X-Shooter characterization of very wide companion candidates to young stars with planets and disks

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- Introducing the capabilities of X-Shooter
- Introducing the targets
- Criteria for determining a new wide companion candidate
- Results of the characterization
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Wide companions (1000au-1pc) are important
- Benchmarks for studying stellar/planet evolution (multiplicity statistics, dynamical environment of stars w/wo planets, w/wo disks)
- Constraining the age of the associated stellar system

Selected based on their similar kinematic properties to the central star (Gaia DR2) that is already a member of a stellar association

Characterizing unknown objects belonging to a stellar association is important
- New members will be identified
- We can constrain the age of the association more accurately
- Disk fraction of the association can be studied
X-Shooter

- The first 2nd generation instrument of the ESO Very Large Telescope (VLT)
- Very efficient
- Single-target
- Intermediate-resolution spectrograph (R \sim 4000–17,000, depending on wavelength and slit width)
- In a single exposure, covers the spectral range from 300 to 2500 nm

| Characteristic                        | Specification                                      |
|---------------------------------------|----------------------------------------------------|
| Wavelength range                      | 300-2500 nm split over 3 arms                     |
| UV-Blue arm                           | Range: 300-550 nm in 11 orders                    |
| Resolution:                           | 4500 (1" slit)                                    |
| Detector:                             | 4k x 2k E2V CCD                                   |
| Visual-red arm                        | Range: 550-1000 nm in 14 orders                   |
| Resolution:                           | 7000 (1" slit)                                    |
| Detector:                             | 4k x 2k MIT/LL CCD                                |
| Near-IR arm                           | Range: 1000-2500 nm in 16 orders                  |
| Resolution:                           | 4500 (1" slit)                                    |
| Detector:                             | 2k x 1k Hawaii 2RG                                 |
| Slit length                           | 12"                                               |
| Beam separation                       | Two high efficiency dichroics                     |
| Atmospheric dispersion compensation  | In the UV-Blue and Visual-red arms                |
| Integral field unit                   | 1.8" x 4" reformatted into 0.6" x 12"             |
X-Shooter Characterization of New Wide Companions

| Name       | Distance $^a$ (pc) | Association | SpT  | $T_{\text{eff}}$ (K) | $A_v$ (mag) | Wide companion | Separation ($''$) | Separation (au) |
|------------|--------------------|-------------|------|----------------------|-------------|-----------------|------------------|-----------------|
| V4046Sgr   | 72.4               | β-Pictoris MG | K5/K7| 4370/4100            | 0 $^b$      | 2MASS J1815-3249| 901              | 65232           |
| HIP 74865  | 123.53             | Sco-Cen (UCL) | F3V  | 6720                 | 0           | 2MASS J1517-3028| 90               | 11118           |
| HIP 65426  | 109.21             | Sco-Cen (LCC) | A2V  | 8840                 | 0           | 2MASS J1324-5129| 142              | 15508           |
| HIP 73145  | 133.65             | Sco-Cen (UCL) | A2IV | 8840                 | 0           | 2MASS J1457-3543| 280              | 37422           |
| GQ Lup     | 151.82             | Sco-Cen (Lupus I) | K7V | 4070                 | 0.7 $^c$    | 2MASS J1549-3539| 16               | 2429            |

$^a$ Distances are calculated based on the objects’ parallax reported in Gaia DR2 catalog.

$^b$ (Stempels & Gahm 2004)

Majidi et al. 2020 (A&A)

- Upper Centaurus-Lupus (UCL) – 15±3 Myr (Pecaut & Mamajek 2016)
- Lower Centaurus-Crux (LCC) – 16.0±2.2 Myr (Pecaut & Mamajek 2016)
- Upper Scorpius (US) – 11±2 Myr (Pecaut et al. 2011)
# X-Shooter Characterization of New Wide Companions

## Criteria

| Name                  | Consistent kinematic properties with the stellar system (yes/no) | Age        | Active (yes/no) | Contains Li T (yes/no) | Conclusion                                      |
|-----------------------|----------------------------------------------------------------|------------|-----------------|------------------------|-------------------------------------------------|
| 2MASS J1815-3249      | no                                                             | MS         | no              | no                     | field object                                    |
| 2MASS J1517-3028      | yes                                                            | PMS        | yes             | yes                    | UCL member + HIP 74865 probable wide companion  |
| 2MASS J1324-5129      | yes                                                            | PMS        | yes             | yes                    | ambiguous                                       |
| 2MASS J1457-3543      | no                                                             | PMS        | yes             | ambiguous              | Lupus I new member + GQ Lup probable wide companion |
| 2MASS J1549-3539      | yes                                                            | PMS        | yes             | yes                    |                                                 |

