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New members of the TW Hydrae Association and two accreting M-dwarfs in Scorpius–Centaurus

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ABSTRACT

We report the serendipitous discovery of several young mid-M stars found during a search for new members of the 30–40 Myr-old Octans Association. Only one of the stars may be considered a possible Octans(-Near) member. However, two stars have proper motions, kinematic distances, radial velocities, photometry and Li I λ6708 measurements consistent with membership in the 8–10 Myr-old TW Hydrae Association. Another may be an outlying member of TW Hydrae but has a velocity similar to that predicted by membership in Octans. We also identify two new lithium-rich members of the neighbouring Scorpius–Centaurus OB Association (Sco–Cen). Both exhibit large 12 and 22 μm excesses and strong, variable Hα emission which we attribute to accretion from circumstellar discs. Such stars are thought to be incredibly rare at the ~16 Myr median age of Sco–Cen and they join only one other confirmed M-type and three higher mass accretors outside of Upper Scorpius. The serendipitous discovery of two accreting stars hosting large quantities of circumstellar material may be indicative of a sizeable age spread in Sco–Cen, or further evidence that disc dispersal and planet formation time-scales are longer around lower mass stars. To aid future studies of Sco–Cen, we also provide a newly compiled catalogue of 305 early-type *Hipparcos* members with spectroscopic radial velocities sourced from the literature.

Key words: stars: formation – stars: low-mass – stars: pre-main sequence – open clusters and associations: individual: TW Hydrae, Scorpius–Centaurus (Sco OB2).

1 INTRODUCTION

Nearby stars with ages of 5–20 Myr are ideal laboratories in which to investigate the later stages of star and planet formation. It is on these time-scales that the gas-rich discs which feed giant planet formation and circumstellar accretion dissipate and are replaced by dusty debris discs replenished by the collisions of rocky bodies (Wyatt 2008; Williams & Cieza 2011). Such stars are also prime targets for direct imaging observations of young, bright exoplanets and substellar companions (e.g. Marois et al. 2008; Lagrange et al. 2010). The discovery of young moving groups in the solar neighbourhood over the last two decades (see reviews by Zuckerman & Song 2004; Torres et al. 2008) has enabled the study of circumstellar material and processes in this important age range at high spatial resolution and sensitivity across a wide range of stellar masses.

Foremost amongst the nearby moving groups is the retinue of coeval pre-main-sequence stars (age 8–10 Myr; Weinberger, Anglada-Escudé & Boss 2013; Ducourant et al. 2014) within a few tens of degrees and comoving with the T Tauri star TW Hydra (Rucinski & Krautter 1983). The so-called TW Hydrae Association (TWA; de la Reza et al. 1989; Kastner et al. 1997; Torres et al. 2008; Schneider, Melis & Song 2012a, and references therein) now includes approximately 30 systems, spanning spectral types of A0 through to brown dwarfs. Its members were identified by a variety of means, most commonly as common proper motion sources detected in X-rays by the *ROSAT* mission (e.g. Webb et al. 1999; Zuckerman et al. 2001; Song, Zuckerman & Bessell 2003), but also through near-IR photometry (Gizis 2002; Looper et al. 2007, 2010), circumstellar disc excesses (Gregorio-Hetem et al. 1992; Schneider et al. 2012b) and activity (Shkolnik et al. 2011). The current membership of TWA is dominated by K- and M-type stars, although there appears to be a dearth of members later than ~M3 (Shkolnik et al. 2011). This is partly a consequence of the heavy reliance of previous searches on the *ROSAT* All Sky Survey (Voges et al. 1999), which, for the saturated coronal X-ray emission commonly seen in young stars ($L_X/L_{bol} \approx -3$), had a limiting spectral type of around M2 at the ~60 pc mean distance of TWA. Recent efforts exploiting deeper UV photometry from the *GALEX* mission (Martin et al. 2005) have proven successful at identifying young stars from their enhanced

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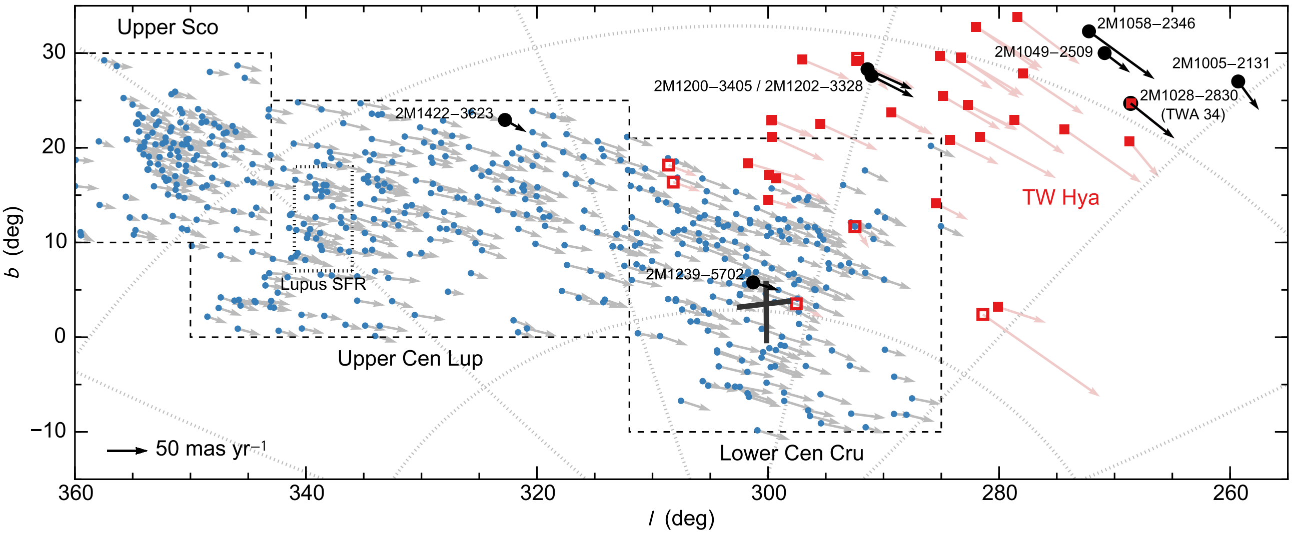

Figure 1. Galactic positions and proper motions of the eight lithium-rich stars identified in this work (black points). Also plotted are proposed Sco–Cen (blue dots; de Zeeuw et al. 1999) and TWA members (red squares; Ducourant et al. 2014). Open TWA symbols denote non-members, most of which are probably background LCC stars. The star near $l = 280°$ with the large proper motion is TWA 22, a likely β Pictoris member (Teixeira et al. 2009). For reference, the well-known Southern Cross asterism is also plotted at $l = 300°$ and an equatorial coordinate grid is shown by the dotted lines.

chromospheric activity (Rodriguez et al. 2011; Shkolnik et al. 2011; Murphy & Lawson 2015), especially in conjunction with modern photometric and proper motion surveys.

Immediately south of TWA lies the Scorpius–Centaurus OB Association (Sco–Cen, Sco OB2; Blaauw 1964; de Zeeuw et al. 1999; Preibisch & Mamajek 2008), the closest site of recent massive star formation and the dominant population of pre-main-sequence stars in the solar neighbourhood. The association has been implicated in the formation of several nearby young moving groups, including TWA (Mamajek & Feigelson 2001; Fernández, Figueras & Torra 2008; Murphy, Lawson & Bessell 2013). Sco–Cen has traditionally been divided into three subgroups (Fig. 1), each with subtly different mean distances, ages and velocities: Upper Scorpius (US, 145 pc), Upper Centaurus Lupus (UCL, 140 pc) and Lower Centaurus Crux (LCC 120 pc; de Zeeuw et al. 1999). The subgroups have median ages of approximately 10, 16 and 17 Myr, respectively (Mamajek, Meyer & Liebert 2002; Pecaut, Mamajek & Bubar 2012). While the full mass function of US is well known (e.g. Preibisch et al. 1998; Lodieu, Dobbie & Hambly 2011; Rizzuto, Ireland & Kraus 2015), the older and more southern UCL and LCC subgroups are understudied below 1 $M_{\odot}$. Only ∼100 K- and M-type members are known, mostly detected by *ROSAT* (Mamajek, Meyer & Liebert 2002; Preibisch & Mamajek 2008; Song, Zuckerman & Bessell 2012) but also more recently by *GALEX* (Rodriguez et al. 2011). Any reasonable mass function predicts several thousand low-mass members awaiting discovery across Sco–Cen.

In this contribution, we describe the serendipitous discovery and spectroscopic confirmation of one existing and up to three new M-type members of TWA, as well as two previously unknown members of Sco–Cen exhibiting signs of accretion from circumstellar discs. These six stars, and another two spectroscopically young stars not yet attributable to any known group, were identified during an ongoing search for members of the 30–40 Myr-old Octans Association (Torres et al. 2008; Murphy & Lawson 2015). In the following section, we briefly describe the candidate selection procedures and observations, deferring a full description of the Octans survey to an upcoming work (Murphy et al., in preparation).

