RX J0942.7−7726AB: an isolated pre-main-sequence wide binary

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ABSTRACT

We report the discovery of two young M-dwarfs, RX J0942.7−7726 (M1) and 2MASS J09424157−7727130 (M4.5), that were found only 42 arcsec apart in a survey for pre-main-sequence stars surrounding the open cluster η Chamaeleontis. Both stars have convergent proper motions and near-infrared photometry. Medium-resolution spectroscopy reveals that they are coeval (age 8–12 Myr), codistant (100–150 pc) and thus almost certainly form a true wide binary with a projected separation of 4000–6000 au. The system appears too old and dynamically fragile to have originated in η Cha and a trace-back analysis argues for its birth in or near the Scorpius–Centaurus OB association (Sco–Cen). RX J0942.7−7726AB joins a growing group of wide binaries kinematically linked to Sco–Cen, suggesting that such fragile systems can survive the turbulent environment of their natal molecular clouds while still being dispersed with large velocities. Conversely, the small radial velocity difference between the stars (2.7 ± 1.0 km s$^{-1}$) could mean the system is unbound, a result of the coincidental ejection of two single stars with similar velocity vectors from the OB association early in its evolution.

Key words: binaries: visual – stars: formation – stars: kinematics and dynamics – stars: low-mass – stars: pre-main-sequence – open clusters and associations.

1 INTRODUCTION

Since the discovery of a group of young stars associated with the ‘isolated’ T Tauri star TW Hydrae (de la Reza et al. 1989; Gregorio-Hetem et al. 1992; Kastner et al. 1997) it has become clear that the solar neighbourhood is bestrewn with sparse associations of stars with ages substantially less than the Pleiades (Zuckerman & Song 2004; Torres et al. 2008). Although members of these associations share similar kinematics, ages and distances, their proximity to us means they are spread over vast swathes of sky.

The youngest and best characterized of the groups are associated with the nearby (<100 pc) bright stars TW Hydrae (~10 Myr; Webb et al. 1999), β Pictoris (~12 Myr; Barrado y Navascués et al. 1999; Zuckerman et al. 2001b) and the neighbouring η and ε Chamaeleontis (<8 Myr; Mamajek, Lawson & Feigelson 1999; Feigelson, Lawson & Garmire 2003; Murphy, Lawson & Bessell 2010, hereafter MLB10). All four associations are located in the southern hemisphere around the Scorpius–Centaurus OB association (Sco–Cen; Fig. 1), the closest site of recent large-scale massive star formation (Blaauw 1964; de Zeeuw et al. 1999).

Much work has been done to understand their origins (e.g. Mamajek, Lawson & Feigelson 2000; Mamajek & Feigelson 2001; Sartori, Lépine & Dias 2003; Makarov 2007; Fernández, Figueras & Torra 2008). Most recently, Ortega et al. (2009) undertook a detailed kinematic study of the region and concluded that the groups were likely formed in small molecular cloudlets on the outskirts of the Lower Centaurus Crux (LCC) and Upper Centaurus Lupus (UCL) subgroups of Sco–Cen, triggered into star formation by the bulk flows and shocks formed by colliding stellar wind and supernovae-driven bubbles around the subgroups. With the exception of the denser η Cha cluster, which appears to have only recently lost its natal molecular material (Mamajek et al. 2000), the cloudlets later dispersed to reveal sparse, unbound associations of stars with similar ages and velocities. Fernández et al. (2008) proposed a similar scenario, with the star formation agent being the passage of a spiral density wave through the region.

Such models are reminiscent of the ‘in situ’ star formation process proposed by Feigelson (1996) to explain the discovery of isolated pre-main-sequence (pre-MS) stars around the Chamaeleon and Taurus–Auriga dark clouds. Under this scenario, stars born in different parts of a molecular cloud inherit the region’s turbulent velocity dispersion, which can be up to 10 km s$^{-1}$ on scales of 10–100 pc (Larson 1981). In the maximal case, 10-Myr-old stars can hence be dispersed up to ~100 pc away from the main cloud (1 km s$^{-1}$ ≈ 1 pc Myr$^{-1}$), several tens of degrees on the sky at the distances of these complexes. Young, unbound associations such as TW Hya and β Pic were presumably dispersed from Sco–Cen in a similar manner, but with smaller internal velocity dispersions (1–2 km s$^{-1}$), appropriate for their smaller spatial scales.
In this paper we describe the discovery and characterization of a pair of isolated, young, low-mass stars with common ages, distances and kinematics. Only 42 arcsec apart, we will show they form a wide (4000–6000 au) ~10-Myr-old binary system which may have been born in the region surrounding Sco–Cen, near one of the young groups described above. As such wide, fragile systems are prone to disruption by N-body encounters, they offer insight into the dynamical conditions throughout the formation and evolution of sparse young groups and associations.

### 2 RX J0942.7–7726 and 2MASS J0942

RX J0942.7–7726 (=2MASS J09424962–7726407) and 2MASS J09424157–7727130 (hereafter 2MASS J0942) were identified by MLB10 (see also Murphy 2012) in their survey for dispersed members of the southern open cluster η Cha, between the cluster and the neighbouring ε Cha association (3–7 Myr, 90–120 pc). The LCC subgroup of the Sco–Cen OB association is immediately northward, with an estimated age of 11–17 Myr and a distance of 110–120 pc (Preibisch & Mamajek 2008) (Fig. 1).