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**Pecaut & Mamajek (2016)**

**White & Basri (2003)**
GQ Lup’s new wide companion candidate, GQ Lup C

- a wide (projected separation ~16".0, or 2400 AU) companion of the GQ Lup A-B system
- a bonafide low-mass (~0.15 $M_{\odot}$) young stellar object (YSO) with stellar and accretion/ejection properties typical of Lupus YSOs of similar mass
- with kinematics consistent with that of the GQ Lup A-B system
- the disk of the target was resolved on the HST images (Lazzoni et al. 2020)
- (roughly aligned with the disk of the GQ Lup)
  ** Both of them are roughly aligned with the Lupus I dust filament containing GQ Lup.
- Not-conclusive: a possible scenario for the formation of the triple system is that GQ Lup A and C formed by fragmentation of a turbulent core in the Lup I filament, while GQ Lup B (BD companion of GQ Lup A at 0".7), formed in-situ by the fragmentation of the circumpprimary disc
  -- The recent discoveries that stars form along cloud filaments would favor the scenario of turbulent fragmentation for the formation of GQ Lup A and C.

Alcala’, Majidi, Desidera, et al. 2020 (A&A)
# X-Shooter Characterization of New Wide Companions

IRAF + Pecaut & Mamajek 2016 + Baraffe et al. 2015 isochrones

| Name          | SpT    | $T_{\text{eff}}$ (K) | $A_V$ (mag) | RV (km/s) | $L_*$ ($L_\odot$) | $R_*$ ($R_\odot$) | $M_*$ ($M_\odot$) | Age (Myr) | log $g$ |
|---------------|--------|----------------------|-------------|-----------|-------------------|-------------------|-------------------|-----------|--------|
| 2MASS J1517-3028 | M4.5±0.5 | 3100                 | 0           | 1.2±6.9   | 0.018             | 0.47              | 0.11              | 7.9       | 4.13   |

**ROTFIT**

| Name          | $T_{\text{eff}}$ (K) | log $g$   | RV (km/s) | $v \sin i$ (km/s) | Age (Myr) |
|---------------|----------------------|-----------|-----------|--------------------|-----------|
| 2MASS J1517-3028 | 3077±22             | 4.49±0.21 | 1.4±2.4   | 26±6               | 7.4±0.5   |

**BANYAN Σ**

(Gagné et al. 2018)  
UCL membership (> 98%)

**UCL sub-association’s age (15±3 Myr)**

| Name          | parallax (mas) | $\mu_\alpha$ (mas/yr) | $\mu_\delta$ (mas/yr) | RV (km/s) |
|---------------|----------------|------------------------|------------------------|-----------|
| 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   |

**Hosts a BD**

| Name          | $EW_{\text{Li}}$ (nm) | $EW_{H\alpha}$ (nm) | $EW_{H\beta}$ (nm) | $EW_{H\gamma}$ (nm) |
|---------------|------------------------|----------------------|---------------------|---------------------|
| 2MASS J1815-3249 | < 0.0036              | 0.012±0.001          | -0.034±0.003        | -0.013±0.005 |
| 2MASS J1517-3028 | 0.038±0.008           | -1.083±0.055         | -1.019±0.067        | -1.126±0.201        |
| 2MASS J1324-5129 | 0.070±0.020           | -1.068±0.142         | -0.659±0.149        | -0.723±0.129        |
| 2MASS J1457-3543 | < 0.039              | -0.983±0.090         | -0.789±0.166        | -0.886±0.135        |

Asensio-Torres et al. (2019), Feiden (2016)
**X-Shooter Characterization of New Wide Companions**

**IRAF + Pecaut & Mamajek 2016 + Baraffe et al. 2015 isochrones**

| Name         | SpT | $T_{\text{eff}}$ (K) | $A_U$ (mag) | RV (km/s) | $L_\star$ ($L_\odot$) | $R_\star$ ($R_\odot$) | $M_\star$ ($M_\odot$) | Age (Myr) | log $g$ |
|--------------|-----|-----------------------|-------------|-----------|------------------------|------------------------|------------------------|-----------|--------|
| 2MASS J1324-5129 | M6.5±0.5 | 2710 | 0 | 15.3±5.8 | 0.0024 | 0.22 | 0.04 | 18.2 | 4.35 |

**ROTFIT**

| Name         | $T_{\text{eff}}$ (K) | log $g$ | RV (km/s) | $v \sin i$ (km/s) | Age (Myr) |
|--------------|-----------------------|--------|-----------|-------------------|-----------|
| 2MASS J1324-5129 | 2646±50 | 4.0±0.1 | 17.9±3.0 | < 8.0 | 16±2.2 |

