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Search for wide substellar companions to young nearby stars with the VISTA Hemisphere Survey.

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Abstract

We have performed a search for substellar objects as common proper motion companions to young nearby stars (including members of the Young Moving Groups AB Doradus, TW Hydrae, Tucana-Horologium and Beta Pictoris, and the Upper Scorpius young association) up to separations of 50,000 AU, using the VISTA Hemisphere Survey and 2MASS astrometric and photometric data. We have found tens of candidates with spectral types from M to L, and estimated masses from low-mass stars to the deuterium-burning limit mass. For some of these candidates, we have also obtained optical and/or near-infrared spectroscopy confirming them as true companions. We present the preliminary results of our searches and discuss the most outstanding cases. Our studies show that the frequency of young companions is higher than of the field-age ones.

1 Introduction

Substellar objects (brown dwarfs and planetary-mass objects) have masses below the minimum mass required to stably burn hydrogen in their interiors. This limit is theoretically established around 0.072–0.080 solar masses [2], depending on factors such as metallicity.

Because of the lack of a stable hydrogen burning phase, substellar objects keep on cooling down with time, and their effective temperature and spectral type strongly depend on their age (see Fig. 10 in [8]). This makes it difficult to characterize the properties of substellar objects, such as the mass, when the age is unknown. Also, they become fainter with time, making it more difficult to find and observe them when they are old.

Searching for wide companions to young nearby stars have advantages to find, analyze and characterize new substellar objects. We can derive important properties, such as the age, the metallicity and the distance, from their brighter primaries. Moreover, substellar objects orbiting at very wide distances give us the opportunity to carry out a complete photometric and spectroscopic characterization, which is very challenging to obtain in the case of objects orbiting at very close distances from their primaries.

Theoretical evolutionary and atmospheric models in the substellar regime can be tested against these new benchmark objects. The known population of ultra-cool companions is still very limited, for example only a dozen of young planetary-mass objects have been found by direct imaging at distances higher than >100 AU (see [1] and references therein). Most of them have been found using adaptive optics, and are too close to their primaries to permit a thorough spectral characterization.

2 Looking for wide substellar companions: Search method

We have used direct imaging to search for common proper motion companions orbiting young nearby stars at separations up to 50,000 AU in the Upper Scorpius OB association (USco) and four Young Moving Groups (YMGs): AB Doradus, Beta Pictoris, Tucana-Horologium and TW Hydrae. To identify these companions, we have used proprietary data of the Vista Hemisphere Survey (VHS)[12] in combination with other public surveys.

VHS is a near infrared survey that will cover the whole southern celestial hemisphere to a depth around ∼4 magnitudes deeper than 2MASS and DENIS (up to $J < 20$, $Ks < 18$, Vega mag). It is carried out by the VISTA Telescope, a 4.1m modified Ritchey-Chrétien telescope operated by ESO in Cerro Paranal Observatory, Chile. This survey is almost complete at the moment.

To build the sample, we have made a compilation of ∼1,300 and ∼1,500 known members and candidates of USco and YMGs from the literature, respectively.

Then, we have cross-correlated the VHS catalog with near-infrared catalogs from public surveys to measure proper motions. For the YMGs search, we use the Two Micron All Sky Survey (2MASS) catalog [3], since the members of the YMGs are widely spread in the sky, and 2MASS covers the whole sky surface, although it is not as deep as VHS. For the search in USco, we use the UKIRT Infrared Deep Sky Survey Galactic Clusters Survey (UKIDSS GCS) [9], which covers the USco region in JHK to a similar depth as VHS.

We have also collected all the available photometric data from other catalogs such as 2MASS, DENIS, USNO, AllWise, PanSTARRS and SDSS to complete our study of the candidates. Gaia DR2 has also provided accurate proper motions and parallaxes for most of the primaries and the brightest candidate companions. This allowed us to discard casual