2 CANDIDATE SELECTION AND OBSERVATIONS

The aim of our photometric and proper motion survey was to identify new Octans members on the cool side of its lithium depletion boundary (LDB) in order to better refine the age of the association. Candidates for spectroscopy were selected from the SPM4 proper motion catalogue (Girard et al. 2011) in a similar manner to Murphy & Lawson (2015), with initial cuts of $V_{\rm SPM4} < 20$, $V - K_{\rm s} > 5$, $J - H < 0.7$ and proper motion errors of less than 10 mas yr^{-1}. From this list, we then selected stars whose proper motions agreed with the Octans space motion, $(U, V, W) = (-13.7, -4.8, -10.9)$ km s^{-1} (Murphy & Lawson 2015), at better than $2\sigma_{\mu}$, where σ_{μ} is the total proper motion uncertainty. Using the resulting kinematic distances, we also required each candidate lie within the spatial bounds of the Octans/Octans-Near (Zuckerman et al. 2013) complex, $-100 < X < 150$ pc, $-150 < Y < 50$ pc and $-100 < Z < 50$ pc. To further limit the sample, we finally required a match against near-UV photometry from the *GALEX* mission. Following these cuts, 369 candidates remained over the SPM4 footprint ($\delta < -20°$). After visual inspection to eliminate galaxies and objects with obviously erroneous photometry, spectroscopic observations concentrated on the reddest stars lying above a Pleiades isochrone (Stauffer et al. 2007) with the best proper motion matches and near-UV excesses (Rodriguez et al. 2011).

We obtained spectroscopic observations of 25 high-priority candidates and a selection of velocity and spectral type standards using the Wide Field Spectrograph (WiFeS; Dopita et al. 2007) on the Australian National University 2.3-m telescope at Siding Spring Observatory during 2015 March 6–11. The instrument set up, data reduction and analysis, including the derivation of spectral types and radial velocities, was the same as that described in Murphy & Lawson (2015) and we refer the reader to that work for more information. All spectra were flux-calibrated using observations of the white dwarf EG 21 (Bessell 1999). Further WiFeS observations of two interesting candidates (2M1239−5702 and 2M1422−3623, see Section 3.2) were taken with the same

Table 1. Lithium-rich candidates observed with 2.3-m/WiFeS during 2015 March–April. Spectral types are estimated from $V - K_s$ colours and comparison to standards. *V* magnitudes are from SPM4, except for 2M1058−2346 and 2M1202−3328 which are from APASS-DR6. Photometry for 2M1028−2830, 2M1200−3405 and 2M1422−3623 are derived from photographic plates and will be of poorer quality than SPM4 CCD photometry. 2M1200−3405 has a broadened CCF which may indicate binarity. Candidates displaying emission lines are noted (see Table 3).

2MASS designation (*J*2000)	Spectral type (±0.5)	*V* (mag)	K_s (mag)	EW(Li) (±50 mÅ)	EW(Hα) (±1 Å)	v_{10}(H α) (±10 km s^{-1})	RV (±2 km s^{-1})	Notes
2MASS J10055826−2131142	M4.9	16.72	10.70	630	−11.5	172	11.0	–
2MASS J10284580−2830374	M4.9	16.03	10.03	600	−10.9	162	20.0	TWA 34; [O I]
2MASS J10491880−2509235	M4.9	17.08	11.08	800	−11.5	186	19.0	–
2MASS J10585054−2346206	M5.1	15.58	9.43	700	−11.3	151	2.0	–
2MASS J12002750−3405371	M4.7	14.55	8.72	650	−9.9	312	11.0	Broad CCF
2MASS J12023799−3328402	M4.8	15.77	9.85	700	−9.5	169	6.0	–
2MASS J12392312−5702400	M5.0	17.35	11.25	650	[−63, −27]	[238, 331]	16.0	He I
2MASS J14224891−3623009	M5.0	17.31	11.27	600	[−91, −33]	[236, 341]	9.0	He I, [O I], Na I

instrument settings between 2015 March 30 and April 6 as part of another programme.[1]

3 RESULTS

Only 4/25 candidates had radial velocities within 5 km s^{-1} of those predicted by Octans membership. The relationship of these stars (only one of which is lithium-rich) to Octans will be discussed in a future work. Eight candidates showed strong Li I λ6708 absorption (equivalent width–EW(Li) > 100 mÅ). These stars are listed in Table 1 and their WiFeS *R*7000 spectra are shown in Fig. 2 . The detection of lithium is an indicator of youth in M-type stars, but with a strong stellar mass dependence (Soderblom 2010). At ages of 10–20 Myr lithium absorption disappears at early and mid-M spectral types only to reappear at lower masses as one crosses the LDB (e.g. Basri, Marcy & Graham 1996). With spectral types of ∼M5, the eight stars in Table 1 are demonstrably younger than the Pleiades (LDB M6.5; Stauffer, Schultz & Kirkpatrick 1998), and are likely no older than the nearby ∼20 Myr β Pictoris Association (LDB M4.5; Binks & Jeffries 2014). The sky positions and proper motions of the lithium-rich stars are plotted in Fig. 1 in Galactic coordinates. All either lie within or near TWA and Sco–Cen.

3.1 New members of TWA

2M1058−2346, 2M1200−3405 and 2M1202−3328 have positions and proper motions similar to nearby TWA members (Fig. 1). The latter two stars lie within 2° of the confirmed M1 member TWA 23 (Song et al. 2003) and all three have strong lithium absorption similar to other M-type members. Shkolnik et al. (2011) identified 2M1200−3405 as a UV-bright TWA candidate but did not report any Hα emission in their Magellan/MagE spectrum. Based on this non-detection they disregarded 2M1200−3405 as a possible member and did not obtain a higher resolution spectrum or radial velocity. However, subsequent examination of the raw MagE frame shows clear Hα emission and that the star was inadvertently excluded as a likely member (E. Shkolnik, personal communication). The WiFeS spectrum of 2M1200−3405 plotted in Fig. 2 has strong Hα emission (EW = −9.9 Å) typical of an active mid-M dwarf. The broad velocity width (v_{10} = 312 km s^{-1}) may be the result of spectroscopic binarity (see Section 3.1.1). We find 2M1200−3405 has a *GALEX* NUV−*J* excess consistent with other nearby young stars (Rodriguez et al. 2011), while 2M1058−2346 and 2M1202−3328 are borderline UV-excess sources.

To support the membership of 2M1058−2346, 2M1200−3405 and 2M1202−3328 in TWA we use the BANYAN II web service (version 1.3; Malo et al. 2013; Gagné et al. 2014).[2] BANYAN is a Bayesian analysis tool which compares a star's Galactic position (*XYZ*) and space velocity (*UVW*) to the observed distributions of young groups and the field. No photometric information is used. It utilizes a naive Bayesian classifier to calculate membership probabilities, marginalizing over the unknown distance and taking into account the expected populations (prior probabilities) of each group and the field, as well as uncertainties on the observables. Within BANYAN, we adopt the 'young' field hypothesis (age <1 Gyr) given the clear youth of the lithium-rich stars. Using only their sky positions and SPM4 proper motions, BANYAN returns TWA membership probabilities of 83, 99 and 98 per cent for 2M1058−2346, 2M1200−3405 and 2M1202−3328, respectively, with the balance of membership probabilities going to the field hypothesis. The predicted radial velocities of 10.3 ± 1.4 and 9.9 ± 1.5 km s^{-1} for 2M1200−3405 and 2M1202−3328 agree well with the WiFeS values in Table 1, further supporting the stars' membership in TWA.[3] Including these observations in BANYAN gives membership probabilities of 99 and 97 per cent, with implied distances of ∼60 pc for both stars.

The resultant space motions of 2M1200−3405 and 2M1202−3328 are listed in Table 2 and plotted in Fig. 3 with confirmed TWA members. Their velocities are in excellent agreement with the other members, as expected. The mean space motion of the 24 members in this diagram is (*U*, *V*, *W*) = (−10.8, −18.3 − 5.0) ± (2.0, 1.7, 1.6) km s^{-1} (1σ variation). BANYAN uses a different set of 18 members in its TWA model, whose principle spatial and velocity axes are not aligned to standard Galactic coordinates (see Gagné et al. 2014). However, both samples have almost identical mean velocities ($\Delta v < 1$ km s^{-1}).

On the contrary, the WiFeS radial velocity of 2M1058−2346 (2 ± 2 km s^{-1}) disagrees by 4σ with that predicted by BANYAN for membership in TWA. However, it is the only lithium-rich star to

[1] Reduced spectra of the lithium-rich stars and machine-readable versions of Table A1 can be found on the FIGSHARE service at the following DOI: http://dx.doi.org/10.6084/m9.figshare.1491506

[2] http://www.astro.umontreal.ca/~gagne/banyanII.php

[3] 2M1202−3328 was observed with the ESO 2.2-m/FEROS (programme ID 090.C-0200A) on 2013 February 17 as part of the *GALEX* Nearby Young-Star Survey (GALNYSS; Rodriguez et al. 2011, 2013). The pipeline-reduced spectrum is heavily contaminated by residual sky emission and strong noise spikes. By combining line velocities for Hα, Hβ and the Na I λ8200 absorption doublet we derive a mean radial velocity of 8.3 ± 1.7 (s.d.) km s^{-1}, in good agreement with the WiFeS and BANYAN values.

