A SURVEY FOR A COEVOL, COMOVING GROUP ASSOCIATED WITH HD 141569

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ABSTRACT

We present the results of a search for a young stellar moving group associated with the star HD 141569—a nearby, isolated Herbig AeBe primary member of a ≈ 3 Myr-old triple star system on the outskirts of the Sco–Cen complex. Our spectroscopic survey identiﬁed a population of 21 Li-rich, ≲ 30 Myr-old stars within 30° of HD 141569 which possess similar proper motions with the star. The spatial distribution of these Li-rich stars, however, is not suggestive of a moving group associated with the HD 141569 triplet, but rather this sample appears cospatial with Upper Scorpius (US) and Upper Centaurus Lupus (UCL). We apply a modiﬁed moving cluster parallax method to compare the kinematics of these youthful stars with those of the US and UCL. Eight new potential members of US and ﬁve new potential members of UCL are identiﬁed. A substantial moving group with an identiﬁable nucleus within 15° (≈ 30 pc) of HD 141569 is not found in this sample. Evidently, the HD 141569 system formed ∼ 5 Myr ago in relative isolation, tens of parsecs away from the recent sites of star formation in the Ophiucus–Scorpius–Centaurus region.

Key words: open clusters and associations: individual (HD 141569) – stars: evolution – stars: individual (HD 141569) – stars: kinematics – stars: pre-main sequence

Online-only material: color ﬁgures, machine-readable and VO tables

1. INTRODUCTION

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comovement with HD 141569. In the first search, 10 stars were found through a query of the Hipparcos catalog (Perryman & ESA 1997) for objects within 10′ of HD 141569 with similar distances (99 ± 8 pc, as reported in Perryman & ESA 1997) and proper motions. Eight objects from the ROSAT Faint Source Catalog (Voges et al. 2000) supplemented this sample, as previous low-resolution observations (A. Weinberger 2004, private communication) showed evidence for spectroscopic signatures indicative of youth. A second search was performed in which the ROSAT Bright Source Catalog (Voges et al. 1999) was probed for X-ray sources within a 30′′ radius of HD 141569. Of the 1114 resulting targets, ∼ 400 sources had Tycho-2 (Høg et al. 2000) cataloged proper motions. We required proper motions to be within ±15 and ±20 mas yr⁻¹ in right ascension and declination of HD 141569′s proper motion, respectively, based on the range of proper motions observed in the widely dispersed and similarly aged TW Hydrae Association (Zuckerman et al. 2001; Webb et al. 1999). Finally, we required that the ROSAT sources not be extended and that they be cospatial with the Tycho coordinates. This procedure resulted in ∼ 70 objects desirable for further study to establish youth and space motions. A map of the observed sample is shown in Figure 1; members of other nearby associations are also shown for added context and perspective.

2.2. Observations

Forty-nine stars of our input catalog were observed spectroscopically over the course of three observing runs in order to measure spectral types, radial velocities, and Li i and Hα EWs. Four targets were found to be close visual binaries so their companions were observed as well; of these four, two were determined to be background objects on the basis of apparent magnitudes and spectral type in comparison to the primary and are thus not discussed further. An observing log of the 51 stars (49 targets + two visual companions) which form our final sample for this work is presented in Table 1. Photometry, proper motions, and parallax measurements from the literature are documented in Table 2.

On 2001 June 18 (UT), the 10 Hipparcos-selected targets and the five FSC targets were observed using the Hamilton Echelle Spectrometer at Lick Observatory. The Hamilton echelle covers a wavelength range of ∼ 3500–9800 Å with a resultant resolving power of 60,000 at 6000 Å when using a slit width of 1′′/2. During 2002 April, a further 36 target stars of the second catalog search were observed using the echelle spectrograph on the Irénée du Pont telescope at Las Campanas Observatory (LCO). The du Pont spectrograph observes a wavelength range of ∼ 3700–9800 Å with a resolving power of 40,000 at a slit width of 0′′75.

On both observing runs, comparison arc spectra were taken to establish a pixel-to-wavelength calibration. At LCO, Thorium–Argon lamp spectra were taken between each object exposure because the spectrograph is situated at the Cassegrain focus, whereas the Coudé-fed Hamilton echelle required less frequent arc calibration, with arc spectra being taken at the beginning and end of the night.

