	20	710	Lafrenière *et al.* (submitted)
1RSX 1541-2656	0.70	30-40	850	Lafrenière *et al.* (in prep.)
UpSco 1610-1913	1.80	70	915	Lafrenière *et al.* (in prep.)

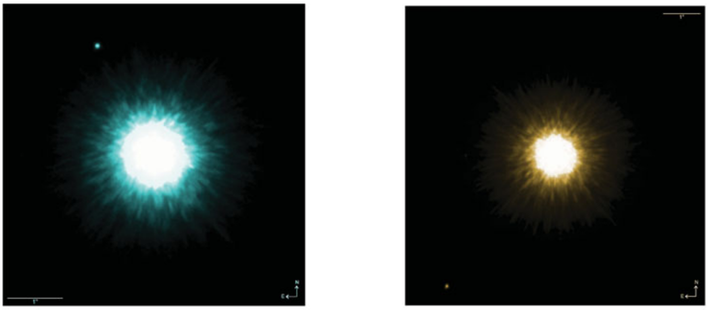
The smallest of these companions, first announced in September 2008 and now confirmed with common proper motion (see Lafrenière *et al.* 2010), is a 8 M_{Jup} planet around the roughly solar-mass star 1RXS 1609 (Fig. 2(a)). We have obtained multi-band infrared imaging and spectroscopy of it, which reveal evidence of its youth, temperature (1800K) and mass as well as absorption features due to CO, H2, and H2O. The planet's projected separation of 330 AU is quite surprising for such a low-mass object.

Two of the other sub-stellar companions in our Upper Sco sample have even larger projected separations:

- A 30-40 M_{Jup} companion at ~850 AU from UpSco 1610-1913 (Fig. 3(b)). The primary has a tight companion (0.14", 20 AU see Kraus 2008), so this forms a triple system. Interestingly, the tight companion could be at the star/BD boundary, 80 M_{Jup}.

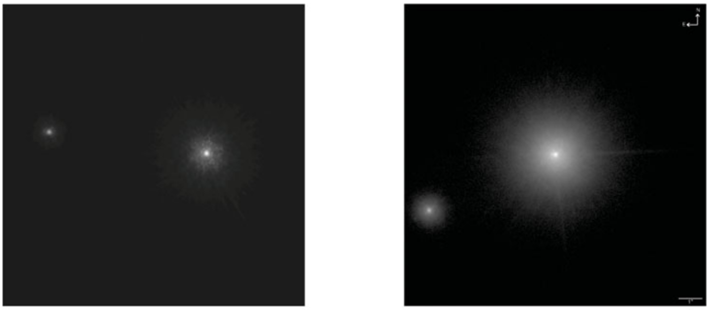
- A 70-80 M_{Jup} companion at 6.3" (915 AU) from 1RXS 1541-2526 (Fig. 3(a)).

In addition to those, a 20 M_{Jup} companion has been imaged at 710 AU from HIP 78530 (Fig. 2(b)). The latter has also been confirmed to be co-moving, via proper motion measurements (Lafrenière *et al.* submitted).



(a) 1RXS-1609 (b) HIP 78530

Figure 2. Composite of J-, H- and K-band images of 1RXS-1609 (a) and HIP 78530 (b) and their companions, respectively in the upper left and lower left corners.



(a) 1RXS 1541-2656 (b) UpSco 1610-1913

Figure 3. K-band images of 1RXS 1541-2526 (a) and UpSco 1610-1913 (b) and their companions, respectively in the upper left and lower left corners.

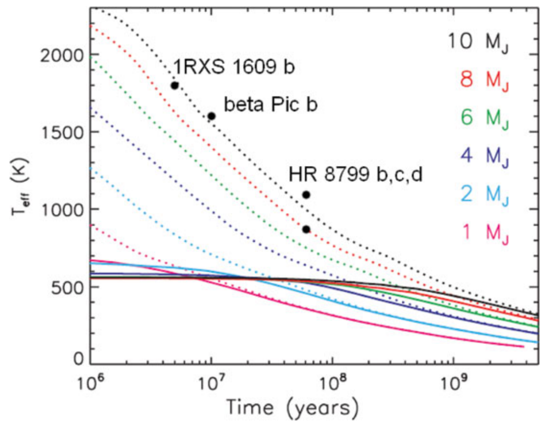


Figure 4. Comparison of hot-start (dotted lines) and cold-start (solid lines) evolutionary models (see Fortney *et al.* (2008) for the original plot) with the values corresponding to β Pic b (Quanz *et al.* 2010), HR 8799 b, c, d (Marois *et al.* 2008) and 1RXS 1609b (Lafrenière *et al.* 2008, 2010)

3. Discussion and Conclusions

The separation of the companions we found in our survey places them among the widest known sub-stellar companions to stars. Moreover, the extreme mass-ratio of HIP 78530 and 1RXS 1609 are comparable to those of directly imaged planets, even though the mass of HIP 78530b is above the deuterium-burning limit. Thus, the existence of

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these objects presents new challenges to all formation scenarios, blurring the distinction between giant planets and brown dwarfs.

On the other hand, these new discoveries provide observational constraints for the planet atmosphere and evolutionary models. In fact 1RXS-1609b, together with β Pic b and the planets in the HR 8799 system, seems to be better consistent with the hot-start than the cold-start models at the respective ages (see Fig. 4). The cold-start models, never reaching temperature above 700 K, even for the youngest ages.

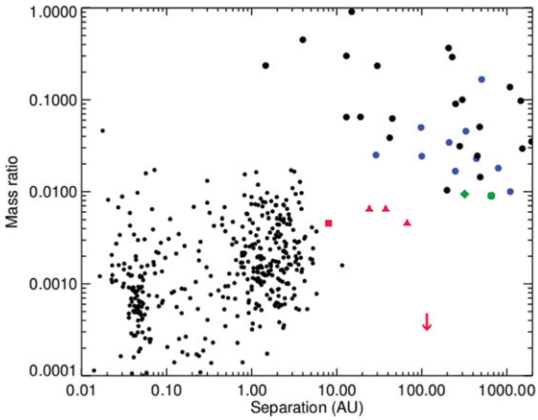

Figure 5. Mass ratio as a function of separation for various sub-stellar companions to stars. The green filled circle is HIP 78530b and the green filled diamond is 1RXS J160929.1- 210524b. The blue filled circles are all other directly imaged low-mass sub-stellar companions ($< 25M_{Jup}$). The large black filled circles are more massive directly imaged sub-stellar companions. The red triangles, square and down arrow are HR 8799b, c and d (Marois*et al.* 2008), β Pic b (Lagrange *et al.* 2009, 2010) and Fomalhaut b (Kalas *et al.* 2008), respectively. The small black circles indicate planets found by the radial velocity and microlensing techniques from the Extrasolar Planets Encyclopaedia (http://exoplanet.eu/).

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