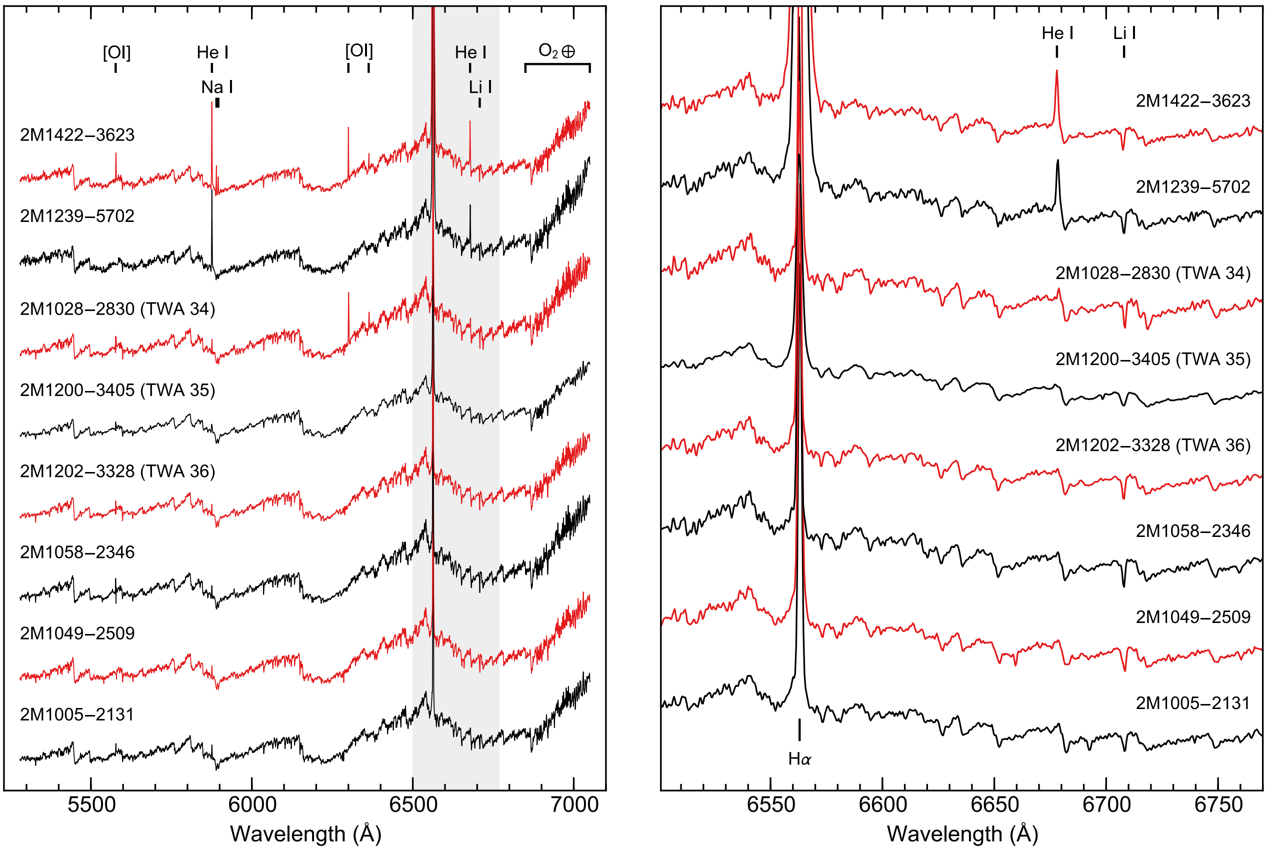

Figure 2. 2.3-m/WiFeS *R*7000 spectra of the lithium-rich stars identified in this work. The full 5300–7050 Å spectra are plotted in the left panel and the shaded region around Hα and Li I λ6708 is enlarged on the right. All spectra are normalized over 6100–6150 Å. The broader spectral features of 2M1200−3405 (especially around Li I) are readily apparent. Only first epoch spectra of 2M1422−3623 and 2M1239−5702 are plotted (see Table 3).

Table 2. Kinematics and memberships of the lithium-rich stars. All proper motions are from SPM4. Distances are from BANYAN (BAN) or purely kinematic estimates from the projected group velocity (kin). The latter are assumed to have a 20 per cent parallax error (10 per cent for 2M1239−5702). *UVW* velocities define a right-handed triad with *U* positive towards the Galactic Centre. Uncertainties were calculated following the prescription of Johnson & Soderblom (1987) using the uncertainties in proper motion, radial velocity and parallax. The space motion of 2M1028−2830 (also see Fig. 3) assumes the higher precision radial velocity ($13.3 \pm 0.1\,\mathrm{km\,s^{-1}}$) obtained by Rodriguez et al. from ALMA observations (see Section 3.1.2).

2MASS designation (*J*2000)	$\mu_\alpha \cos\delta$ (mas yr^{-1})	μ_δ (mas yr^{-1})	Dist. (pc)	Ref.	*U* (km s^{-1})	*V* (km s^{-1})	*W* (km s^{-1})	Membership
2MASS J10055826−2131142	-41.7 ± 4.6	-13.4 ± 4.2	75^{+19}_{-12}	kin.	-10.8 ± 2.4	-14.1 ± 2.1	-6.9 ± 2.9	?
2MASS J10284580−2830374	-68.6 ± 2.7	-11.4 ± 2.5	47 ± 6	BAN.	-11.5 ± 1.5	-16.3 ± 0.6	-4.3 ± 1.4	TWA (34)
2MASS J10491880−2509235	-39.0 ± 2.0	-7.9 ± 1.8	95^{+24}_{-16}	kin.	-12.8 ± 2.7	-22.8 ± 2.2	-1.1 ± 2.4	?
2MASS J10585054−2346206	-98.3 ± 1.9	-20.6 ± 1.7	38^{+9}_{-6}	kin.	-13.2 ± 2.7	-8.6 ± 2.2	-9.1 ± 2.3	Oct-Near/TWA?
2MASS J12002750−3405371	-55.6 ± 3.2	-19.2 ± 3.0	61 ± 7	BAN.	-8.5 ± 1.7	-18.2 ± 2.0	-2.9 ± 1.5	TWA (35)
2MASS J12023799−3328402	-58.4 ± 3.8	-17.3 ± 3.5	62 ± 7	BAN.	-11.2 ± 1.9	-14.4 ± 2.0	-4.8 ± 1.6	TWA (36)
2MASS J12392312−5702400	-32.0 ± 3.5	-10.4 ± 3.7	119^{+13}_{-11}	kin.	-6.6 ± 2.5	-23.4 ± 2.2	-5.1 ± 2.2	Sco–Cen (LCC)
2MASS J14224891−3623009	-17.0 ± 6.3	-25.6 ± 5.8	142^{+35}_{-24}	kin.	-0.1 ± 3.5	-21.4 ± 4.8	-7.2 ± 4.3	Sco–Cen (UCL)

have a space motion consistent with membership in Octans (Fig. 3; $\mathrm{RV_{Oct}} = -2.2\,\mathrm{km\,s^{-1}}$) and the only one associated with a *ROSAT* source (1RXS J105849.9−234623; Voges et al. 1999). We estimate $F_\mathrm{X} \approx 2 \times 10^{-13}$ erg s^{-1} cm^{-2} (near the *ROSAT* detection limit) and $\log L_\mathrm{X}/L_\mathrm{bol} \approx -3.2$ using the relations in Fleming, Schmitt & Giampapa (1995) and Pecaut & Mamajek (2013). Detection by *ROSAT* at this spectral type immediately implies the star is closer than the majority of TWA members. BANYAN predicts a distance of 41 ± 4 pc, similar to that implied by membership in Octans (38 pc), placing it near the periphery of the 'Octans-Near' group (Zuckerman et al. 2013; Murphy & Lawson 2015). If Octans-Near is the same age as Octans and similar to the Tucana–Horologium Association (30–40 Myr; see discussion in Murphy & Lawson 2015), the strong lithium absorption observed in 2M1058−2346 (EW = 700 mÅ) implies it is on the cool side of the Octans LDB, the first such member to be discovered (see Fig. 4). Alternatively, given its congruent sky position and proper motion vector it is possible 2M1058−2346 is a spectroscopic binary member of TWA or that its single-epoch WiFeS radial velocity is erroneous. In this case, the lower membership probability in BANYAN could be due to its location