2.3. Reduction Procedure

The echelle data were reduced using IRAF to perform standard spectral reduction procedures. Instrumental effects were accounted for via measurements of bias level and read noise, variations in pixel-to-pixel CCD response were removed in the flat-fielding process, and dead columns were identified (which then prevented the measurement of the Hα 6563 Å

\begin{table}
\centering
\caption{Observing Log}
\begin{tabular}{llllll}
\hline
Object Name & R.A. & Decl. & Observation Time & Integration Time & S/N & Comment(s) \\
& [12000] & [12000] & [UT] & (s) & \\
\hline
2001 Jun 18 : UCO/Lick & & & & & & \\
Alpha Boo & 14:15:39.67 & +19:10:56.7 & 04:17:13.0 & 1 & 200 & K2III v, Standard \\
HD 137396 & 15:26:05.91 & −1:41:55.7 & 04:28:35.0 & 720 & 127 & \\
RHS 48 & 15:23:46.0 & −0:44:25 & 04:52:38.0 & 1500 & 158 & \\
HD 138969 & 15:35:47.41 & −12:51:32.9 & 05:25:23.0 & 720 & 105 & \\
HD 140574 & 15:44:26.30 & −03:50:18.5 & 05:45:22.0 & 720 & 132 & \\
& & & & & & \\
\hline
\end{tabular}
\end{table}

\begin{figure}
\centering
\includegraphics{figure1.png}
\caption{Galactic coordinate map of HD 141569 and nearby associations is presented. The open circles indicate our sample stars, while the dashed boxes indicate regions studied by de Zeeuw et al. (1999). Details of objects plotted herein are to be found in the following papers: US (Preibisch et al. 2002), UCL and LCC (Mamajek et al. 2002; de Zeeuw et al. 1999), TW Hya (Mamajek 2005), η and ε Cha (Zuckerman & Song 2004; Zuckerman et al. 2001), and IC 2602 (Robichon et al. 1999). In all subsequent plots, the letter A denotes the position of HD 141569.}
\end{figure}
line). A basic reduction process was then followed to locate and extract the echelle orders as well as remove scattered light. The Thorium–Argon arcs were similarly extracted, and their features identified so as to wavelength-calibrate the object spectra. The examples of IRAF routines employed include apall, ecidentify, refspec, and dispcor.

3. ANALYSIS

We aim to identify the subset of our sample which shows evidence of youth consistent with membership to a young, $\sim 5$ Myr-old association. Additionally, we wish to assess kinematic properties and test for comovement. To these ends, from the literature, we obtain effective temperatures as well as NIR photometry and proper motions. From the spectra, we measure LiI EWs as well as radial velocities. Utilizing these data, we estimate ages and select a youthful, high-luminosity sample, and test for kinematic similarity against the velocity models of nearby, young moving groups.

3.1. Effective Temperatures

Spectral types for the majority of our sample are reported in the literature (Houk 1982; Houk & Smith-Moore 1988; Houk & Swift 1999; Torres et al. 2006). These are converted to $T_{\text{eff}}$ using the main-sequence spectral type–$T_{\text{eff}}$ relationship of Kenyon & Hartmann (1995). We supplement these with spectral types determined from low-resolution spectra obtained with the Lick KAST spectrograph (A. Weinberger, unpublished data) as well as $T_{\text{eff}}$ determined from the Fe i-to-Sc i line ratio (see Stassun et al. 2004; Steffen et al. 2001) observed in our high-resolution spectra (Section 2.2). The line ratios measured for our spectral type standards are in good agreement with the calibration of Basri & Batalha (1990); we thus adopt their line-ratio spectral-type scale in assigning types to our sample. In some cases, primarily for more massive stars, the Fe i and Sc i lines were not present or could not be measured with confidence above the noise level. $T_{\text{eff}}$ values are summarized in Table 3. Where multiple $T_{\text{eff}}$ values are available, they generally show good consistency with one another to within $\sim 300$ K (corresponding to $\sim 2$ spectral subclasses). For our final set of effective temperatures, we adopt literature spectral types where available and line-ratio spectral types if not. For one object, HD 157310B, neither were available, and thus we interpolated its Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) $(H - K_s)$ color over the effective temperature–color relationship of Kenyon & Hartmann (1995). The set of adopted temperatures is reported in the final column of Table 3.