Although 2MASS J0942 lay within ~1 mag of the empirical η Cha isochrone and had an intermediate gravity suggestive of youth, it was rejected as a cluster member by MLB10 due to a low Li I 6708 equivalent width (EW) compared to known members (~350 mÅ; see Section 5.2). RX J0942.7–7726 was similarly excluded on account of its bad kinematic solution and colour–magnitude diagram (CMD) placement. At the time, MLB10 noted that RX J0942.7–7726 may be an outlying member of LCC but did not recognize it lay only 42 arcsec from 2MASS J0942 and possessed a similar proper motion and radial velocity (Table 1).

### Table 1. RX J0942.7–7726 and 2MASS J0942.

<table>
<thead>
<tr>
<th></th>
<th>RX J0942.7–7726</th>
<th>2MASS J0942</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral type</td>
<td>M1</td>
<td>M4.5</td>
<td>This work</td>
</tr>
<tr>
<td>V (mag)</td>
<td>13.59</td>
<td>–</td>
<td>P06</td>
</tr>
<tr>
<td>i (mag)</td>
<td>11.49</td>
<td>14.11</td>
<td>DENIS</td>
</tr>
<tr>
<td>i − J (mag)</td>
<td>1.127</td>
<td>1.726</td>
<td>2MASS</td>
</tr>
<tr>
<td>μα cos δ, μδ (mas yr⁻¹)</td>
<td>(−23, +17) ± 6</td>
<td>(−16, +23) ± 9</td>
<td>PPMXL</td>
</tr>
<tr>
<td>μα sin i (mas yr⁻¹)</td>
<td>(−20, +8) ± 7</td>
<td>(−22, +13) ± 5</td>
<td>SSA</td>
</tr>
<tr>
<td>RV (km s⁻¹)</td>
<td>20.7 ± 0.4</td>
<td>18.0 ± 0.9</td>
<td>This work</td>
</tr>
<tr>
<td>v sin i (km s⁻¹)</td>
<td>9 ± 3</td>
<td>–</td>
<td>C97</td>
</tr>
<tr>
<td>Hz EW (Å)</td>
<td>−3</td>
<td>−7</td>
<td>MLB10</td>
</tr>
<tr>
<td>Li I EW (mÅ)</td>
<td>450 ± 50</td>
<td>350 ± 50</td>
<td>MLB10</td>
</tr>
<tr>
<td>490 ± 15</td>
<td>–</td>
<td>C97</td>
<td></td>
</tr>
<tr>
<td>log LX/Lo,ₙ</td>
<td>−2.66 ± 0.18</td>
<td>–</td>
<td>A97</td>
</tr>
</tbody>
</table>

Weighted average

|                  | 19.9 ± 0.5       | –           |
| μα, μδ (mas yr⁻¹) | (−21, +19) ± (5, 5) | PPMXL |

### 3 Other stars in the vicinity

Because RX J0942AB lay at the bottom of the ±1.5 mag selection band in the η Cha CMD, there may be other young stars in the Sco–Cen OB association. RX J0942.7–7726 was found to be the weak-lined T Tauri star (WTTS) counterpart to a ROSAT X-ray detection by Alcala et al. (1995, 1997) during their survey of Chamaeleon X-ray sources. They obtained low-resolution spectroscopy which confirmed the youth of the star and assigned a spectral type of K7–M0. Covino et al. (1997) refined the spectral type to M0, and from a high-resolution (R ≈ 20 000) spectrum derived a stellar rotational velocity (v sin i ≈ 9 km s⁻¹), radial velocity (16.4 ± 2 km s⁻¹) and strong lithium absorption (EW = 490 mÅ). No close companions have been found around the star, down to separations of 0.13 arcsec and a K-band contrast of <3.8 mag (Köhler 2001).

2MASS J0942 is not as well characterized. Aside from survey photometry and astrometry, and the spectroscopy presented in MLB10, the mid-M pre-MS star remains largely unstudied.

Observed parameters for each star are given in Table 1. The radial velocities in the table are updates to the multi-epoch, medium-resolution (R = 7000) values described by MLB10 and are derived from seven to 10 observations of each star. As orbital motions are generally negligible (<1 km s⁻¹) in this regime, the components of wide binaries should have kinematics that agree within errors. While their mean radial velocities only agree at the 2.7σ level, RX J0942.7–7726 and 2MASS J0942 have congruent proper motions in both the SuperCOSMOS (Hambly et al. 2001) and Extended Position and Proper Motion (PPMXL; Roeser, Demleitner & Schilbach 2010) catalogues (RX J0942.7–7726 is also found in UCAC3). We adopt the proper motions from PPMXL as it is the largest homogeneous astrometric catalogue on the International Celestial Reference System currently available and (unlike the higher precision UCAC3) returns matches for both stars. A Digitized Sky Survey finder chart for the system is plotted in Fig. 2. For the sake of brevity we hereafter refer to it as RX J0942AB.
Figure 2. $3 \times 3$ arcmin$^2$ DSS2-IR finder chart centred on the ROSAT position of RX J0942.7$-$7726 (red cross). The 1σ uncertainty in this X-ray position is $\sim 20$ arcsec, comparable to the 22 arcsec offset between it and the optical position. 2MASS J0942 was not detected by ROSAT. The optical sources of RX J0942.7$-$7726 and 2MASS J0942 are 42 arcsec apart. Their PPMXL proper motions are shown in red and trace the expected motion on the sky over $\sim 2000$ yr. Thin grey arrows depict the $\pm 1σ$ error bounds.