**Hosts a planet**

| Name         | parallax (mas) | $\mu_\alpha$ (mas/yr) | $\mu_\delta$ (mas/yr) | RV (km/s) |
|--------------|----------------|------------------------|------------------------|-----------|
| 2MASS J1324-5129 | 8.01±0.35 | -31.85±0.53 | -17.07±0.44 | 15.29±5.75 |
| HIP 65426     | 9.16±0.62 | -34.25±0.10 | -18.81±0.093 | 12.2±0.3 |

**New member of LCC (16±2 Myr)**

BANYAN Σ (Gagné et al. 2018) LCC membership (∼94%)
X-Shooter Characterization of New Wide Companions

| Name            | SpT     | $T_{\text{eff}}$ (K) | $A_V$ (mag) | $RV$ (km/s) | $L_*$ ($L_{\odot}$) | $R_*$ ($R_{\odot}$) | $M_*$ ($M_{\odot}$) | Age (Myr) | log $g$ |
|-----------------|---------|----------------------|-------------|-------------|----------------------|----------------------|----------------------|------------|--------|
| 2MASS J1324-5129| M6.5±0.5| 2710                 | 0           | 15.3±5.8    | 0.0024               | 0.22                 | 0.04                 | 18.2       | 4.35   |

ROTFIT

| Name            | $T_{\text{eff}}$ (K) | log $g$ | $RV$ (km/s) | $v$ sin $i$ (km/s) | Age (Myr) |
|-----------------|----------------------|--------|-------------|-------------------|------------|
| 2MASS J1324-5129| 2646±50              | 4.0±0.1| 17.9±3.0    | < 8.0             | 16±2.2     |

Andrews et al. (2017)

$$\Delta v_{\text{max}} = 2.11\sqrt{1000\alpha u/s (km/s)}$$

$$\Delta v = \sqrt{(v_{t1, pmra} - v_{t2, pmra})^2 + (v_{t1, pmdec} - v_{t2, pmdec})^2 + (RV1 - RV2)^2},$$

BANYAN $\Sigma$ (Gagné et al. 2018)

LCC membership ($\sim$94%)
# X-Shooter Characterization of New Wide Companions

## Conclusion

| Name            | Consistent kinematic properties with the stellar system (yes/no) | Age | Active (yes/no) | Contains Li I (yes/no) | Conclusion                                      |
|-----------------|---------------------------------------------------------------|-----|-----------------|------------------------|--------------------------------------------------|
| 2MASS J1815-3249 | no                                                            | MS  | no              | no                     | field object                                     |
| 2MASS J1517-3028 | yes                                                           | PMS | yes             | yes                    | UCL member + HIP 74865 probable wide companion  |
| 2MASS J1324-5129 | yes                                                           | PMS | yes             | yes                    | LCC new member                                    |
| 2MASS J1457-3543 | no                                                            | PMS | yes             | ambiguous              | ambiguous                                         |
| 2MASS J1549-3539 | yes                                                           | PMS | yes             | yes                    | Lupus I new member + GQ Lup probable wide companion |

**Pecaut & Mamajek (2016)**

**White & Basri (2003)**
X-Shooter Characterization of New Wide Companions

Conclusions

Two (three?) probable triple systems

- 2MASS J1517-3028 as the wide companion of HIP 74865 and HIP 74865 B (Majidi et al. 2020, A&A)
  (no disk, not accreting matter)
- GQ Lup C as the wide companion of GQ Lup and GQ Lup B (Alcala’, Majidi, Desidera et al. 2020, A&A)
  (disk, accreting matter)

- HD 284149 ABb triple system configuration (Bonavita et al. 2017) – substellar companion (HD 284149 b) has a larger separation from the central star compared to the low-mass stellar companion (HD 284149 B).

- Different formation mechanisms
- Hinting at larger multiple systems
  1) Multiple systems are three times more likely to have a distant companion within 10 kau
  2) Ultra-wide companions are biased towards high multiplicity at shorter separations (Joncour et al. 2017)
  3) Cascade fragmentation scenario of the natal molecular core (Joncour et al. 2017)
Thank You!
X-Shooter Characterization of New Wide Companions

| Name          | SpT   | $T_{\text{eff}}$ (K) | $A_v$ (mag) | RV (km/s) | $L_*$ ($L_\odot$) | $R_*$ ($R_\odot$) | $M_*$ ($M_\odot$) | Age (Myr) | log $g$ |
|---------------|-------|----------------------|-------------|-----------|-------------------|-------------------|-------------------|-----------|--------|
| 2MASS J1815-3249 | M3±0.5 | 3410                 | 0           | −17.7±2.4 | 0.03              | 0.5               | 0.3               | > 150     | 4.95   |

** ROTFIT **

| Name          | $T_{\text{eff}}$ (K) | log $g$ | RV (km/s) | $\nu$ sin $i$ (km/s) | Age (Myr) |
|---------------|----------------------|--------|-----------|----------------------|-----------|
| 2MASS J1815-3249 | 3562±30              | 4.68±0.14 | −20.1±2.0 | < 8.0               | > 150     |