In Figure 2, we show these effective temperatures as a function of the objects’ observed 2MASS $(H - K_s)$ colors; also plotted is the $T_{\text{eff}}$–$(H - K_s)$ relationship from Kenyon & Hartmann (1995). For comparison, the standard stars observed (Table 1) are also shown in this parameter space. The observed $(H - K_s)$ colors follow the expected relationship with $T_{\text{eff}}$ with a scatter of $\sim 300$ K, consistent with the scatter in $T_{\text{eff}}$ from the above spectral types. This indicates that our sample in general suffers relatively little extinction. Indeed, radio survey column-density

| Plot ID | Object Name | $P^a$ | $H^b$ | $K_s^c$ | $\mu_b^d$ (mas yr\(^{-1}\)) | $\mu_h^e$ (mas yr\(^{-1}\)) | Parallax$^c$ (mas) |
|---------|-------------|------|------|--------|-----------------|-----------------|-----------------|
| A       | HD 141569   | 5.01 | 6.41 | 7.13   | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 1       | TYC 6242-0104-1 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 2       | TYC 6191-0552 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 3       | TYC 6234-1287-1 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 4       | TYC 7312-0236-1 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 5       | TYC 7327-0689-1 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 6       | TYC 6781-0415-1 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 7       | TYC 6803-0897-1 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 8       | TYC 6214-2384-1 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 9       | TYC 6806-0888-1 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 10      | BD +04 3405B | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 11      | HD 144713    | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 12      | HD 153439    | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 13      | HD 148936    | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 14      | TYC 7334-0429-1 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 15      | TYC 6817-1757-1 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 16      | HD 157310    | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 17      | HD 142016    | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 18      | CD -25 11942 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 19      | 2MASS J17215666-2010498 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 20      | TYC 6790-1227-1 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |
| 21      | TYC 7346-1182-1 | 5.01 | 6.41 | 7.13 | $-17.3 \pm 0.6$ | $-15.5 \pm 0.6$ | $28.5 \pm 0.6$  |

Notes. For star 19, we adopt proper motions of its companion, star 1.

$^a$ From 2MASS Catalog.

$^b$ Tycho-2 proper motions.

$^c$ Hipparcos parallaxes.

$^d$ Proper motions from UCAC2.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
### Table 3: Effective Temperatures and Lithium Equivalent Widths