Figure 3. The 768 stars within 10 arcmin of RX J0942AB with iJHK photometry and PPMXL proper motions. The two blue labelled points are discussed in the text. Top-left: CMD with a 12 Myr Baraffe et al. (1998) isochrone at 150 pc for reference. Top-right: 2MASS two-colour diagram with dwarf (solid line) and giant (dashed) loci from Bessell & Brett (1988), transformed to 2MASS colours. Bottom-left: PPMXL proper motions. The cross shows the weighted average proper motion of RX J0942AB. Bottom-right: the 10-arcmin-radius field on the sky.

immediate vicinity of the pair that were missed by MLB10. Fig. 3 shows the 768 stars within 10 arcmin of RX J0942.7$-$7726 with Deep Near Infrared Survey of the Southern Sky (DENIS; Epchtein et al. 1997) and Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) photometry and PPMXL proper motions. Only two stars have elevated positions in the CMD similar to RX J0942AB. Star A (2MASS J09405860$-$7720117) lies at the edge of the 10-arcmin field but has similar photometry to RX J0942AB. However, its 2MASS colours are giant like and its proper motion is significantly smaller. HD 84964 is a K1 star that Olsen (1994) identified as a giant from Strömgren photometry. We note it has 2MASS colours consistent with an early K-giant and $E(B - V) \approx 0.2$, the reddening attributed to the region (see Section 4). Although HD 84964 is only 1.5 arcmin from RX J0942AB and has a proper motion vector near both stars, it is likely unrelated.

To confirm this we observed HD 84964 and Star A with the Wide Field Spectrograph (WiFeS)/7R000 (see Section 4.1) on the Australian National University (ANU) 2.3-m telescope in 2011 July and found them both to be mid-K stars (from visual comparison to radial velocity standards) with strong Hα absorption and negligible ($<50$ mÅ) Li i 6708 EWs. Their radial velocities (67 $\pm$ 2 and 1.4 $\pm$ 2 km s$^{-1}$, respectively) are also inconsistent with either RX J0942.7$-$7726 or 2MASS J0942 (weighted mean velocity 19.9 $\pm$ 0.5 km s$^{-1}$).

We now address the likelihood that RX J0942AB is a true wide binary, rather than the chance alignment of unrelated young stars. Given the low spatial density of pre-MS stars in the region (Alcala et al. 1997; MLB10), it is unlikely that two such stars should lie only 42 arcsec apart and share similar kinematics. To qualify this statement we considered the $\sim 2.5 \times 10^3$ cross-matched 2MASS/DENIS detections within 3° of RX J0942AB. Of the 1574 stars lying in a band $\pm 1$ mag around both stars with $(J_{\text{DENIS}} - J_{\text{2MASS}}) > 1$, 819 had a PPMXL proper motion within 20 mas yr$^{-1}$ of RX J0942AB. Using these 819 stars we performed a nearest neighbour analysis, after correcting for isolated pairs (where $d_{\text{AB}} = d_{\text{PA}}$). Of the 567 unique nearest neighbour distances, only four are less than 42 arcsec. This implies that the chance alignment probability of RX J0942AB is only $P(d < 42$ arcsec$) = 4/567 = 0.7 \pm 0.4$ per cent (Poisson error). Even ignoring their obvious youth, it is thus highly unlikely RX J0942AB is the coincidental alignment of two unrelated M-dwarfs with similar proper motions. To confirm bina-

4 INTERSTELLAR REDDING TO RX J0942AB

Assuming an M0 spectral type, Alcala et al. (1997) used the $(V - I_C)$ colour of RX J0942.7$-$7726 to derive a reddening of $E(B - V) = 0.27$ mag. Sartori et al. (2003) found a lower value (0.17 mag) from comparison to updated model atmosphere colours, again using an M0 spectral type. The integrated reddening in the direction of the system is $E(B - V) = 0.34$ mag (Schlegel, Finkbeiner & Davis 1998).

However, these are likely overestimates of the true reddening to RX J0942AB. In MLB10 we estimated the reddening towards 2MASS J0942 to be negligible from its synthetic $(R - I_C)$ colour. This is consistent with the study of Knude & Hog (1998), who estimated the extinction in Chamaeleon as a function of distance using Hipparcos. While RX J0942AB lies just outside their surveyed area, they found that the reddening within 150 pc is small ($<0.05$–0.1 mag) but increases by a factor of 4 at the distance of the background Cha I & II clouds (160–200 pc; also see Whitet et al. 1997). Furthermore, the position of RX J0942AB in the 2MASS two-colour diagram (Fig. 3) does not support large reddenings. Comparing the photometry of RX J0942.7$-$7726 and 2MASS J0942 to that of (unreddened) η Cha members again suggests $E(B - V) < 0.1$ mag as an upper limit on the reddening to the system.

4.1 Observations

To garner conclusive spectral types and robust reddenings we observed RX J0942.7$-$7726 and 2MASS J0942 with WiFeS on the
The only previous spectral type for 2MASS J0942.7−7726 was determined by MLB10 solely from $(R - I)_C$ synthetic photometry. The emergence of molecular bands (e.g. TiO, VO, CaH) in the spectra of M-dwarfs enable a spectral type determination that can be effectively reddening independent. To derive a spectral type for 2MASS J0942 we adopted a selection of molecular indices from the compilation of Riddick, Roche & Lucas (2007) which have been shown to vary smoothly with spectral type across the mid-M subclasses (see their table 3). These gave an average spectral type of M4.6 ± 0.2. The agreement between this and the spectral type derived from broad-band photometry immediately suggests any reddening towards 2MASS J0942 must be small. Indeed, visual comparison of 2MASS J0942 to the M4.4 η Cha member RECX 9 (Lyo et al. 2004) shows an excellent match (Fig. 4), with an upper limit for the reddening of $E(B - V) < 0.1$ mag. Similarly, 2MASS J0942 has an earlier spectral type than ECHA J0841.5−7853 (M4.7), but is later than the M4 SDSS standard, regardless of reddening.

