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# Characterization of YSOs with XSHOOTER*

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**Abstract.** XSHOOTER is the first, second-generation spectrograph mounted at ESO/VLT, covering an impressive wide spectral range from 300-2500 nm in one exposure. One of the scientific aims of this state-of-the-art spectrograph is the full characterization of young stellar objects. The full characterization of a young stellar object entails obtaining its stellar parameters such as effective temperature, luminosity, and radius, as well as its kinematic properties such as radial velocity and projected rotational velocity. This makes XSHOOTER an ideal instrument for studying young stellar objects as members of stellar associations or wide companion candidates of young stars. In this paper, we study the limitations of XSHOOTER for the full characterization of very young stars, especially the faintest ones in the capability of the instrument to observe, with ages younger than 20 Myrs in Scorpius-Centaurus stellar association and $\beta$ Pictoris Moving Group.

**Key words.** Stars: young stellar objects – Instruments: VLT/XSHOOTER – Stars: young stellar populations – Stars: wide companions – Stars: radial velocity measurements – Stars: M-dwarfs

## 1. Introduction

This paper is an attempt to address several issues regarding the characterization of the Young Stellar Objects (YSOs) with VLT/XSHOOTER, in accordance with the topic of the HACK100 conference "Past, Present, and Future of Astrophysical Spectroscopy". XSHOOTER is the first second-generation, intermediate-resolution spectrograph of ESO VLT (Vernet et al., 2011), and has been vastly used for the full characterization of YSOs in young star forming regions in a series of papers (Alcalá et al., 2014, 2017, 2019; Frasca et al., 2015, 2017; Manara et al., 2013, 2017). In this paper, I address the limitations of performing spectroscopy for YSOs with this state-of-the-art spectrograph and the improvements in these cases that can be expected from the next-generation spectrographs. To this aim, I collectively discuss i) specific wide companion candidates located in Scorpius-Centaurus stellar association and $\beta$ Pictoris Moving Group, and ii) YSOs as new members of young star-forming regions (Scorpius-Centaurus stellar association and

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specifically Lupus I cloud) with XSHOOTER which have been thoroughly discussed in my previous and ongoing works (Majidi et al., 2020, and Majidi et al. 2022 submitted).

The discovery of multiple systems in young associations is of high importance because we expect the kinematics of these systems to still have a memory of the initial conditions of their parental cloud and be unaffected by interactions with nearby bodies, and this would especially contribute to our understanding of cloud fragmentation and star formation processes. For the case of close binaries, according to El-Badry & Rix (2019), $100 - 200$ (*au*) is the separation range below which binaries have a higher probability of forming via fragmentation of individual gravitationally unstable disks rather than through turbulent core fragmentation. Based on the findings of (Kouwenhoven et al., 2010; Moeckel & Clarke, 2011), in contrast, wider binaries appear to have formed during the dissolution phase of young star clusters and they cannot be explained through the star formation process or by dynamical interactions in the field. In line with this description, we expect the wide binaries to be younger and consequently be destroyed by dynamical interactions with individual stars and giant molecular clouds (Weinberg et al., 1987; Caballero, 2009; Jiang & Tremaine, 2010).

The wide companion candidates that I introduce in this paper were selected based on their similar kinematic properties to their central stars, which in turn are members of the large, young star-forming region, Scorpius-Centaurus, and only one of them belongs to the $\beta$ Pictoris Moving Group. The search for these targets was conducted using *Gaia* DR2 (for more details on the selection criteria see Majidi et al., 2020; Alcalá et al., 2020, and Majidi et al. 2022, submitted). It is noteworthy that all the targets analyzed in our works are M-dwarfs, with $J \leq 15$, which is the limiting observation magnitude for XSHOOTER. Already for objects with $14 \geq J \leq 15$ magnitude range, observed in a favorable condition, there are considerable uncertainties associated with their measured stellar parameters due to the intrinsic faintness of the targets and the rather low signal-to-noise ratio (SNR).