| Plot ID | Object Name | Li\text{\textsc{ii}} EW (mÅ) | Li\text{\textsc{ii}} EW (mÅ) GFit | Cmm (mÅ) | Hα Flag | Spectral Type | Type Source | $T_{\text{eff}}$ (K) | $\lambda_{6200}/\lambda_{6210}$ Line Ratio | Spectral Type | $T_{\text{eff}}$ (K) | Adopted $T_{\text{eff}}$ (K) |
|---------|-------------|--------------------------|--------------------------|---------|---------|-------------|-------------|----------------|---------------------------------|-------------|----------------|-----------------|
| 1       | TYC 6242-0104-1 | 491                      | 487                       | 25      | e*      | K5 Ve       | 2           | 4350            | 1.07                           | K5           | 4350            | 4350            |
| 2       | TYC 6191-0552  | 481                      | 492                       | 15      | e*      | K2          | 1           | 4900            | 1.91                           | K2           | 4900            | 4900            |
| 3       | TYC 6191-1187-1 | 464                      | 452                       | 18      | e*      | K4 Ve       | 2           | 4590            | 2.65                           | K1.5         | 4990            | 4590            |
| 4       | TYC 6191-0552  | 434                      | 433                       | 15      | e*      | K2 Ve       | 2           | 4900            | 2.30                           | K2           | 4900            | 4900            |
| 5       | TYC 7327-0689-1 | 416                      | 414                       | 15      | e*      | K2 Ve       | 2           | 4900            | 2.52                           | K2           | 4900            | 4900            |
| 6       | TYC 6781-0415-1 | 409                      | 426                       | 13      | e*      | G9 IVe      | 2           | 5410            | 4.69                           | G9.5         | 5330            | 5410            |
| 7       | TYC 6803-0897-1 | 408                      | 413                       | 14      | a       | ..         | ..          | ..              | 3.62                           | K0.5         | 5165            | 5165            |
| 8       | TYC 6242-0104-1 | 397                      | 398                       | 14      | a       | K1 IV       | 2           | 5080            | 2.48                           | K2           | 4900            | 5080            |
| 9       | TYC 6806-0888-1 | 320                      | 345                       | 12      | a       | G8 IV       | 2           | 5520            | 11.3                           | G3           | 5830            | 5520            |
| 10      | BD+04 3405B    | 233                      | 242                       | 5       | a       | F4          | 5           | 6590            | ..                            | ..           | 6590            | ..              |
| 11      | HD 144713      | 164                      | 193                       | 5       | a       | F5 V        | 3           | 6440            | ..                            | ..           | 6440            | ..              |
| 12      | HD 153439      | 180                      | 198                       | 5       | a       | F5 V        | 3           | 6440            | ..                            | ..           | 6440            | ..              |
| 13      | HD 148396      | 197                      | 216                       | 14      | a       | K1/2 + F   | 3           | 5080            | 8.09                           | G8.5         | 5465            | 5080            |
| 14      | TYC 7334-0429-1 | 368                      | 378                       | 15      | a       | K2e         | 2           | 4900            | 3.99                           | K0           | 5250            | 4900            |
| 15      | TYC 6817-1757-1 | 274                      | 244                       | 13      | e*      | K0 Ve       | 2           | 5250            | 6.03                           | G9           | 5410            | 5250            |
| 16      | HD 137310      | 52                       | 76                        | 1       | a       | A7 H/III    | 5           | 7850            | ..                            | ..           | 7850            | ..              |
| 17      | HD 142016      | 20                       | 57                        | 0       | o       | A4 IV/V    | 3           | 8460            | ..                            | ..           | 8460            | ..              |
| 18      | CD-25 11942    | 307                      | 324                       | 13      | a       | K0 IV       | 2           | 5250            | 8.72                           | G8.5         | 5250            | 5250            |
| 19      | 2MASS J17215666-2010498 | 223 | 226 | 20 | e* | .. | .. | .. | 0.58 | K7.5 | 4060 | .. | 4060 |
| 20      | TYC 6790-1227-1 | 324                      | 344                       | 13      | a       | G9 IV       | 2           | 5410            | 4.53                           | G9.5         | 5330            | 5410            |
| 21      | TYC 7346-1182-1 | 256                      | 262                       | 12      | a       | G8 V       | 2           | 5520            | 5.94                           | G9           | 5410            | 5520            |

**Notes.** We report here two Li $\lambda$6707 measurements—“Integ.” in Column 3 refers to direct integration over the line profile, and “Gfit” in Column 4 indicates the result of fitting a Gaussian to the absorption feature. In Column 5, we also report contamination (denoted “Cmm.”) of the Li line; see Section 3.2 for description of its derivation. $\dagger$ Blended line; result indicates Gaussian feature fit to Li i in deblending. $\ddagger$ denotes cases in which the line ratio could not be measured from the spectrum either due to extreme rotational broadening or the lack of presence of either or both lines in question. $^*$ Effective temperature determined via interpolation of dereddened $H − K$ color over the color–effective temperature relationship of Kenyon & Hartmann (1995), see Figure 2.

- Indicator flags are defined as follows: absorption, a; core filling observed, c; double peaked emission, e*; P-Cygni like feature, p; emission with overlaid absorption, o.
- Spectral types drawn from the following sources: typed by A. J. Weinberger using KAST low-resolution spectrograph, 1; Torres et al. (2006; SACY), 2; Michigan spectral atlas (Houk 1982; Houk & Smith-Moore 1988; Houk & Swift 1999), 3, 4, and 5, respectively; HD Catalog spectral type, 6.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