Finally, we computed synthetic photometry on the WiFeS spectrum using the passbands of Bessell (2005). This gave $(R - I)_C = 1.85 ± 0.03$ and a spectral type of M4.8, based on the relation of Bessell (1991). The new colour agrees with that derived from the earlier spectrum in MLB10 (1.80 ± 0.03). We adopt a spectral type of M4.5 as a sensible compromise between the various estimates, with an uncertainty of ±0.3 subclasses for both stars. This includes any residual reddening and flux calibration errors.

### 5 AGE OF RX J0942AB

We noted in MLB10 that 2MASS J0942 and RX J0942.7−7726 appeared to be slightly older than the immediately adjacent 5–8 Myr η Cha cluster. This was based on their smaller than expected Li i 6708 EWs and the more dwarf-like gravity of 2MASS J0942 when compared to mid-M η Cha members. Obtaining a robust estimate of their ages (and demonstrating their coevality) is crucial in confirming the true binary nature of RX J0942AB.

#### 5.1 Low-gravity features

The strength of the Na i 8183/8195 absorption doublet is highly dependent on surface gravity in mid-to-late M-type stars (Lyo et al. 2004; Slesnick, Carpenter & Hillenbrand 2006). It can therefore be used as an age proxy for pre-MS stars contracting towards their main-sequence radii. Lawson, Lyo & Bessell (2009) used Na i doublet strengths to rank the ages of several young associations in the solar neighbourhood at a resolution of 1–2 Myr. While there is some scatter in the gravity indices for each association, the mean trends (Fig. 5) agree completely with the isochronal (and lithium depletion, see Section 5.2) age ranking of the groups.

To place RX J0942AB in Fig. 5 we computed the same Na i index, $\int F_{8148-8172}/\int F_{6076-6200}$, after smoothing the WiFeS R3000 spectra to the $R \approx 800$ resolution of the Lawson et al. data and resampling to the same wavelength scale. As expected for an M1 star, RX J0942.7−7726 is not discernible from older field dwarfs in this diagram. In contrast, 2MASS J0942 has a gravity index between dwarfs and giants, consistent with an age equal or greater than that of the β Pic association (10–12 Myr; Torres et al. 2008). We estimate an approximate upper age limit for 2MASS J0942 in this diagram of 40–50 Myr by comparing the star to AP Columbae, a recently identified, nearby (8.4 ± 0.1 pc) member of the Argus association (Riedel et al. 2011). Both stars have similar spectral types (≈M4.5)
but AP Col has the stronger doublet strength, indicative of a slightly older age. This has been well established as 40–50 Myr through a variety of methods, including Hertzsprung–Russell (HR) diagram placement, lithium depletion and accurate kinematics.

### 5.2 Lithium measurements

Stars that achieve temperatures greater than ~2.5 × 10^6 K in their cores will start to burn lithium. The deep convection zones in low-mass stars ensure that once lithium burning has begun it will rapidly deplete the element throughout the star. Hence, the amount of lithium depletion seen in low-mass stars can serve as a mass-dependent clock over pre-MS time-scales. We plot in Fig. 6 the Li I λ6708 EWs of 110 K and M-dwarfs from the high-resolution study of da Silva et al. (2009), who investigated lithium depletion in many of the recently identified young associations reviewed by Torres et al. (2008). EWs for RX J0942AB are plotted, with the high-resolution value of Covino et al. (1997) (490 ± 15 mÅ) used for RX J0942.7–7726. Following the work of da Silva et al., effective temperatures were estimated from (V – I) (RX J0942.7–7726) and (R – I) (2MASS J0942) colours and the transformation of Kenyon & Hartmann (1995). While improved contemporary M-dwarf temperature scales exist in the literature (e.g. Luhman et al. 2003), for consistency with the da Silva et al. sample we adopt the Kenyon & Hartmann scale. The exact choice of transformation used in Fig. 6 is unimportant as we are interested only in relative ages. RX J0942.7–7726 has a Li I λ6708 EW consistent with the 8–10 Myr old TW Hya Association (TWA), some of whose late-type members have already begun to show significant depletion. We discuss the three TWA members with T_eff < 3700 K and EW < 400 mÅ briefly below. TWA 16 is among the group of members (TWA 14–19) proposed by Zuckerman et al. (2001a) that lie south of TW Hya near HR 4796. By comparing photometric rotational periods, Lawson & Crause (2005) claimed TWA 14–19 are in fact background LCC members. TWA 20 was rejected as a TWA member by Song, Zuckerman & Bessell (2003) based on its low lithium EW. Mamajek (2005) and Torres et al. (2008) have computed kinematic distances to TWA 16 and TWA 20. Compared to the 90–110 pc distance to the inner edge of LCC, their ~70 pc distance means both stars are likely true outlying TWA members (however TWA 20 is a suspected spectroscopic binary; Jayawardhana et al. 2006). TWA 5B is a confirmed member with a distance of 45 pc (Mamajek 2005). The accelerated lithium depletion seen in these three stars is likely related to surface activity or rotation (Jeffries 2006; King et al. 2010).