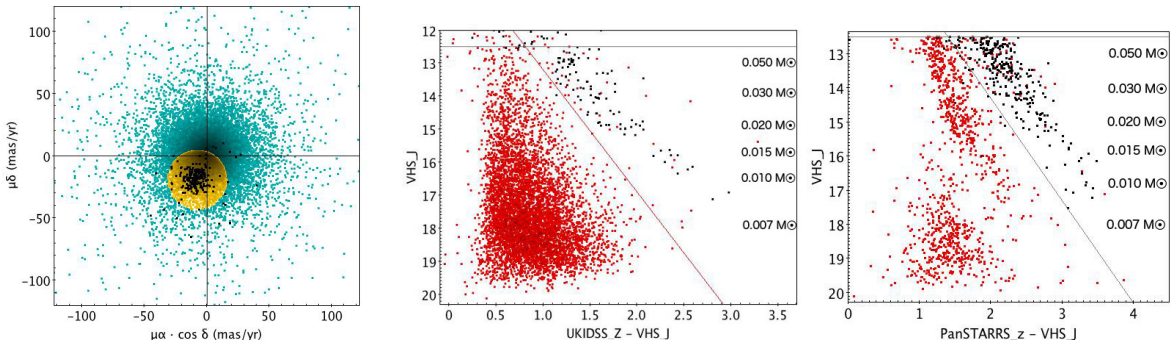

Figure 1: (Left panel) Proper motion selection of the USco candidates. Known members of USco are indicated as black dots, selected proper motion candidates within the circle as yellow dots, objects discarded as contaminants as green dots. (Middle and right panels) J vs Z-J color-magnitude diagrams with VHS+UKIDSS, and VHS+PanSTARRS photometry, in the middle and right panel respectively. USco known members are marked in black, objects selected by proper motion are marked in red. We used the lower envelope of the USco sequence in each diagram to select photometric candidates. We limit the selection to $J > 12.5$ mag to avoid saturated targets.

alignments and confirm the companionship of some of these systems.

3 Upper Scorpius

Upper Scorpius is a nearby young association, with an age of 5–10 Myr and placed at a distance of around ∼145 pc [13] [15].

For this search, we have cross-correlated VHS and UKIDSS GCS in a region of 60 arcsec around every known USco member or candidate member. This corresponds to separations up to ∼9,000 AU around each member at the mean distance of the association.

Figure 1 (left) shows the proper motion diagram for the selection of the candidates. Using VHS and UKIDSS GCS, we find a proper motion of $(-7.1, -18.3) \pm (6.9, 8.6)$ mas/yr for USco members. Candidates were selected with proper motions consistent with USco within a radius of 14.4 mas/yr, which is the RMS of the background objects with null motion. Since the proper motion is relatively low, and our selection criteria are generous, the results of this first selection step contain a high number of contaminants.

To filter out the contaminants, we have performed a photometric selection using J vs. J-Z color-magnitude diagrams. We determined the lower envelope of the distribution of known members in the color-magnitude diagram, and selected as good candidates those located above this envelope. We obtained Z-band photometry from UKIDSS GCS only for a fraction of the candidates, since this survey does not cover all the region in the Z-band, so for the candidates without Z-band information in GCS, we used PanSTARRS to perform a similar selection. Only targets with $J > 12.5$ mag were selected, as objects brighter than

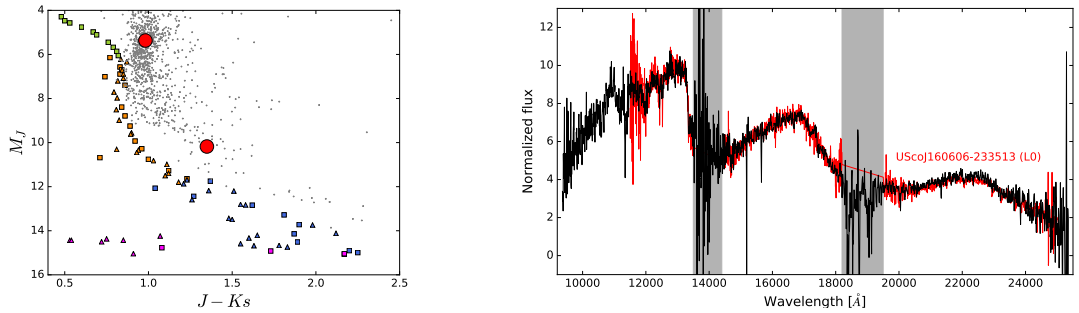

Figure 2: (Left panel) J vs *J-Ks* color-magnitude diagram for the USco M2.5+L0 system. USco known members are shown as gray dots. Field sequence from [14] (squares), [11] (orange triangles) and [4] (blue and pink triangles). Primary and companion are shown as red circles. (Right panel) Near Infrared spectrum of the wide L0 companion from NTT/SOFI (black). Spectrum of the USco known L0 member J160606-233513 from [10] (red) for comparison.

this may be affected by saturation in VHS. The middle and right panels of Figure 1 show the resulting color-magnitude diagrams.

We also used Gaia DR2 parallax and proper motion data for the brightest candidates, to discard foreground or background contaminants located at different distances than the association and distinguish true companions from chance alignments of USco members located at close positions in the sky but at different distances within the association. From Gaia DR2, we obtained a mean proper motion for Upper Scorpius of $(-11.7, -23.6) \pm (3.8, 3.3)$ mas/yr, which is more accurate than the previously reported value.

As a result of our searches, we found 35 wide companion candidates, 16 of which are new discoveries. Their expected spectral types range from M to L. The separation range explored for this search is 400–9,000 AU. These candidates have been already spectroscopically observed, and are under analysis and pending of confirmation at the moment. If confirmed, the rate of wide companions is $\sim$3%.

3.1 Example: A L0 companion to a M2.5 member of Upper Scorpius

One of the most interesting systems found in this search is a $J = 15.9$ mag brown dwarf companion, classified in the near-infrared as an L0 dwarf, orbiting at 3,000 AU of an M2.5 USco low-mass star. The estimated mass is around 15–20 Jupiter masses, which is slightly above the deuterium burning mass limit.