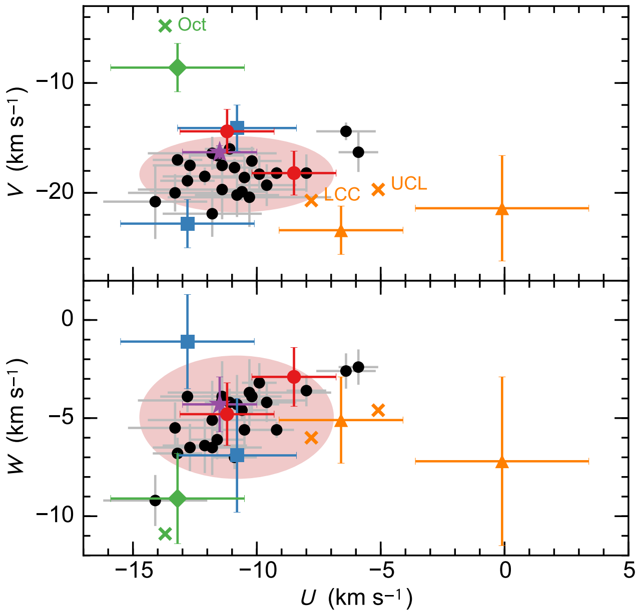

Figure 3. Candidate space motions (see Table 2), coloured by their proposed memberships: 2M1200−3405 and 2M1202−3328 (TWA, red points), 2M1028−2830/TWA 34 (TWA, purple star), 2M1058−2346 (Octans/TWA?, green diamond), 2M1239−5702 and 2M1422−3623 (Sco–Cen, orange triangles) and 2M1005−2131 and 2M1049−2509 (unknown, blue squares). Also plotted are confirmed TWA members with trigonometric parallaxes (black points, with $\pm 2\sigma$ range shaded; Ducourant et al. 2014).

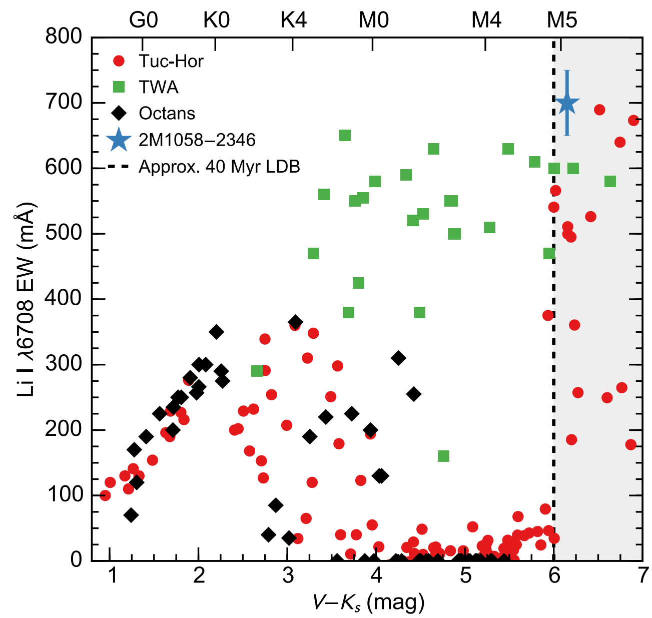

Figure 4. Li I λ6708 EW of 2M1058−2346 compared to members of TWA (Schneider et al. 2012a), Tuc-Hor (da Silva et al. 2009; Kraus et al. 2014) and Octans (Murphy & Lawson 2015). The 30–40 Myr-old Tuc-Hor LDB is clearly visible at $V - K_s \approx 6$ (dashed line).

near the edge of the TWA spatial ellipsoid. Further radial velocity measurements are necessary to distinguish between these two scenarios.

As a final check, we plot in Fig. 5 the M_V versus $V - K_s$ colour–magnitude diagram (CMD) for the lithium-rich stars, together with empirical sequences for TWA, β Pictoris and the Pleiades.

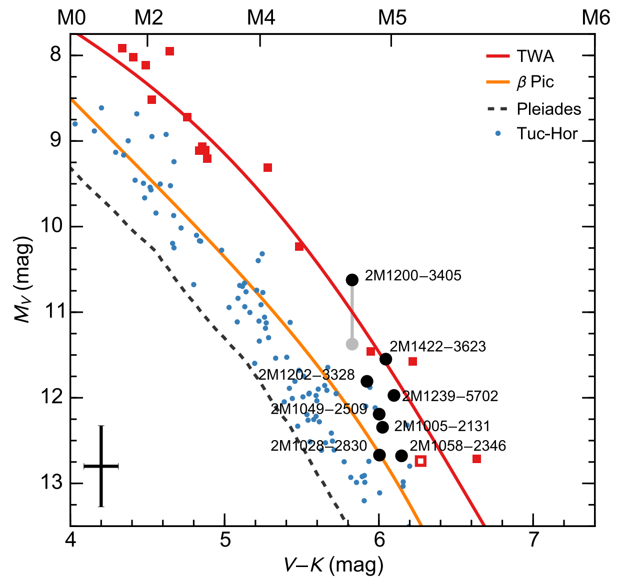

Figure 5. CMD of the lithium-rich candidates. The grey point assumes 2M1200−3405 is a corrected equal-brightness system (see Section 3.1.1). Also plotted are members of TWA (red squares; Ducourant et al. 2014) and Tuc-Hor (blue dots; Kraus et al. 2014). Lines show fits to TWA (red) and β Pic (orange) members from Riedel et al. (2011) and the Pleiades sequence (Stauffer et al. 2007). The maximal error bar represents a 20 per cent parallax error and 0.1 mag photometric errors.

2M1058−2346 and 2M1202−3328 have CCD-derived APASS (Henden et al. 2012) *V* magnitudes which we adopt over the SPM4 values (but which agree within 0.2 mag), while for 2M1028−2830, 2M1200−3405 and 2M1422−3623 the SPM4 *V* magnitude was measured from photographic plates and should be treated with caution. No APASS data exist for these stars. Both 2M1200−3405 and 2M1202−3328 fall close to the mean locus of TWA members (Riedel et al. 2011). In conjunction with their kinematic and spatial match from BANYAN, the CMD placement, strong lithium absorption and NUV excesses of 2M1200−3405 and 2M1202−3328 confirm their youth and membership in TWA. Following the nomenclature for TWA members, we designate 2M1200−3405 as TWA 35 and 2M1202−3328 as TWA 36. Neither star displays excess emission above photospheric levels in 3–22 µm *AllWISE* photometry (Wright et al. 2010). The CMD position of 2M1058−2346 is consistent with a β Pic-like age or the upper envelope of Tuc-Hor members, but still marginally consistent with TWA. Until a better velocity measurement is available we refrain from assigning the star to either TWA or Octans.

3.1.1 Possible binarity of 2MASS J12002750–3405371

The mean width of the cross-correlation function (CCF) for 2M1200−3405 (FWHM = 3.4 px) is much broader than the other candidates and standards (FWHM < 2.5 px; see fig. 4 of Murphy & Lawson 2015). This broadening is also visible in the raw spectrum (Fig. 2) and Hα v_{10} velocity width (Table 1), and is usually indicative of fast rotation (e.g. Soderblom, Pendleton & Pallavicini 1989), unresolved spectroscopic binarity or a combination of the two. Using 2M1202−3328 as a narrow-lined template, we can reproduce the level of broadening observed in 2M1200−3405 with either a $v \sin i$ or SB2 velocity shift of $\sim$50 km s^{-1}, close to the $c\Delta\lambda/\lambda \approx 45$ km s^{-1} WiFeS velocity resolution. No broadening is evident at velocities $\lesssim 20\,\mathrm{km\,s^{-1}}$ ($c\Delta\lambda/2\lambda$). Such a high implied rotation speed is unusual for single TWA stars (Jayawardhana et al. 2006) and so may instead arise in the blending of lines from a close companion. However, in the absence of higher resolution observations we cannot yet confirm this. If 2M1200−3405 is a binary then the unresolved CCF peak we measured should still trace the systemic velocity, assuming the binary is close to equal mass.

3.1.2 2MASS J10284580–2830374 (=TWA 34)

Another candidate, 2M1028−2830, is the recently proposed TWA member and disc host TWA 34 (Schneider et al. 2012b). We confirm the M4.9 spectral type and EW(H α) = −9.6 Å reported by Schneider et al. and measure EW(Li) = 600 mÅ and RV = $20 \pm 2\,\mathrm{km\,s^{-1}}$ from our higher resolution WiFeS spectrum. From the modest strength and velocity width of its Hα line (v_{10} = $162\,\mathrm{km\,s^{-1}}$), TWA 34 does not appear to be accreting from its disc. However, we also detect strong forbidden [O I] λ6300 (EW = −3.0 Å) and λ6363 (−0.6 Å) emission, indicating the presence of low-density gas usually attributed to a wind or outflow (e.g. Appenzeller & Mundt 1989; Rigliaco et al. 2013; Zuckerman, Vican & Rodriguez 2014). Due to uncertainties in subtracting the strong auroral sky line, we do not unambiguously detect [O I] λ5577 emission from any candidate. The SPM4 proper motion of TWA 34 yields a BANYAN II membership probability of 95 per cent, with an implied distance and radial velocity of 47 ± 6 pc and $13.5 \pm 1.3\,\mathrm{km\,s^{-1}}$. Rodriguez et al. (2015, in preparation) have obtained Atacama Large Millimeter/submillimeter Array (ALMA) observations of TWA 34 and from a Keplerian fit to the CO velocity map derived a barycentric velocity of $13.3 \pm 0.1\,\mathrm{km\,s^{-1}}$, in excellent agreement with the BANYAN prediction and other members (Fig. 3). This suggests our WiFeS radial velocity may be erroneous, although we cannot yet rule out spectroscopic binarity.