measurements (Kalberla et al. 2005) in the direction of our targets indicate that $E(H − K_s)$ reddening toward our sample should be $\lesssim 0.1$ mag. Via comparison with expected intrinsic $(H − K_s)$ for a star of given effective temperature, we derive $K_s$-band extinction values, $A_{K_s}$, and deredden the sample accordingly. $(H − K_s)$ colors are plotted in Figure 3; lines illustrate dereddening by connecting colors before and after the dereddening. Also displayed for comparison are the dwarf sequence from Bessell & Brett (1988) as well as reddening vectors assuming the standard ratio of total-to-selective extinction $R_V = 3.12$. For visual clarity, we only display the 21 targets identified as lithium-rich (Section 3.2). The $K_s$-band extinction corresponding to the applied dereddenings is in all cases $A_{K_s} < 0.15$ mag, with the exceptions of 2MASS J17215666−2010498 and TYC 6191-0552-1 (objects 19 and 2 in the data tables) for which $A_{K_s} = 0.33$ mag and $A_{K_s} = 0.16$ mag, respectively. We have checked Spitzer 24 μm data (A. Weinberger 2008, private communication) and find that while most of the high-lithium sample lacks 24 μm excess, 2MASS J17215666−2010498 has a substantial excess. TYC 6191-0552-1 was analyzed by Meyer et al. (2008) and was found to have moderate 24 μm excess. For both objects, apparent excess in the $H$ and $K_s$ bands in concert with 24 μm excess confirms disk presence, and thus we cannot and do not apply a standard interstellar dereddening law.

![Figure 2](image-url)
3.2. Lithium Equivalent Width

We measured the EW of the \( \lambda 6707 \) line of Li\( \text{I} \) from our spectra using the IRAF routine \textit{Splot}. For each star, EW measurements were obtained both by directly integrating the flux in the line and by calculating the area of a best-fitting Gaussian. Our measured EW-values include contributions from the small Fe\( \text{I} \) and CN line at 6707.44 Å, leading to measured Li\( \text{I} \) EWs that are representative of a slightly (10–20 mÅ) overestimated photospheric Li presence. For instance, Soderblom et al. (1993) report that this Fe line blend has an EW = \([20(B - V) - 3]\) mÅ for main sequence solar-type stars. We correct for contamination following this prescription and find that the median value for the sample is 10 mÅ; we report in Table 3 the Li\( \text{I} \) EWs for each target via both measurement methods as well as the Fe line blend contribution. For all targets, the rms of the difference between the EWs determined using both methods is 18.4 mÅ. With the aim of conservatively selecting a sample, we utilize the lower of the two measured values; these are plotted in Figure 4.

To identify the young stars in the sample, Li\( \text{I} \) EWs were compared to the upper envelope of EWs as a function of \( T_{\text{eff}} \) reported in the literature for the \(~ 30 \) Myr-old clusters IC 2602 and IC 2391 (Randich et al. 1997, 2001; our Figure 4). Twelve stars are found to have Li\( \text{I} \) EWs above this envelope—compelling evidence of youth. In what follows, we refer to these 12 stars as the “High-Li” sample.

Also of interest, the H\( \alpha \) profiles of several objects are in emission in our spectra and some possess double-peaked profiles. Another six stars show elevated lithium levels (\( \gtrsim 200 \) mÅ but are below the threshold shown in Figure 4), placing them in the upper envelope of the IC 2602 and IC 2391 loci. An additional two stars have temperatures greater than 7500 K and EWs above the locus; although these are potentially older stars, which simply lack deep-enough convective zones to deplete primordial lithium abundances—we include them in the analyses for completeness. We also include star 13 in this group as it is in a double system separated by \( \sim 1\)\" while the seeing that night was \( \sim 1.5\)\", making Li\( \text{I} \) line filling likely. In Figure 4, this star is plotted with its measured EW doubled (denoted as “13b”) to demonstrate which sample group it would potentially belong to. In what follows, we refer to these nine stars as the “Moderate-Li” sample, two of which show double-peaked H\( \alpha \) in emission (Table 3).

These 21 stars, which are the most likely in our sample to be of comparable age to HD 141569, will be the focus of the remainder of our analyses. For ease in tracking these stars through our analysis, they are labeled with a running numerical identifier in the data tables and figures, and all EW and line profile information is reported in Table 3.