Lithium depletion is already well advanced in the ~12-Myr-old β Pic association, with a steep decline in EW visible down to its lithium depletion boundary (LDB; dashed line). The mass sensitivity of lithium burning means that stars less massive than this limit still retain appreciable amounts of the element. RX J0942.7–7726 is not as depleted as the early-M-type members of β Pic. We therefore estimate an upper age limit of ~12 Myr from Fig. 6. Depletion ages for single stars must be interpreted with caution however, as star-to-star variations within an association (see above) can imply vastly different ages for a presumably coeval population.

Like RX J0942.7–7726, 2MASS J0942 also has a level of lithium depletion consistent with a β Pic or TWA-like age, appearing older in this diagram than η and ϵ Cha members. The star is cooler than the β Pic LDB so we cannot use this to constrain its age. It is however slightly warmer than the LDB of the open cluster IC 2391, which Barrado y Navascués, Stauffer & Jayawardhana (2004) place at (R – I) eff ≈ 1.90 (spectral type ~M5). The detection of significant lithium absorption in 2MASS J0942 (R – I = 1.85) implies it must be younger than the lithium age of IC 2391, which both Barrado y Navascués et al. (2004) and Jeffries & Oliveira (2005) find to be 50 ± 5 Myr. Despite lithium depletion ages appearing systematically older than isochronal ages from HR diagrams (see Song, Bessell & Zuckerman 2002; Yee & Jensen 2010, among others), the relative ages still stand and 2MASS J0942 appears younger than IC 2391 (main-sequence turn-off age ~35 Myr; Barrado y Navascués et al. 2004).

### 5.3 Activity: X-ray emission, He and rotation

Young low-mass stars are well known to possess active coronae and chromospheres, which are manifestations of their strong magnetic
fields and fast rotation rates (Feigelson & Montmerle 1999). Unfortunately for reliable age determinations, M-dwarfs have a long adolescence, with enhanced activity that can last for many Gyr (e.g. Hawley, Gizis & Reid 1996). The diagnostics outlined below are therefore necessary but insufficient indicators of youth.

X-ray emission from RX J0942.7−7726 was identified from ROSAT observations by Alcala et al. (1995, 1997). They found a saturated ratio of X-ray to bolometric luminosity typical for young, low-mass stars, log (Lx/Lbol) ≈ −2.66 ± 0.18. Old field M-dwarfs can possess similar levels of emission, so the detection of X-rays from the star cannot constrain its age. No X-rays have yet been detected from 2MASS J0942, though given the limiting flux of the ROSAT All Sky Survey (2 × 10^{-13} erg cm^{-2} s^{-1}; Schmitt, Fleming & Giampapa 1995), in the absence of flares an M4.5 star with saturated X-ray emission would need to lie within ~30 pc (10 Myr age) or ~20 pc (40 Myr) to have been detected by the satellite.

Both stars exhibited weak Hα emission throughout the WiFeS observations (Table 1). No emission variability was detected within the measurement uncertainties on time-scales of days to months. The low levels of emission (EW ≤ 7 Å) are the result of quiescent chromospheric activity, not flares or accretion from a circumstellar disc, which are characterized by strong, variable emission (Murphy et al. 2011). Similar levels are observed in older field dwarfs.

The rotation of a star (v sin i) may be used as a crude clock, as young stars are expected to rotate rapidly and spin-down as they age. From their echelle spectrum, Covino et al. (1997) measured v sin i = 9 ± 3 km s^{-1} for RX J0942.7−7726. In a sample of 123 M-dwarfs, Browning et al. (2010) found only seven stars rotating faster than their v sin i ≈ 2.5 km s^{-1} detection limit. They further estimated <10 per cent of all early-M stars are detectably rotating. The measurement of significant rotation in the RX J0942.7−7726 (M1) is therefore more (albeit qualitative) evidence of its youth.

5.4 Infrared observations

RX J0942.7−7726 was observed as part of the Spitzer Space Telescope Cores to Discs (c2d) programme (Padgett et al. 2006). No excess emission above photospheric levels was detected out to 30 μm, which would otherwise indicate the presence of a dusty circumstellar disc. Both stars also show no excess emission to 22 μm in the Wide-field Infrared Survey Explorer All-Sky Data Release (Cutri et al. 2012). This generally implies an age greater than 5−10 Myr, by which time most inner discs are observed to have dissipated (Hernández et al. 2008). However, such a relation only holds in a statistical sense (there are still strong disc excesses seen in several TW Hya and β Pic members for instance) and is complicated by the fact that binary disc lifetimes (especially in the presence of a wide companion) are not well constrained (e.g. Kastner et al. 2012).

5.5 Age of the system

The two most quantitative age indicators – surface gravity and lithium depletion – yield an age for both stars similar to that of the TW Hya and β Pic associations, around 8−12 Myr. While the gravity index of Fig. 5 cannot constrain the age of RX J0942.7−7726 (and hence coevality), the star’s position in Fig. 6 restricts its age to ≲12 Myr. The lithium data for 2MASS J0942 are also consistent with this value, which agree with the gravity-derived age of the star. None of the other, more qualitative age indicators (X-ray and Hα emission, measurable rotation, lack of IR excess) contradict these estimates. We therefore conclude that RX J0942AB is a pair of coeval pre-MS stars with an approximate age of 8−12 Myr.
period is $\sim 325,000$ yr and 2MASS J0942 has an orbital velocity of $\sim 0.3$ km s$^{-1}$ around RX J0942.7$-$7726. Statistically, the orbital semimajor axis is likely to be slightly larger than the projected separation, yielding an even longer period and smaller orbital velocity (Fischer & Marcy 1992). Hence, a change in relative velocity of even $\sim 1$ km s$^{-1}$ would be enough to perturb 2MASS J0942 out of such a wide orbit. To have avoided disruption, RX J0942AB must therefore have been born in a quiescent dynamical environment and never interacted closely with other stars over its short lifetime.