## 2. Uncertainties associated with the spectroscopic physical parameters of YSOs

In Majidi et al. (2020), we used two techniques to evaluate the stellar parameters of our YSO candidates. We used the Image Reduction and Analysis Facility (IRAF)[1] and our own software, ROTFIT, developed in IDL environment[2], optimized for performing spectral fitting for XSHOOTER spectra (Frasca et al., 2017). In the following, I discuss the limitations we encountered while analyzing the XSHOOTER spectra of our targets for understanding i) whether two objects are physically bound, ii) whether a YSO is a genuine member of a young star-forming region.

### *2.1. Wide companion candidates*

#### 2.1.1. Radial velocity measurements

For wide companion candidates (in addition to being coeval and having consistent parallax and proper motions with the central star), to determine whether two objects are physically bound, their radial velocities (RVs) should be consistent. The RVs and $v \sin i$ of our targets are determined using the ROTFIT code (Frasca et al., 2017). With the XSHOOTER spectra, the precision of RVs at best is ~2 km/s. In order to understand whether two objects with similar kinematic properties are gravitationally bound, we calculated the maximum total velocity difference ($\Delta V_{max}$) as a function of projected separation between the binary components, suggested by Andrews et al. (2017). It should be noted, however, that the theoretical maximum velocity difference modeled by Andrews et al. (2017) is only valid for binaries (and systems

[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of the Universities for Research in Astronomy, inc. (AURA) under cooperative agreement with the National Science Foundation.

[2] IDL (Interactive Data Language) is a registered trademark of Harris Corporation.

**Table 1.** Kinematic properties of the targets characterized in Majidi et al. (2020) in addition to their associated stellar systems, presented in each block separately. The RVs that are not cited are measured by Majidi et al. (2020), the rest of the RVs are borrowed from the literature.

| Name | parallax (mas) | $\mu_\alpha$ (mas/yr) | $\mu_\delta$ (mas/yr) | RV (km/s) |
|---|---|---|---|---|
| 2MASS J1815-3249 | 13.12±0.054 | 1.07±0.095 | −52.74±0.078 | −20.1±2.0 |
| V4046Sgr | 13.81±0.064 | 3.49±0.11 | −52.75±0.087 | −6.94±0.16[1] |
| GSC 7396-00759 | 13.99±0.052 | 3.08±0.10 | −52.64±0.08 | −6.10±0.5[2] |
| 2MASS J1517-3028 | 8.16±0.11 | −21.67±0.21 | −28.31±0.18 | 1.4±2.4 |
| HIP 74865 | 8.09±0.061 | −21.07±0.11 | −28.42±0.10 | 2.0±0.3[3] |
| 2MASS J1324-5129 | 8.01±0.35 | −31.85±0.53 | −17.07±0.44 | 15.29±5.75 |
| HIP 65426 | 9.16±0.062 | −34.25±0.10 | −18.81±0.093 | 12.2±0.3[4] |
| 2MASS J1457-3543 | 9.86±0.42 | −28.68±0.68 | −27.3± 0.65 | 8.0±7.8 |
| HIP 73145 | 7.48±0.20 | −23.35±0.26 | −24.94±0.30 | 3.8±1.6[5] |
| 2MASS J1549-3539 | 6.59±0.05[6] | −14.81±0.97 | −21.95±0.65 | −2.0±2.8 |
| GQ Lup | 6.59±0.05 | −14.26±0.01 | −23.6±0.07 | −3.6±1.3[7] |
| GQ Lup B | 7.2±2.1 | - | - | 2.0±0.4[8] |

[1] RV measured by Stempels & Gahm (2004). [2] RV measured by Sissa et al. (2018). [3] RV measured by Kharchenko et al. (2007). [4] RV measured by Petrus et al. (2021). [5] Private communication with A. Frasca. [6] Due to the unreliable astrometric parameters of GQ Lup C, the parallax of GQ Lup has been adopted for this target; see Alcalá et al. (2020) for more information. [7] RV measured by Frasca et al. (2017). [8] RV measured by Schwarz et al. (2016).

of no higher multiplicity) of total mass 10 $M_\odot$ in circular orbits.