At 47 pc TWA 34 is significantly underluminous compared to other TWA members in Fig. 5, even considering reasonable errors on its photographic V magnitude. A distance of ∼80 pc is required to bring it on to the TWA sequence of Riedel et al. (2011). Schneider et al. (2012b) found congruent kinematic and photometric distances of ∼50 pc when considering M_{K} and an empirical TWA isochrone, but the star is also underluminous in that band. Its optical and near-infrared spectral energy distribution (SED) is well fitted by a 3000 K model atmosphere (Bayo et al. 2008), consistent with its $V - K_{\mathrm{s}}$ colour and spectral type. A possible explanation for the underluminosity is that the photospheric light is intercepted by a flared disc seen at high inclination (similar to ϵ Cha 11; Fang et al. 2013). Liu et al. (2015) obtained *Herschel*/PACS photometry of TWA 34 and modelled its disc. Although the best-fitting inclination angle of $i = 60^{+7.5}_{-45}$ deg is not strongly constrained by the data, their models rule out high inclinations ($i \gtrsim 80°$).

3.2 Two new accreting M-dwarfs in Sco–Cen

The only two other stars in our sample with *AllWISE* infrared excesses, 2M1239−5702 and 2M1422−3623, lie within the classical boundaries of the LCC and UCL subgroups of Sco–Cen, respectively (Fig. 1). Neither star is a member of the seven nearby moving groups tested by BANYAN (TWA, β Pic, Argus, Tuc-Hor, Carina, Columba, AB Dor). The SPM4 proper motions and errors of 2M1239−5702 and 2M1422−3623 correspond to kinematic distances of 119^{+13}_{-11} pc and 142^{+35}_{-24} pc, assuming the mean LCC and UCL space motions of Chen et al. (2011). These are in excellent agreement with the 120 and 140 pc mean distances found by de Zeeuw et al. (1999) for early- and solar-type LCC and UCL members with *Hipparcos* parallaxes (also see Fig. A1). The CMD positions of 2M1239−5702 and 2M1422−3623 in Fig. 5 suggest an age of approximately 10 Myr, similar to TWA and consistent

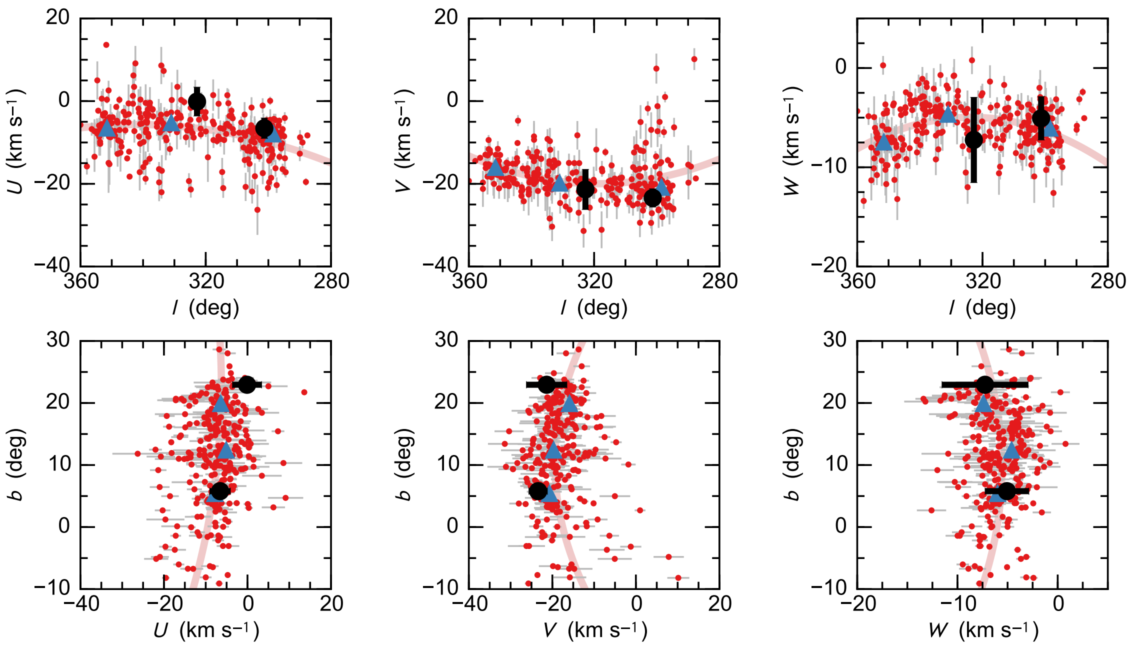

Figure 6. Space motions of Sco–Cen members from de Zeeuw et al. (1999, red points) versus Galactic longitude (top) and latitude (bottom). Quadratic fits are shown to guide the eye. The mean velocities of the US, UCL and LCC subgroups (from left to right and top to bottom) are given by the blue triangles, as derived by Chen et al. (2011). The space motions of 2M1239−5702 and 2M1422−3623 from Table 2 are plotted as large black points.

with recent age ranges for UCL and LCC (Pecaut et al. 2012; Song et al. 2012). The age of Sco–Cen and possible age spreads in the association are discussed in greater detail in Section 4.2.

At these distances 2M1239−5702 and 2M1422−3623 are 3 and 6 km s^{-1}, respectively, from the Chen et al. mean space motions (Fig. 3), compared to uncertainties of 2–4 km s^{-1} in each velocity component. However, unlike smaller, more coherent moving groups, OB associations are expected to show spatial and kinematic substructure. To examine the trend and spread of velocities across Sco–Cen, we plot in Fig. 6 over 270 high-probability members from de Zeeuw et al. (1999) with radial velocities and updated *Hipparcos* astrometry. This is the largest available compilation of Sco–Cen members with six-dimensional phase space information and a full description of its construction is given in Appendix A. The space motions of 2M1239−5702 and 2M1422−3623 are perfectly consistent with the surrounding higher mass members in this diagram. As expected, the mean subgroup velocities closely follow the longitude and latitude trends, albeit with significant scatter in individual velocities and minimal differentiation into the classical subgroups. Much of this scatter likely results from observational errors and single-epoch velocities of unknown spectroscopic binaries. For reference, de Bruijne (1999) found a one-dimensional internal velocity dispersion of <1–1.5 km s^{-1} from *Hipparcos* astrometry. Figs 6 and A1 appear to confirm the suggestion of Rizzuto, Ireland & Robertson (2011) that Sco–Cen can be well modelled as continua in spatial position and velocity rather than three discrete subgroups. The addition of many more low-mass members with radial velocities and *Gaia* parallaxes will better resolve the velocity and spatial substructure of Sco–Cen in coming years.

The few Myr-old Lupus star-forming region (Comerón 2008) lies within UCL and its members have similar distances and kinematics to Sco–Cen. It is therefore plausible that 2M1422−3623 may be a young, outlying member of Lupus instead of the older Sco–Cen population. However, we do not believe this is likely. 2M1422−3623 is some 15–20° from the dark clouds which define the star-forming region, and a recent kinematic and membership reanalysis of stars in the area by Galli et al. (2013) did not find any legitimate 'off-cloud' Lupus members within 9° of 2M1422−3623. The results of Galli et al. (2013) strongly support the hypothesis that the majority of the ∼150 late-type, older pre-main sequence stars found around the Lupus clouds in X-ray surveys (e.g. Krautter et al. 1997; Wichmann et al. 1997) are in fact members of UCL/Sco–Cen (Mamajek et al. 2002; Preibisch & Mamajek 2008). 2M1239−5702 is situated close to the centre of LCC, only 1° from the foreground M-giant and Southern Cross member γ Cru. It lies a few degrees north of the so-called 'Park & Finley' stars (Park & Finley 1996; Preibisch & Mamajek 2008), a group of four young K- and M-type LCC members discovered in the vicinity of the B0.5 member β Cru (Feigelson & Lawson 1997; Alcalá et al. 2002). None of these stars appear to be accreting or host circumstellar discs.