Fig 2 (left) shows the J vs *J-Ks* color-magnitude diagram for this system. Fig 2 (right) shows the infrared spectrum of the L0 companion obtained using SOFI spectrograph at NTT telescope in La Silla Observatory, in Chile.

4 Young Moving Groups: AB Doradus, Beta Pictoris, Tucana-Horologium and TW Hydrae.

For this search, we have cross-correlated VHS and 2MASS in the regions corresponding to physical separations up to 50,000 AU around each member, using their parallaxes from Gaia DR2, or their spectrophotometric distance for those primaries with no parallax.

We have included only YMG members belonging to the southern hemisphere (with available data from VHS), and proper motions higher than 60 mas/yr, to avoid contaminants. Around 650 primaries satisfied these criteria.

In this case, we have also performed a proper motion selection for the candidates, and we have used *J* vs. *J-Ks* color-magnitude diagrams to identify candidates compatible with being located at the same distance. For the brightest targets, we have also used Gaia DR2 parallaxes and proper motions to discard chance alignments or confirm companionship. For the candidates with no parallax, we have also used optical photometry from PanSTARRS, SDSS, DENIS and USNO when available to discard contaminants.

Table 1 shows the number of candidates found and expected companion rate. The results show a frequency of companion candidates higher than the frequency for field age [6], and also a possible tendence to a higher companion rate for the youngest moving groups. These results are preliminary and should be taken with caution since the newly identified candidates require spectroscopical confirmation and characterization.

Table 1: Companion candidates found

YMG	Age	Primaries searched	Systems found[a]	Comp. cand. rate	Comp. cand. rate (>M5)
AB Doradus	∼150 Myr	197	12	6.1±1.8%	3.6±1.3%
Tuc-Hor	∼45 Myr	320	19	5.9±1.4%	2.5±0.9%
β Pictoris	∼25 Myr	159	13	8.2±2.3%	3.1±1.4%
TW Hydrae	∼10 Myr	69	6	8.7±3.5%	7.2±3.2%

[a]Candidates need to be spectroscopically confirmed.

4.1 Example: An L-type companion to an M6 brown dwarf in Beta Pictoris

In these searches we have found a very interesting substellar object orbiting at 1,200 AU from the Beta Pictoris M6 brown dwarf 2MASS J0249-0557. The system is located at 30 pc from our Solar System. Using optical spectroscopy, we classified this object as a young L3 ± 1 dwarf. The estimated mass of the companion is around the deuterium burning mass limit.

The discovery of this companion has been recently reported by [5], who also find that the primary of the system is itself a binary.

Fig. 3 (left panel) shows the proper motion diagram for the 2MASS J0249-0557 system.

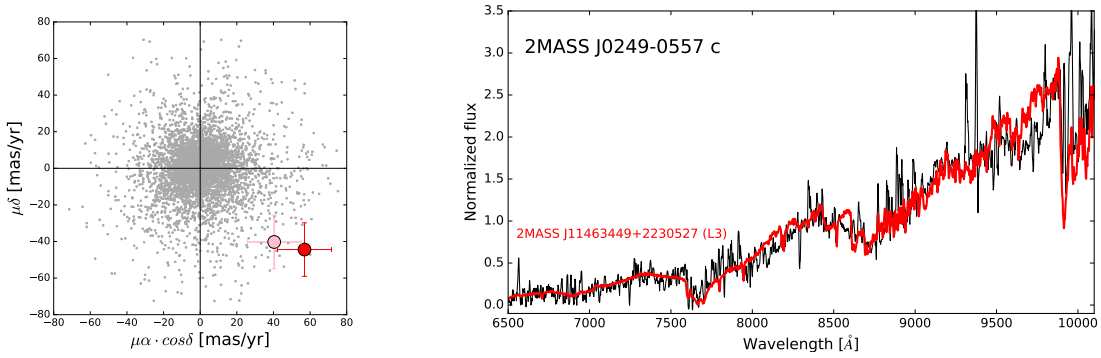

Figure 3: (Left) Proper motion diagram for the 2MASS J0249-0557 system. Primary is plotted in light pink, companion in red. (Right) Optical spectrum of 2MASS J0249-0557 c (black) from eBOSS, overplotted for comparison with an L3 standard (red) from [7].

Fig. 3 (right panel) shows the eBOSS optical spectrum of the L companion.

5 Summary and final remarks

- We have performed a search for common proper motion companions to young nearby stars in Upper Scorpius (∼5–10 Myr) and four Young Moving Groups: AB Doradus (∼150 Myr), Tucana-Horologium (∼45 Myr), Beta Pictoris (∼25 Myr) and TW Hydrae (∼10 Myr).

- We find an estimated companion rate for Upper Scorpius (mid-M to L) of around 3%.

- The preliminary companion rates for Young Moving Groups and USco are higher than the ones found for the field age and might depend on age.

- The candidate companions require spectroscopic confirmation.

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