The results of the test are displayed in Fig. 1, and the kinematic properties of our targets and their candidate central stars are listed in Table 1. For convenience, the name of our targets are consistently abbreviated as: 2MASS J18152222-3249329 is referred to as 2MASS J1815-3249, 2MASS J15174874-3028484 as 2MASS J517-3028, 2MASS J13242119-5129503 as 2MASS J1324-5129, 2MASS J14571503-3543505 as 2MASS J1457-3543, and 2MASS J15491331-3539118 as 2MASS J1549-3539. These targets are fully introduced in Majidi et al. (2020), and their observation log can be found in Table 2, as well as their colors in NIR and VIS bands in Table 3.

As indicated in Fig. 1, the errors associated with the measured $\Delta V$ for all pairs of objects are rather large. In order to conclusively determine whether two objects are gravitationally bound, an RV precision of the order of a few m/s is required (Kervella et al., 2017), hence, with XSHOOTER, we can only determine wide companion *candidates* and whether these candidates are physically associated will be answered through follow-up programs with next generation spectrographs that can both observe faint targets and measure RVs with higher precision. At the moment, considering both the faintness of the targets and the resolution of XSHOOTER, there are no available spectrographs that can fulfill this task.

**Table 2.** Observation log of the targets characterized in Majidi et al. (2020). SLCF stands for slit loss correction factor. Nodding slits, the allocated exposure time to each arm (with the number of single observations presented as a multiplication factor), seeing, and SLCF are reported in order for UVB, VIS, and NIR arms. $T_{tot}$ presents indicates the total execution.

| Name | Date (yyyy-mm-dd) | $\alpha$ (J2000) (h:m:s) | $\delta$ (J2000) (d:m:s) | Nodding slits ($''$) | Exposure time (sec) | Seeing ($''$) | $T_{tot}$ (hour) | SLCF | airmass |
|---|---|---|---|---|---|---|---|---|---|
| 2MASS J1815-3249 | 2019-05-24 | 18 15 22.23 | −32 49 33.07 | 0.″5,0.″4,0.″4 | 2×/450/400/450 | 0.955/0.875/0.805 | 0.7 | 1.35/1.35/1.35 | 1.01 |
| 2MASS J1517-3028 | 2019-05-24 | 15 17 48.75 | −30 28 48.42 | 1.″0,0.″9,0.″9 | 2×/800/750/800 | 1.01/1.01/1.01 | 1 | 1.5/1.5/1.6 | 1.09 |
| 2MASS J1324-5129 | 2019-07-04 | 13 24 21.18 | −51 29 50.39 | 1.″0,0.″9,0.″9 | 4×/800/750/800 | 0.905/0.905/0.895 | 1.5 | 1.47/1.34/1.45 | 1.21 |
| 2MASS J1457-3543 | 2019-05-30 | 14 57 15.03 | −35 43 50.64 | 1.″0,0.″9,0.″9 | 4×/800/750/800 | 0.66/0.66/0.66 | 1.5 | 1.22/1.22/1.39 | 1.18 |
| 2MASS J1549-3539 | 2019-06-25 | 15 49 13.30 | −35 39 11.79 | 1.″0,0.″9,0.″9 | 4×/800/750/800 | 1.98/1.965/1.965 | 1.5 | 2.6/2.2/2.0 | 1.05 |

**Table 3.** Photometric colors of the targets characterized in Majidi et al. (2020).

| Name | *BP-RP* (mag) | *J* (mag) | *H* (mag) | *Ks* (mag) | *G* (mag) |
|---|---|---|---|---|---|
| 2MASS J1815-3249 | 2.25 | 11.07 | 10.44 | 10.2 | 13.6 |
| 2MASS J1517-3028 | 3.18 | 12.54 | 11.93 | 11.64 | 15.8 |
| 2MASS J1324-5129 | 3.87 | 14.59 | 14.04 | 13.63 | 18.71 |
| 2MASS J1457-3543 | - | 14.13 | 13.5 | 13.1 | 18.52 |
| 2MASS J1549-3539 | 2.75 | 14.85 | 14.08 | 13.82 | 18.37 |