### 6.2 Space motion

Having estimated a distance to the system, its heliocentric $UVW$ space motion can be determined. Plotted in Fig. 8 are the velocities derived for RX J0942AB from 5 to 20 Myr isochronal distances and the weighted average PPMXL proper motion and WiFeS radial velocity (Table 1). This clearly shows that, irrespective of the assumed distance (age) to the stars or model isochrones, the space motions do not agree with any of the known young kinematic groups in the solar neighbourhood. This is perhaps not surprising considering the location of the system. Ruling out membership in any of the nearby Chamaeleon groups ($\eta$ Cha, $\epsilon$ Cha, Cha I, II) due to their younger ages, only TWA and $\beta$ Pic have ages congruent with RX J0942AB ($\sim 8$–12 Myr). However, the system lies many tens of degrees on the sky from the main concentration of either group, and at a much greater distance. Given its fragile configuration and the dearth of high-density regions or high-mass stars to power any dynamical interactions, it is implausible RX J0942AB was ejected from either group early in its evolution. Alternatively, RX J0942AB has a similar age, distance and lies adjacent to the nearby LCC subgroup of Sco–Cen (see Fig. 1), whose southern extent may be as young as 11–12 Myr (Preibisch & Mamajek 2008). However, the space motion of the system in Fig. 8 also does not agree with that previously found for the subgroup (Chen et al. 2011), so it is possible some sort of dispersal process may be at work.

To test this hypothesis and obtain kinematic distances and ejection velocities, we performed dynamical trace-back simulations, following the method described in MLB10 and using the epicyclic approximation to Galactic dynamics formulated by Makarov, Olling & Teuben (2004). We took the present-day velocities and positions of TW Hya, $\beta$ Pic and other young groups from Torres et al. (2008) and those of LCC and UCL from Mamajek et al. (2000) and Chen et al. (2011).

The simulations were performed over a range of plausible ejection times ($-20 < t < 0$ Myr) and current distances ($50 < d_0 < 150$ pc). Because the proper motion and radial velocity of RX J0942AB$-$7726 dominate the weighted average of the pair, we ran the simulations for both the PPMXL/WiFeS average values and those of RX J0942AB$-$7726 alone, using the best-available data from UCAC3 and FEROS (see Section 8).

The results of the trace-back simulations are summarized in Table 2. Only five of the 14 groups plotted in Fig. 8 gave acceptable $\Delta UVW$ values (see notes to Table 2). Notably, $\beta$ Pic is ruled out as a possible birthplace for the system. Although permitted by the simulations, origin in TW Hya requires an implausibly large ejection velocity of $6–7$ km s$^{-1}$. Also allowed were the 20–40 Myr-old Carina and Columba associations (subdivisions of the Great Austral Young Association, GAYA; Torres et al. 2008).

Although known members of Carina (almost all solar type) overlap the position of RX J0942AB (Fig. 1) and lie at similar distances ($85 \pm 35$ pc), both groups are much older than the 8–12 Myr we find for RX J0942AB. The similarly aged Tuc–Hor association is also a constituent of GAYA and is clearly more lithium depleted than RX J0942AB$-$7726 in Fig. 6. Moreover, the ejection epochs for Carina and Columba are well after the formation of the groups

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2 Unlike $\eta$ Cha, which can be considered a point source, the other groups have considerable spatial extent ($\sigma_{XYZ} \approx 10–40$ pc). The simulations assume the mean group position and velocity are representative of the ejection point and can be used to trace its motion back in time. Ejection from another position will change the implied ejection velocity, distance and epoch.
(when interactions should be rare) and require velocity changes of 4–7 km s\(^{-1}\) to move RX J0942AB to its present location.

### 7 ORIGIN OF RX J0942AB

The simulations yielded kinematic distances and ejection times from UCL and LCC similar to the distances and ages of the subgroups (110–140 pc, 11–17 Myr; Preibisch & Mamajek 2008). Ages at the upper end of this range are ruled out by the lithium data for RX J0942.7–7726, which suggests an age no older than \(\beta\) Pic. A significant age spread in the subgroups could alleviate this problem; Mamajek, Meyer & Liebert (2002) estimated that star formation in the groups ceased around 5–10 Myr ago, so it is possible some members may be younger than the quoted age. In light of the dynamical simulations, which suggest Sco–Cen could have been complicit in the formation of RX J0942AB, we have identified two likely mechanisms for the origin of the system.

#### 7.1 ‘In situ’ formation in a turbulent gas flow

The ‘ejection’ velocities required by the simulations (4–7 km s\(^{-1}\)) are typical of the bulk turbulent or thermal motions in molecular clouds (Larson 1981). We speculate that RX J0942AB was born in such a turbulent flow associated with the subgroups during their early evolution. If the flow was laminar over scales of several thousand astronomical units it could presumably impart a large velocity to the system whilst keeping it intact. This scenario is analogous to those proposed for the birth of TWA, \(\beta\) Pic and \(\epsilon\) Cha at around the same time (Fernández et al. 2008; Ortega et al. 2009) and closely resembles the ‘in situ’ star formation of Feigelson (1996), in which stars born in different parts of a molecular cloud inherit the region’s turbulent velocity and disperse into the field over several Myr.