3.2.1 Disc and accretion properties

The SEDs of 2M1422−3623 and 2M1239−5702 are compiled in Fig. 7 . Both stars exhibit strong excesses in the *W*3 (12 μm) and *W*4 (22 μm) *WISE* bands. These are consistent with evolved, 'homologously depleted' discs which are becoming optically thin without forming an inner hole or gap, and show a strong flux decrement at all infrared wavelengths relative to optically thick 'full' discs (Espaillat et al. 2012; Luhman & Mamajek 2012). The observed ($K_s - W4$) excesses of 2M1422−3623 and 2M1239−5702 are similar to discs around K5–M5 stars in Upper Scorpius (age ∼10 Myr), which already show evidence of significant evolution compared to Taurus (Luhman & Mamajek 2012). Although not necessarily physical, double-temperature blackbody models with a cool ∼230 K outer component and a warmer 800–900 K inner component provide a good fit to the *WISE* photometry in both cases. Assuming $L_\star = 0.03\,L_\odot$ (Fig. 7) and large (blackbody) grains, these temperatures correspond to disc radii of 0.25 au and ∼0.02 au, respectively (Backman & Paresce 1993). Further infrared and millimetre observations (e.g. with SOFIA, VLT/VISIR or ALMA) will help elucidate the structure and chemistry of the discs, for instance by resolving the 10 μm silicate feature if it exists, or detecting cold dust and CO gas emission.

Accretion of gas from the inner disc on to the star is usually accompanied by enhanced Balmer and other line emission (Muzerolle, Hartmann & Calvet 1998). Hα velocity profiles for 2M1239−5702 and 2M1422−3623 are given in Fig. 8 . The broad and strong emission at all epochs (also see Table 3) confirms both stars are accreting, with EWs greater than the 15–18 Å threshold for M3–M6 stars suggested by Fang et al. (2009) and v_{10} velocity widths in excess of

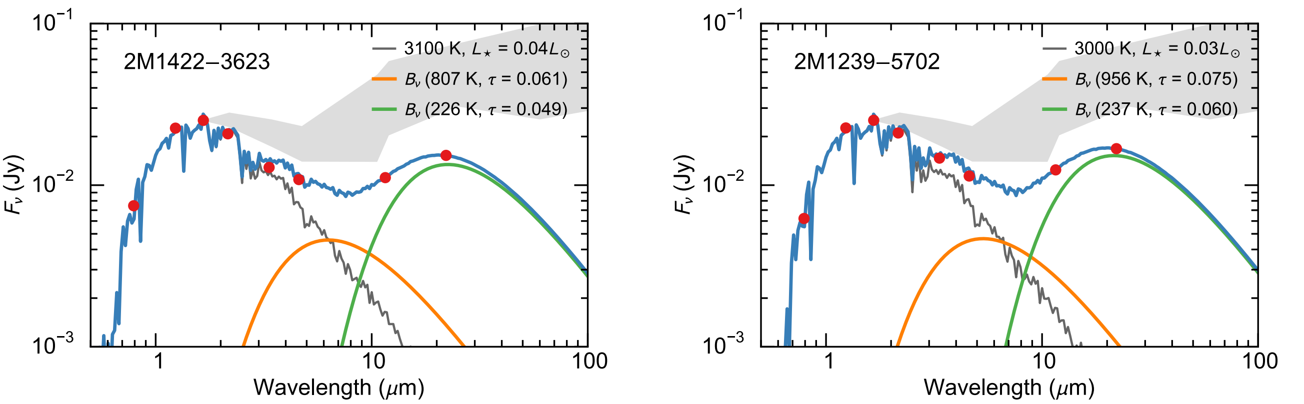

Figure 7. SEDs of 2M1422−3623 (left) and 2M1239−5702 (right). Photometric measurements from DENIS (*I*), 2MASS and *WISE* are plotted in red. The total SED (blue line) is approximated by a solar metallicity BT-Settl model (grey line; Allard, Homeier & Freytag 2012) fitted to the DENIS and 2MASS data, and two blackbodies (green and orange lines). The characteristic emitting area of each component is given by the factor $\tau = L_{IR}/L_\star$. The interquartile range of K5–M2 Class I Taurus sources from D'Alessio et al. (1999) is shown by the shaded region, normalized at 1.6 μm.

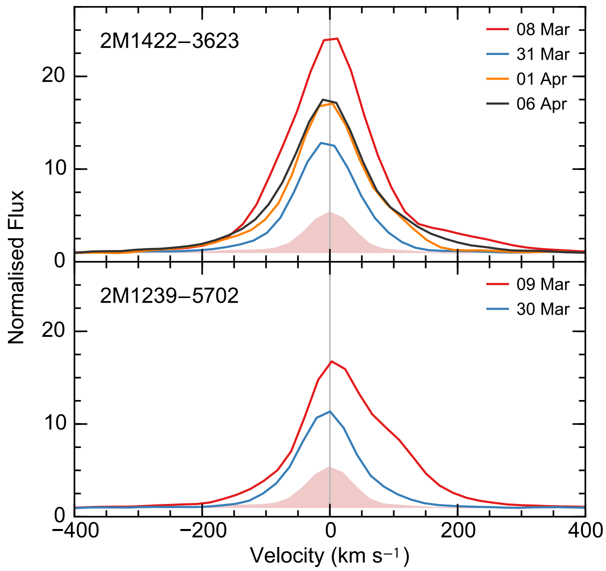

Figure 8. 2.3-m/WiFeS RV-corrected Hα velocity profiles of the accretors 2M1422−3623 (top) and 2M1239−5702 (bottom). For comparison, each panel also shows the profile of the new TWA member and non-accretor 2M1202−3328 (shaded region; EW = −9.5 Å, v_{10} = 169 km s^{-1}).

the 270 km s^{-1} accretion criterion of White & Basri (2003).[4] Both stars presented weaker Hα emission in the second-epoch observations, falling just below the 270 km s^{-1} threshold but still above the EW limit. Subsequent observations of 2M1422−3623 show a recovery in both EW and v_{10}. Applying the v_{10}(H α)–$\dot{M}$ relation of Natta et al. (2004) to the velocities in Table 3 yields mass accretion rates of $\sim 10^{-9.5}$ $M_\odot$ yr^{-1} at peak and a factor of ten lower at minima, comparable to those in older groups like TWA and η Cha (Muzerolle et al. 2000; Lawson, Lyo & Muzerolle 2004). Similar behaviour is seen in the ∼6 Myr-old η Cha members RECX 5 and 2M0820−8003, which are borderline accretors but have undergone sporadic episodes of strong accretion in multi-epoch observations (Lawson et al. 2004; Murphy et al. 2011). Unlike RECX 5, which hosts a transitional disc with an inner hole and gap (Bouwman et al. 2010), 2M0820−8003, 2M1239−5702 and 2M1422−3623 show excesses at $\lesssim$5 μm, indicating the presence of dust in the inner disc. Their variable accretion is presumably driven by 'clumpy' residual gas-rich material in this region.

In addition to Hα, we also observed Na I D and forbidden [O I] λ6300/6363 emission in 2M1422−3623 and strong He I λ5876/6678 emission in both stars (Fig. 2 and Table 3). The strength of the Na I and He I emission was generally correlated with Hα, as expected from their common origin in magnetospheric infall regions (Muzerolle et al. 1998), whereas the outflow-driven forbidden emission remained approximately constant. Continuum excess is another indicator of accretion and activity in T Tauri stars, particularly in the UV (Bertout, Basri & Bouvier 1988). 2M1239−5702 and 2M1422−3623 both show enhanced *GALEX* near-UV emission compared to the other lithium-rich stars and most stars in the Torres et al. (2008) sample of young moving group members. Comparing Li I λ6708 line strengths we deduce that only the 2015 March 8 spectrum of 2M1422−3623 was noticeably veiled (when accretion was strongest). On that night, we measure an EW of 550 mÅ, compared to values of 600–630 mÅ at the other three epochs.

[4] Jayawardhana, Mohanty & Basri (2003) suggest a lower accretion threshold of 200 km s^{-1} for M5–M8 objects. Whatever the adopted criterion, it is clear from the large EWs and the presence of other indicators that 2M1239−5702 and 2M1422−3623 are accreting from gas-rich inner discs.

3.3 Other lithium-rich stars

2M1005−2131 and 2M1049−2509 both have smaller proper motions, inconsistent with neighbouring TWA members and indicative of larger distances. We find satisfactory matches to the TWA space motion at 75 and 95 pc, respectively (Fig. 3). However, at these distances the stars are very far from other TWA members in space (e.g. Weinberger et al. 2013) and still sit below the mean CMD trend in Fig. 5. Adopting the UCAC4 proper motion for 2M1005−2131 (−55.3 ± 7.1, −9.7 ± 5.3 mas yr^{-1}) increases its BANYAN membership probability from 13 to 50 per cent (including RV), but at the implied distance of 42 pc the star lies near the Pleiades sequence and its predicted proper motion is much larger than observed.