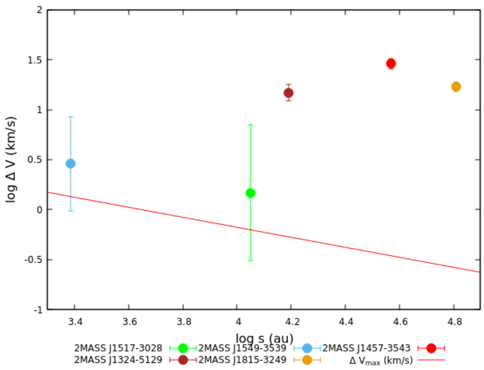


**Fig. 1.** Log–log plot of total velocity difference $\Delta V$ (km/s) vs. projected separation $s$ (au) for the five wide companions studied in Majidi et al. (2020). $\Delta V_{max}$ (km/s) (diagonal, red line) indicates the maximum total velocity difference that bound binaries with a total mass of 10 $M_{\odot}$ in circular orbits can have.

### 2.1.2. The curious case of 2MASS J1457-3543

The YSOs introduced in this paper are all expected to be younger than ∼25 Myrs. For these objects, besides directly determining their age according to their luminosity and effective temperature with the aid of isochrones such as (Baraffe et al., 2015), the detection of Li I (6707 Å) absorption line in their spectra is a major signature of youth. The non-detection of Li I, hence, can cast doubt over the membership of a target in young star-forming regions, or even its very youth.

Among our fully characterized targets in Majidi et al. (2020), we could not detect Li I in the spectrum of 2MASS J1457-3543 ($EW_{\mathrm{Li\,I}} <$ 0.39 Å, with three sigma upper limits on the measurement). This target with an age of 14.1 Myr and spectral type of M8±0.5, has a locally low SNR around the lithium line (∼2.5 as measured directly on the spectrum), and is a particularly fast rotator ($v \sin i = 62.0 \pm 10.0$ km/s). While its spectral lines are very broad, there are no indications of the blending of additional components. Its renormalized unit weight error (RUWE) is less than 1.4, which confirms that its astrometry is reliable and further proves that there are no signs of binarity associated with the target. The lack of Li I in its spectrum thus may hint at an older age (80-150 Myrs), which is consistent with its high activity level and fast rotation. Or, the non-detection of Li I can be simply associated with the intrinsic faintness of the star ($J$ = 14.13 mag) and low SNR, which makes 2MASS J1457-3543 an interesting target to be followed up by next-generation spectrographs to shed light on its stellar parameters.

The required SNR for measuring the $EW_{LiI}$ with an assumed error of 0.1 Å(with a three-sigma upper limit) would be at least 12 (Cayrel, 1988), which is six times the SNR measured on the spectrum of this target. 2MASS J1457-3543 was supposed to be the wide companion of HIP 73145, and we were hoping that finding a gravitationally bound companion to this star could provide us with hints on the formation of the multi-belt architecture of its disk. Hence, we conclude that because there are no stellar and massive brown dwarf companions over the full range of separations, the features in the disk of HIP 73145 cannot be linked to external objects.

## 2.2. New members of the Lupus I cloud

Among the wide companions studied in the previous subsection, 2MASS J1549-3539 (GQ Lup C) was found to be a strong accretor and surrounded by a disk (Alcalá et al., 2020; Lazzoni et al., 2020), a genuine wide companion of GQ Lup stellar system, and a new member of the Lupus I cloud. This target had surprisingly escaped the $H_\alpha$ surveys, and hence intrigued us to search for similar genuine members of Lupus I that have been neglected in the literature. With this aim, we searched in *Gaia* DR2 for potential members of Lupus I cloud with i) consistent age with those of the Lupus members using a color-magnitude diagram, ii) consistent kinematic properties with the genuine members of the Lupus I.