Such an isolated wide pre-MS binary is not unprecedented – Feigelson et al. (2006) reported the discovery of the \(~10\) Myr, 2000 au \(F0/M0\) binary 51 Eri/GJ 3305. With a distance of 30 pc, they ascribed the pair to the \(\beta\) Pic association. The system lies some 100 pc distant on the sky (110 pc in space) from LCC, the supposed birthplace of \(\beta\) Pic. 51 Eri/GJ3305 would need to have been born in gas displaced by \(~10\) km s\(^{-1}\) from the LCC group velocity to move to its current location in 10–12 Myr. We have proposed a similar scenario for the birth of RX J0942AB. These two systems join a growing number of similar binaries in the young groups kinematically linked to Sco–Cen, with several members of the TW Hya, \(\beta\) Pic and \(\epsilon\) Cha associations hosting wide (\(a > 10^4\) au) systems (e.g. Caballero 2009; Looper et al. 2010; Kastner et al. 2012). Clearly it seems that the formation of sparse stellar groups can proceed in dynamically quiescent conditions necessary for wide binary survival while still imparting modest velocity dispersions to group members.

As noted in Section 1, many of the apparently ‘isolated’ pre-MS stars were later found to be members of sparse associations, spanning tens to hundreds of square degrees on the sky. While we ruled out the presence of other young stars in the immediate vicinity of RX J0942AB in Section 3, it is possible RX J0942.7–7726 and 2MASS J0942 are the first members of a hitherto-unknown group to be discovered. There are several hundred PPMXL detections within a 10\(^{-3}\) pc radius of the pair that have congruent photometry, distances and space motions (assuming a realistic range of radial velocities and a 10 Myr age), a handful of which lie within an arcminute of a ROSAT X-ray source (a first-order youth indicator). Confirmation of these stars as a coeval, comoving association is outside the scope of this work, but it is possible that RX J0942AB, like 51 Eri/GJ 3305, formed in a small, unbound group on the outskirts of Sco–Cen approximately 10 Myr ago.

#### 7.2 Coincidental ejection from Sco–Cen?

Alternatively, Moeckel & Bate (2010) and Kouwenhoven et al. (2010) found that their \(N\)-body simulations could produce wide (\(a > 10^4\) au) binary systems in the haloes of dynamically evolving young clusters when two stars were coincidently ejected with similar velocity vectors and became weakly mutually bound. Moreover, Moeckel & Clarke (2011) recently showed that a small, transient population of wide binaries can persist in the halo of an evolving cluster and be ‘frozen out’ into the field when the time-scale of binary destruction exceeds that of the decreasing stellar density. Old, wide binaries are rare (only a few per cent of systems have \(a > 10^4\) au in the solar-type sample of Duquennoy & Mayor 1991), but a weakly bound system could explain why RX J0942.7–7726 and 2MASS J0942 have radial velocities that differ by 2.7 km s\(^{-1}\).

Given the errors on the mean velocities, this is a 2.7\(\sigma\) difference and well above the 0.3 km s\(^{-1}\) variation expected due to orbital motion.

The clusters in the \(N\)-body simulations described above are typically very rich. For instance, Moeckel & Bate (2010) evolved a cluster of \(\sim 1200\) stars (stellar mass \(\sim 200\) M\(_{\odot}\)) with a half-mass radius of only 10\(^{4}\) au (0.05 pc). There is no observational evidence that \(\beta\) Pic or TW Hya were \(\textit{ever}\) in such a rich, dense configuration. In contrast, dynamical models show that \(\eta\) Cha may have been initially very dense (10\(^{5}\) stars pc\(^{-3}\); Moraux, Lawson & Clarke 2007), but likely only possessed \(< 100\) members at birth and is spectroscopically older than RX J0942AB. In lieu of a nearby rich

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**Table 2. Results of dynamical simulations for RXJ0942AB and nearby groups.**

<table>
<thead>
<tr>
<th>Association</th>
<th>(\Delta UVW_{\text{min}})</th>
<th>(v_{\text{eject}})</th>
<th>(t_{\text{eject}})</th>
<th>(d_0)</th>
<th>(\Delta UVW_{\text{min}})</th>
<th>(v_{\text{eject}})</th>
<th>(t_{\text{eject}})</th>
<th>(d_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TW Hydr.</td>
<td>2.5</td>
<td>7.1</td>
<td>-13.0</td>
<td>114</td>
<td>1.8</td>
<td>6.0</td>
<td>-13.5</td>
<td>101</td>
</tr>
<tr>
<td>Columba</td>
<td>1.6</td>
<td>6.8</td>
<td>-13.75</td>
<td>108</td>
<td>1.4</td>
<td>5.0</td>
<td>-17.5</td>
<td>100</td>
</tr>
<tr>
<td>Carina</td>
<td>0.6</td>
<td>4.4</td>
<td>-8.0</td>
<td>113</td>
<td>0.8</td>
<td>3.9</td>
<td>-7.5</td>
<td>100</td>
</tr>
<tr>
<td>LCC</td>
<td>2.6</td>
<td>3.9</td>
<td>-20.0</td>
<td>126</td>
<td>1.6</td>
<td>3.6</td>
<td>-20.0</td>
<td>111</td>
</tr>
<tr>
<td>UCL</td>
<td>0.1</td>
<td>7.4</td>
<td>-17.25</td>
<td>130</td>
<td>0.9</td>
<td>7.1</td>
<td>-17.0</td>
<td>115</td>
</tr>
</tbody>
</table>

\(\Delta UVW_{\text{min}}\) is the vector magnitude of the difference between the observed and predicted space motion at each ejection epoch and current distance. The other quantities are given at the point of minimum \(\Delta UVW\).
cluster, the early dynamical evolution of the Sco–Cen OB association – perhaps via the dissolution of non-hierarchical few-body \((N < 10)\) systems (e.g. Sterzik & Durisen 1995) – appears to be the best scenario for the creation of RXJ0942AB from the ejection and mutual capture of two single stars. Indeed, several wide low-mass binaries formed by coincidental ejections from small-\(N\) (<100) groups have been observed in hydrodynamical star formation simulations (e.g. Bate & Bonnell 2005), including in one case the ejection of a highly eccentric \((e = 0.97)\) 3560 AU binary from a group of only 26 stars and brown dwarfs (Bate 2009). This 0.3 \(M_\odot\) + 0.13 \(M_\odot\) system is remarkably similar to RXJ0942AB, which if highly eccentric as well could naturally explain the observed 2.7 km\(^{-1}\) radial velocity difference.