2M1049−2509 was observed with VLT/UVES on 2014 May 11 (programme ID 093.C-0133A) as part of GALNYSS. Examining the pipeline-reduced archival spectrum we find EW(Li) = 680 ± 30 mÅ, EW(H α) = −22 ± 3 Å, and −300 mÅ Ca II infrared triplet emission. The radial velocity of the Na I λ8200 absorption doublet (17 ± 1 km s^{-1}) agrees with our lower resolution WiFeS measurement. The star was also serendipitously observed by both the *Chandra* and *XMM–Newton* X-ray satellites. Its 0.2–12 keV *XMM* luminosity at 95 pc ($10^{28.9}$ erg s^{-1}; Rosen et al. 2015) and log $L_X/L_{\rm bol}$ ≈ −3.0 are both consistent with an age less than the Pleiades. Both 2M1005−2131 and 2M1049−2509 are clearly young, but their exact membership awaits further observations, particularly parallaxes.

4 DISCUSSION

4.1 Other accretors in Sco–Cen

Outside of Upper Scorpius, 2M1239−5702 and 2M1422−3623 join only a handful of known accretors in the older UCL and LCC subgroups. Shkolnik et al. (2011) suggested the M3.5 LCC member 2MASS J11311482−4826279 was accreting based on its broad Hα line (v_{10} = 233 km s^{-1}). However, given its weak EW (−7.3 Å) and that the star has no excess emission visible in *WISE*, we suggest the broad Hα line Shkolnik et al. observed was the result of chromospheric activity. Flares can give rise to broad, multicomponent Hα emission like that seen in 2M1131−4826 and are usually characterized by lower EWs than observed in accretors (Montes et al. 1998; Jayawardhana et al. 2006; Murphy et al. 2011). Rodriguez et al. (2011) proposed another M3.5 LCC accretor, 2MASS J13373839−4736297, based on a strong (−13.7 Å) and asymmetric Hα line. Schneider et al. (2012b) confirmed the star hosts a disc with excesses in all four *WISE* bands. Accretion thus seems a likely explanation for the observed line emission. Zuckerman (2015) report 2M1337−4736 is a 10 arcsec binary of near equal brightness. The secondary does not possess a disc.

The three confirmed M-type accretors in Sco–Cen (2M1337−4736A, 2M1239−5702 and 2M1422−3623) are joined by the Herbig Ae star HD 139614 and two accreting F stars; AK Sco and HD 135344 (Preibisch & Mamajek 2008). These authors noted HD 139614 and 135344 lie near the western edge of the Lupus clouds and so may be younger than the median age of UCL (16 Myr; Pecaut et al. 2012). Mamajek et al. (2002) proposed the K1 T Tauri star MP Mus (=PDS 66) as a southern member of LCC. It was the only star which showed signs of accretion (EW(H α) = −39 Å) in their survey of 110 G- and K-type UCL and LCC stars. However, Murphy et al. (2013) have disputed the

Table 3. Emission line EWs in 2M1239−5702 and 2M1422−3623. The velocity width of the Hα line at 10 per cent of peak flux (v_{10}) is also given. Estimated uncertainties are ±10 km s^{-1} for v_{10}, ±0.1 Å for all lines other than Hα and ±2 Å for the broader Hα line.

Star	Observation date (UT)	v_{10}(Hα) (km s^{-1})	Hα (Å)	He I λ5876 (Å)	He I λ6678 (Å)	[O I] λ6300 (Å)	[O I] λ6363 (Å)	Na I λ5896 (Å)	Na I λ5890 (Å)
2M1239−5702	2015 March 9	331	−63	−5.3	−1.2	–	–	−0.2	−0.2
	2015 March 30	238	−27	−2.4	−0.4	−0.4	–	−0.6	−0.9
2M1422−3623	2015 March 8	335	−91	−5.7	−1.3	−2.5	−0.5	−3.2	−1.9
	2015 March 31	236	−33	−3.4	−0.6	−2.8	−0.8	−2.0	−1.6
	2015 April 1	303	−54	−1.7	−0.3	−3.7	−1.0	−1.8	−1.0
	2015 April 6	341	−68	−3.1	−0.9	−2.4	−0.6	−2.4	−0.8

membership of MP Mus in LCC, claiming a better kinematic and distance match to the 3–5 Myr ϵ Chamaeleontis association which overlaps the south of LCC.

In light of the increasing number of accretors in Sco–Cen, membership of the inconclusive TWA member and confirmed accretor 2MASS J12071089−3230537 (TWA 31; Shkolnik et al. 2011; Schneider et al. 2012a) deserves reevaluation. TWA 31 was rejected by Ducourant et al. (2014) on the basis of its poor USNO-B1.0 proper motion. BANYAN gives a membership probability of only 28 per cent at 59 ± 7 pc. Its SPM4 proper motion, (−52 ± 8, −18 ± 8) mas yr^{-1}, is a better match to TWA, with a membership probability of 98 per cent at 61 ± 7 pc. However, with $V_{\rm SPM4}$ = 18.45 (photographic) TWA 31 would be underluminous at this distance. It is not found in UCAC catalogues and its PPMXL proper motion agrees with USNO-B1.0. At its proposed photometric distance of 110 pc (Shkolnik et al. 2011), TWA 31 has an SPM4 space motion somewhat similar to other TWA members and a reasonable CMD position, but is much further away than the majority of TWA stars. Only TWA 15AB is more distant ($d \approx 115$ pc), but it is far enough south to conceivably be an LCC member (but see discussion in Ducourant et al. 2014). Until better astrometry are available the final status of TWA 31 remains unclear.

4.2 Implications for the age of Sco–Cen and disc lifetimes

The fraction of accreting stars in young groups and star-forming regions is observed to fall rapidly with age, with *e*-folding time-scales of 2–3 Myr (Mamajek 2009; Fedele et al. 2010). For instance, Frasca et al. (2015) recently found accretor fractions of 35–40 per cent for the ∼2 Myr-old Cha I population, falling to only 2–4 per cent in the older (≥10 Myr) γ Velorum cluster. Similar behaviour is observed in young moving groups, where the accretor fraction in the <10 Myr η and ϵ Cha groups is ∼30 per cent (Murphy et al. 2013) but by the age of Upper Scorpius (10 Myr) has fallen to ∼10 per cent (Lodieu et al. 2011) and in UCL and LCC (16–17 Myr) is at most a few per cent (Mamajek et al. 2002). Complicating matters are recent recalibrations of pre-main-sequence cluster and association ages by Bell et al. (2013), which have increased the ages of some benchmark groups by up to a factor of two and therefore increased average circumstellar disc lifetimes. Nevertheless, if 2M1239−5702 and 2M1422−3623 are at the median age of LCC and UCL then they are incredibly rare objects. Assuming exponential decay is an appropriate functional form for the dissipation of inner discs at older ages (see discussion in Mamajek 2009), for a putative population of 10^4 Sco–Cen members we may (very) naively expect only 5–10 stars to show signs of accretion at 16–17 Myr given an *e*-folding time-scale of $\tau = 2.3$ Myr (Fedele et al. 2010). Even with accretor fractions of 1–2 per cent (consistent with $t \approx 8$–10 Myr) there should exist no more than a few hundred examples across the association. The serendipitous discovery of two such stars in a kinematically selected survey not looking at Sco–Cen or targeting accretors and infrared excess sources thus seems very surprising, and demands a more nuanced explanation than simple exponential decay at fixed age and decay time. In the following paragraphs, we consider two possible solutions to this problem – significant age spreads within Sco–Cen and stellar mass-dependent disc dissipation.

After considering the effects of observational uncertainties, Mamajek et al. (2002) concluded that the *intrinsic* 1σ age spreads of G-type stars in UCL and LCC are 3 and 2 Myr, respectively. This implies that almost all star formation ceased in the subgroups approximately 5–10 Myr ago. Pecaut et al. (2012) found similar median ages for UCL (16 Myr) and LCC (17 Myr) F-type members, but with larger intrinsic age spreads of ±4–7 Myr and ±0–8 Myr, depending on the choice of evolutionary models. In the maximal cases, these give 2σ limits on the cessation of star formation which are comparable to the ages of the subgroups themselves. Such age spreads are not unexpected given that star formation in UCL and LCC probably unfolded in a series of small embedded clusters and filaments in a large, dynamically unbound complex (Preibisch & Mamajek 2008). Given the large age spreads observed in higher mass Sco–Cen members, it is therefore plausible that 2M1239−5702 and 2M1422−3623 may be as young as 5–10 Myr and among the last generation of stars to form across the region. In addition to ongoing accretion from dusty inner discs, young ages for 2M1239−5702 and 2M1422−3623 are also supported by their elevated CMD positions and undepleted lithium (Fig. 9).

A second possibility is that the time-scale for circumstellar disc dispersal is stellar mass dependent, with the processes responsible for clearing optically thick primordial discs being less efficient around lower mass stars (e.g. Kennedy & Kenyon 2009). Such a trend has been observed in several young groups, including Upper Scorpius (Carpenter et al. 2006; Luhman & Mamajek 2012). These studies indicate that a significant fraction (∼25 per cent) of inner discs around low-mass stars can survive for at least 10 Myr. There are hints such a phenomenon may extend to the rest of Sco–Cen. Modulo the association mass function, three M-type accretors have now been identified in UCL and LCC, the same number of earlier type members showing signs of accretion. Larger numbers of K- and M-type members are necessary to test this hypothesis. Both 2M1239−5702 and 2M1422−3623 have strong near-UV excesses and were included in the spectroscopic sample for this reason. The inclusion of *GALEX* photometry in future Sco–Cen surveys should be a useful way to select additional active and accreting objects (e.g. Rodriguez et al. 2011, 2013; Shkolnik et al. 2011).