As discussed in the previous section, one of the major signatures of youth for stars is containing Li I (6707 Å). This is especially true for objects within the age range of Lupus members (younger than 3 Myrs). However, there are also confirmed Lupus members which do not contain Lithium, such as Sz 94 in Lupus III cloud (Frasca et al., 2017; Biazzo et al., 2017). According to a very recent study by Binks et al. (2022), there actually might not be a direct correlation between the $v \sin i$ and the lithium depletion of YSOs. On this note, after the full characterization of the new potential members of Lupus I (12 objects in total), according to our primary results, we identified new objects in the region that also do not contain Lithium contrary to our expectations from the YSOs located in the same region:

i) 2MASS J15414827-3501458 : this target is an M4±0.5 star, with the age of ~2 Myrs and $J$ = 11.05 mag. Although the object is bright and its XSHOOTER SNR is sufficient for fulfilling our scientific aims (~100 in the visible range), we could not detect Lithium in its spectrum ($EW_{\mathrm{Li\,I}}$ < 0.012 Å, with three sigma upper limits on the measurement). Like 2MASS J1457-3543, this object is also a fast rotator, $v \sin i$ = 53.3±5.7 (km/s). Similarly, for this target, there are no signs of spectral binarity. Fast rotators, however, have been shown to retain their Lithium (Constantino et al., 2021), unlike slow rotators which are more likely to deplete their Lithium at young ages. Thus, for this target, the same as Sz 94 which is again a fast rotator $v \sin i$ = 38.0±3.0 km/s (Frasca et al., 2017) or 2MASS J1457-3543, there may be other mechanisms involved that have led them to deplete their Lithium at very early ages.

ii) 2MASS J15361110-3444473 : amongst one of the faintest targets observed by XSHOOTER ($J$ = 14.91 mag), 2MASS J15361110-3444473 has shown plenty of particular features. Besides being a strong accretor ($EW_{H_\alpha}$ ~ –71.4±8.77 Å, and log $L_{acc}$ = -2.85 $L_\odot$), this target has an age of ~ 10 Myrs, and is a slow rotator $v \sin i$ = 13.0±10.0 km/s. According to its visible spectrum (500-1000 nm), the target is an M5.5±0.5 star, while according to its NIR spectrum (1000-2500 nm), it is an M8±0.5 star. Hence, we concluded that 2MASS J15361110-3444473 is probably an unresolved binary. Additionally, despite its young age, we again could not detect Lithium in its spectrum ($EW_{\mathrm{Li\,I}}$ < 0.25 Å, with three sigma upper limits on the measurement). With a very low SNR in its visible spectrum (~5) due to its intrinsic faintness, 2MASS J15361110-3444473 was observed in a favorable condition. Hence, it is not feasible to conduct further follow-up for this target with the available spectrographs. But with all its remarkable stellar features, 2MASS J15361110-3444473 is definitely an object of interest for next-generation spectrographs that can comment on its possible binarity and lacking/containing Lithium. Due to its lack of photometric data (except for 2MASS $J, H, K$ colors and $G$ in visible), any further comments on the object's surroundings, for example the possibility of the star containing a disk, is not currently possible.

The details of this study are published in Majidi et al. (2022).

## 3. Conclusions

In this paper, I discussed several issues regarding the characterization of objects with XSHOOTER (Majidi et al., 2020; Alcalá et al., 2020; Majidi et al., 2022). The main highlights of this paper can be summarized as follows:

- With the RV precision of $\sim$2 km/s, at its best, XSHOOTER is not able to identify the genuine stellar wide companions, but rather, identifies the wide companion *candidates*. The advantage of this state-of-the-art instrument is that it can observe faint objects ($J < 15$ mag) that are not possible to be fully characterized with other available instruments.
- There are YSOs for which we could not detect Li I (6707 Å), and for different reasons as discussed in detail, and this would cast doubt on their youth or genuine membership in stellar clusters. We believe that targets such as the one introduced in this paper would contribute to leading, larger studies such as those conducted by Binks et al. (2022) which widely discuss the relationship between $v \sin i$ and Lithium depletion.

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