** Age of β-Pictoris MG 25 ± 3 Myr (Messina et al. 2016c)**

| 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 |
| GSC 7396-00759 | 13.99±0.052    | 3.08±0.10              | −52.64±0.08            | −6.10±0.5 |

| Name          | $E_{\text{W} \lambda_{11}}$ (nm) | $E_{\text{W} \lambda_{H\alpha}}$ (nm) | $E_{\text{W} \lambda_{H\beta}}$ (nm) | $E_{\text{W} \lambda_{H\gamma}}$ (nm) |
|---------------|----------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| 2MASS J1815-3249 | < 0.0036 $^a$                 | 0.012±0.001                        | −0.034±0.003                       | −0.013±0.005                      |
| 2MASS J1517-3028 | 0.038±0.008                    | −1.083±0.055                      | −1.019±0.067                      | −1.126±0.201                      |
| 2MASS J1324-5129 | 0.070±0.020                    | −1.068±0.142                      | −0.659±0.149                      | −0.723±0.129                      |
| 2MASS J1457-3543 | < 0.039 $^a$                   | −0.983±0.090                      | −0.789±0.166                      | −0.886±0.135                      |

$^a$: Uncertainty in the EW measurement.
X-Shooter Characterization of New Wide Companions

IRAF + Pecaut & Mamajek 2016 + Baraffe et al. 2015 isochrones

| Name         | SpT | $T_{\text{eff}}$ (K) | $A_v$ (mag) | RV (km/s) | $L_*$ ($L_\odot$) | $R_*$ ($R_\odot$) | $M_*$ ($M_\odot$) | Age (Myr) | log $g$ |
|--------------|-----|----------------------|-------------|-----------|-------------------|-------------------|-------------------|-----------|--------|
| 2MASS J1457-3543 | M8±0.5 | 2500 | 0 | 4.0±8.9 | 0.002 | 0.24 | 0.02 | 14.09 | 4.00 |

ROTFIT

| Name         | $T_{\text{eff}}$ (K) | log $g$ | RV (km/s) | $v\sin i$ (km/s) | Age (Myr) |
|--------------|----------------------|---------|-----------|------------------|-----------|
| 2MASS J1457-3543 | 2635±80 | 4.30±0.17 | 8.0±7.8 | 62.0±10.0 | 17.75±4.15 |

| Name         | parallax (mas) | $\mu_\alpha$ (mas/yr) | $\mu_\delta$ (mas/yr) | RV (km/s) |
|--------------|---------------|------------------------|------------------------|-----------|
| 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 |

| Name         | $EW_{Li\text{I}}$ (nm) | $EW_{H\alpha}$ (nm) | $EW_{H\beta}$ (nm) | $EW_{H\gamma}$ (nm) |
|--------------|------------------------|----------------------|---------------------|---------------------|
| 2MASS J1815-3249 | < 0.0036 $^a$ | 0.012±0.001 | −0.034±0.003 | −0.013±0.005 |
| 2MASS J1517-3028 | 0.038±0.008 | −1.083±0.055 | −1.019±0.067 | −1.126±0.201 |
| 2MASS J1324-5129 | 0.070±0.020 | −1.068±0.142 | −0.659±0.149 | −0.723±0.129 |
| 2MASS J1457-3543 | < 0.039 $^a$ | −0.983±0.090 | −0.789±0.166 | −0.886±0.135 |

three-sigma upper limit on the flux of the Lithium line (Cayrel 1988)

\[
dEW = 3 \times 1.06 \sqrt{(FWHM) dx / SNR}
\]
Renormalized Unit Weight Error (RUWE)

- 68 out of 588 of them have RUWE > 1.4
- RUWE = 1.174 that is below RUWE \sim 1.4

597 out of 697 UCL members have a significant astrometric-excess-noise

SpT calculated based on G-mag (Kiman et al. 2019)

An age of 80-150 Myr
- compatible with the high activity level and fast rotation.
- alternatively, activity and rotation might be induced by a close companion through tidal locking
- astrometric-excess-noise = 0.99 mas, with a significant astrometric-excess-noise-sigma of 3.29
- however, a very close, tidally-locked binary is not expected to cause significant astrometric effects
- while the spectral lines are very broad, there are no indications of blending of additional components.

Majidi et al. 2020 (A&A)
We were hoping that finding a companion gravitationally bound to this star could provide us with hints on the formation of the multi-belt architecture of its disk. The lack of stellar and massive brown dwarf companions over the full range of separations suggests that these features in the disk are not linked to external objects.

| Name         | Parallax (mas) | $\mu_\alpha$ (mas/yr) | $\mu_\delta$ (mas/yr) | RV (km/s) |
|--------------|----------------|------------------------|------------------------|-----------|
| 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   |