Finally, we comment on the recent suggestion of Song et al. (2012) that UCL and LCC are as young as ∼10 Myr. This age

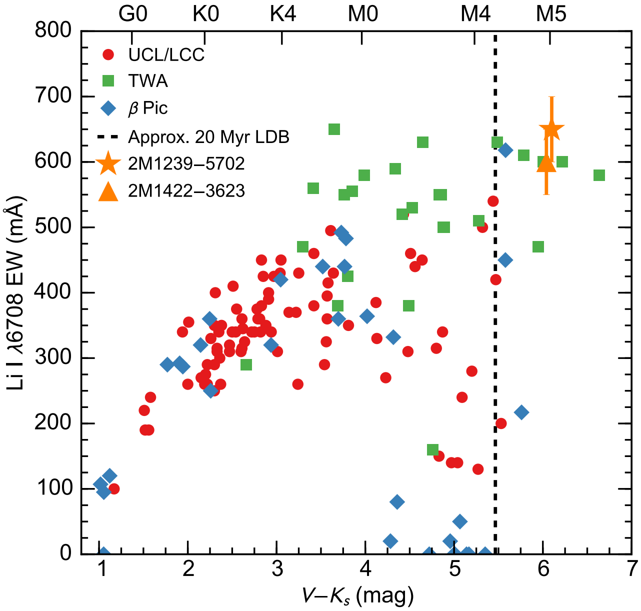

Figure 9. Li I λ6708 EWs of 2M1239−5702 (star) and 2M1422−3623 (triangle) compared to new UCL and LCC members from Song et al. (2012). Members of TWA (Schneider et al. 2012a) and β Pic (da Silva et al. 2009; Binks & Jeffries 2014) are plotted for comparison. The ∼20 Myr-old β Pic LDB is also given (dashed line). Sco–Cen members have lithium depletion levels between TWA and β Pic, corresponding to an age of 10–20 Myr.

estimate was based on ∼90 GKM stars which showed levels of lithium depletion bracketed between TWA (8–10 Myr) and the β Pictoris Association (Fig. 9), which had previously been considered to have an age of ∼12 Myr. Given recent upward revisions of the age of β Pic to 20–25 Myr (Binks & Jeffries 2014; Malo et al. 2014), the Song et al. (2012) results now imply ages between 10 and 20 Myr, consistent with the 16–17 Myr median subgroup ages and age spreads presented by Pecaut et al. (2012) and discussed in this section. Again, many more M-type Sco–Cen members are sorely needed to confirm the lithium depletion age of the association and examine trends with stellar parameters such as rotation and binarity.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table A1. New *Hipparcos* astrometry, literature radial velocities and re-calculated *UVW* space motions and *XYZ* positions of 305 Sco–Cen members proposed by de Zeeuw et al. (1999) (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stv1745/-/DC1).

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APPENDIX A: SCO-CEN MEMBERS WITH *HIPPARCOS* ASTROMETRY AND RADIAL VELOCITIES

Rizzuto et al. (2011) presented a list of 436 Sco–Cen members from the new *Hipparcos* reduction (van Leeuwen 2007), including 382 stars with radial velocities in the CRVAD-2 compilation (Kharchenko et al. 2007), which they used to construct linear models of the Sco–Cen space motion with Galactic longitude. During this work, we discovered that most of the radial velocities in that sample are non-spectroscopic ‘astrometric’ velocities from Madsen, Dravins & Lindegren (2002) which are inappropriate for calculating space motions or memberships. These were apparently sourced from the Pulkovo Compilation of Radial Velocities (PCRV; Gontcharov 2006), however they are not in the published PCRV catalogue. They were part of a preliminary list used to construct CRVAD-2 and later removed prior to publication of the PCRV (G. Gontcharov, personal communication).

To construct Fig. 6, we therefore assembled our own compilation of purely spectroscopic velocities from several large catalogues in the literature. The sample was constructed as follows. We first cross-matched the 521 members proposed by de Zeeuw et al. (1999, hereafter dZ99) against van Leeuwen (2007) and the list of Sco–Cen stars with Magellan/MIKE velocities from Chen et al. (2011). This returned 181 matches. After removing known spectroscopic binaries and non-members 140 stars were retained. We chose as a secondary source the PCRV, which contains mean absolute

Table A1. Radial velocities and space motions of Sco–Cen members proposed by de Zeeuw et al. (1999) from the *Hipparcos* catalogue. The final column lists the source of the radial velocity; either Chen et al. (2011), PCRV (Gontcharov 2006) or CRVAD-2 (Kharchenko et al. 2007). The full table with extra columns is available in machine-readable format with the online version of the article and on the CDS VizieR service.

HIP	RA (°)	Dec. (°)	RV (km s^{-1})	σ(RV) (km s^{-1})	U (km s^{-1})	$\sigma(U)$ (km s^{-1})	V (km s^{-1})	$\sigma(V)$ (km s^{-1})	W (km s^{-1})	$\sigma(W)$ (km s^{-1})	RV source
50520	154.771	−64.676	15.8	0.7	−8.3	0.6	−18.7	0.7	−5.1	0.3	PCRV
50847	155.742	−66.901	12.0	4.2	−10.0	1.4	−15.8	3.9	−3.1	0.6	PCRV
53701	164.808	−61.321	15.7	4.3	−8.8	1.8	−19.7	4.1	−5.8	0.5	PCRV
55334	169.97	−70.618	21.3	0.9	−6.8	0.9	−25.7	0.9	−7.8	0.3	Chen
55425	170.252	−54.491	9.4	5.0	−12.7	1.8	−15.4	4.7	−6.2	0.6	CRVAD2
–	–	–	–	–	–	–	–	–	–	–	–

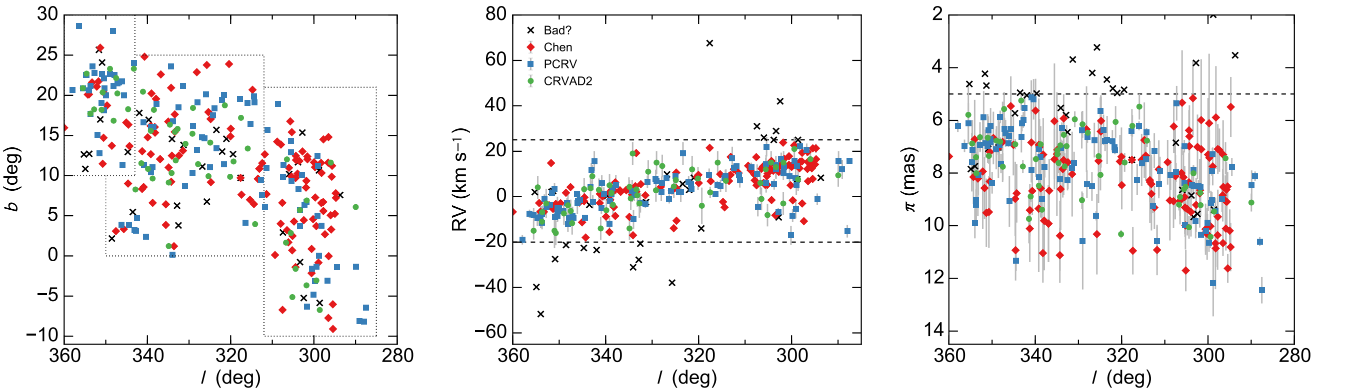

Figure A1. Position, radial velocity and parallax distributions of the stars in Table A1. The source of the RV is indicated: Chen et al. (2011, red diamonds), PCRV (blue squares) or CRVAD2 (green dots). Crosses show the 31 potentially unreliable stars not included in Fig. 6. These have $d > 200$ pc or -20 km s^{-1} > RV > 25 km s^{-1} (dashed lines).

velocities for 35 495 *Hipparcos* stars from over 200 publications, including major surveys. This returned 134 matches against dZ99, and we included the 110 stars not already observed by Chen et al. Finally, we cross-matched dZ99 against CRVAD-2, after removing all objects sourced from the pre-publication PCRV list (ICRV=2). This gave 57 primaries not already in the PCRV or Chen et al. samples. Several stars were found in more than one catalogue, allowing us to eliminate the spectroscopic binaries HIP 82747 and HIP 73666. The result of these crossmatches was a list of 305 Sco–Cen members with high-quality astrometry and radial velocities (median precision 1.5 km s^{-1}). The final compilation is listed in Table A1 and plotted in Fig. A1. Note that Fig. 6 includes additional cuts to remove 31 stars with unusually large velocities (-20 km s^{-1} > RV > 25 km s^{-1}) or distances ($d > 200$ pc) which are less likely to be members.

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