Improved kinematics (ideally from parallaxes) and better knowledge of the dispersed low-mass population of Sco–Cen are needed to ultimately determine the origin of RXJ0942AB. High-resolution radial velocities in particular will make it possible to constrain the eccentricity and boundedness of the system in light of the two formation scenarios described above.

8 FURTHER MULTIPlicity?

Our mean WiFeS radial velocity for RXJ0942.7−7726 (20.7 ± 0.4 km s\(^{-1}\), Table 1) differs significantly from that reported by Covino et al. (1997) (16.4 ± 2 km s\(^{-1}\), circa 1995). The variation is well outside that expected from orbital motion around 2MASS J0942 and so may be evidence of unresolved binary. Since a large fraction of M-dwarfs are seen in multiple systems (e.g. Fischer & Marcy 1992), it is not unreasonable to expect that many of the primaries of wide binaries are in fact close multiple systems. Recent surveys (e.g. Makarov, Zacharias & Hennessy 2008; Faherty et al. 2010) have confirmed this and it is also seen in \(N\)-body cluster simulations including primordial binaries (Kouwenhoven et al. 2010). Moreover, there are hints that the frequency of hierarchical systems may increase with separation, at least for M-dwarf systems (Law et al. 2010).

Köhler (2001) did not detect a companion around RXJ0942.7−7726 in their speckle interferometry and direct imaging survey of Chamaeleon ROSAT sources. Their 0.13 arcsec (3.81 mag) detection threshold, the singly peaked cross-correlation function reported by Covino et al. (1997) and the good fit to the CMD in Fig. 7 put strong constraints on the orbit and mass of any companion. For instance, a 0.1 \(M_\odot\) star in a 5-au (0.05 arcsec at 100 pc) orbit would induce an orbital velocity in RXJ0942.7−7726 of only 1.7 km s\(^{-1}\) with a period of 14 yr. Such a companion could explain the velocity difference without being observed directly.

RXJ0942.7−7726 was observed 19 times during 1999–2005 with the Fiber-fed Extended Range Optical Spectrograph (FEROS) on the ESO 1.5- and 2.2-m telescopes at La Silla.\(^3\) We have obtained the reduced spectra (Gunther, private communication) and derive a mean velocity of 18.5 ± 0.6 km s\(^{-1}\). Velocities were computed by cross-correlation over the region 5900–6500 Å against the M1V star HD 36395, using an archival ELODIE (Prugniel & Soubiran 2007) spectrum and its observed velocity (7.6 ± 0.5 km s\(^{-1}\); White, Gabor & Hillenbrand 2007). No evidence of a companion was visible in the cross-correlation functions and the individual velocities show no trend over 6 yr of observations. Some scatter outside the instrumental errors is present, probably as a result of chromospheric activity (Murphy et al. 2011).


Intriguingly, this FEROS mean velocity bisects the Covino et al. (1997) and our 2010–2011 WiFeS values. It also agrees within errors with the velocity derived for 2MASS J0942. While at first this may indicate that the two stars are comoving, the contemporary WiFeS velocity for RXJ0942.7−7726 (20.7 ± 0.4 km s\(^{-1}\)) is inconsistent with both values. It is possible we are seeing temporal variation in the radial velocity between 1995, 1999–2005 and 2010–2011. The long period and small amplitude of the variation – if it exists at all – means further radial velocity monitoring of RXJ0942.7−7726 (and high-contrast imaging) is necessary to confirm any unresolved binary.

9 CONCLUSION

From new low- and medium-resolution spectroscopy we have shown that RXJ0942.7−7726 and 2MASS J0942 are a pair of isolated, coeval (age ~10 Myr) and codistant (100–150 pc) pre-MS stars deep in the southern sky. Their 42 arcsec separation and the sparsity of other young stars in their vicinity mean they almost certainly form a true wide binary with a projected separation of 4000–6000 au. Both stars have proper motions that agree within errors and similar radial velocities. Their exact origin remains uncertain, but we propose they were born in turbulent gas near the LCC or UCL subgroups of the Sco–Cen OB association. Similar birthplaces have been proposed for other wide pre-MS binaries like 51 Eri/GJ 3305 and the unbound \(\beta\) Pic, TW Hya and \(\epsilon\) Cha associations, whose members were probably born in similar turbulent flows in the region over the past 5–15 Myr.

Alternatively, the small but significant radial velocity difference (2–3 km s\(^{-1}\)) we observed could imply the system is unbound, possibly as a result of the coincidental ejection of two single stars from the subgroups with similar velocity vectors. If confirmed as bound, the existence of RXJ0942AB, 51 Eri/GJ 3305 and other wide binaries kinematically linked to Sco–Cen suggests that such fragile systems can survive the turbulent environment of their natal molecular clouds while still being dispersed with large velocities.

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