3.3. Radial Velocity

Heliocentric radial velocities were obtained using the IRAF task \textit{fxcor} to cross-correlate each target spectrum against the radial-velocity standard star of the closest spectral type (Table 1). Four echelle orders spanning the wavelength ranges 6025–6150 Å, 6150–6275 Å, 6625–6750 Å, and 5120–5220 Å were employed as they contain many deep metallic lines and little or no telluric contamination. In Table 4, we report the mean radial velocities from the four orders.
To determine the extent to which our radial-velocity measurements may be affected by the \( v \sin i \) and signal-to-noise ratio (S/N) of our target spectra, we performed a Monte Carlo simulation in which a narrow-lined, high S/N standard star spectrum was randomly degraded 100 times. This process created artificially noisy spectra at S/N levels of 10–100, well representing the full range of S/N found in our sample. Each degraded spectrum was artificially broadened and cross-correlated against its original high-S/N spectrum. These degraded spectra were furthermore cross-correlated against the other standard stars to assess the effects of spectral-type mismatch on the resulting radial velocities. We find that these effects are negligible (i.e., affecting the resulting radial velocities by \( \lesssim 1 \) km s\(^{-1}\)) unless \( v \sin i > 70 \) km s\(^{-1}\) or S/N < 30. As all of our target spectra have S/N > 30, only very fast rotators are potentially affected (by up to 2.3 km s\(^{-1}\) for \( v \sin i = 100 \) km s\(^{-1}\)). Measured \( v \sin i \) and radial-velocity values are documented in Table 4. In addition to these effects, we note that on an aperture-to-aperture basis, errors in wavelength calibration could affect the measured radial velocity; this can be quantified as the standard deviation of the mean radial velocity measured from the four selected apertures. The final radial-velocity uncertainties quoted in Table 4 are the square root of the internal uncertainty (the standard deviation of the four spectral orders used) and the uncertainty arising from rotational broadening.

### 3.4. Moving Cluster Parallaxes

With observed proper motions and measured radial velocities for the 21 high- and moderate-luminosity stars, a kinematic picture of the sample is almost complete. *Tycho*-2 proper motions were used for consistency throughout (Table 2), the only exception being one of the two close visual binary companions, HD 157310B, for which only UCAC2 (Zacharias et al. 2004) proper motions were available. Proper motion data are not available for the other close companion, 2MASS J17215666-2010498; in what follows, we assume common proper motion with its primary star, TYC 6242-0104-1. *Hipparcos* parallaxes are unavailable for the high-luminosity stars, thus a moving cluster parallax method (de Bruijne 1999) provides the means for determining their parallaxes and hence their distances. With distances, it can be tested then whether these objects are consistent with being members of a coherent moving group.

Our procedure is rooted in the derivation of de Bruijne (1999, see their Section 2 and references therein). The process is executed assuming a velocity vector, and hence a convergent point, for the moving group to which we are testing membership. In analyzing the spatial distribution of the 21 stars of our youthful sample, we note that they are all in closer proximity to US and UCL than HD 141569 (see Figure 5). The youthful sample is highly spatially separated from HD 141569, and these separations indicate two kinematic features. First, it is unlikely for objects with such large separations to be comoving. Second, these stars indeed formed together, large initial velocities (\( \sim 6 \) km s\(^{-1}\), inconsistent with the observed 1–2 km s\(^{-1}\) velocity dispersions of young associations) would be required to bring about the separations presently observed after \( \sim 5 \) Myr of motion. As it is unlikely that these objects are associated with HD 141569, we require estimates of the mean velocity vectors for US and UCL. The velocity vector for US is adopted from Majewski (2008): \( U/V/W = [-5.2, -16.6, -7.3] \) km s\(^{-1}\). This vector incorporates a mean radial velocity for 120 US members, an improvement over prior velocity vectors, which solely relied upon proper motion and parallax information. For UCL, the velocity model used for comparison is derived from the median position, proper motion, and radial velocities of UCL members (de Zeeuw et al. 1999); \( U/V/W = [-5.4, -19.7, -4.4] \) km s\(^{-1}\). We calculate these \( U/V/W \) vectors for US and UCL to precisions of \( \sim \pm 0.3 \) km s\(^{-1}\).
and $\sim \pm 0.4$ km s$^{-1}$, respectively. but note, there exist discrepancies between UVW vectors derived by various authors. The reason for the systematic differences between published convergent points and velocity vectors for the OB subgroups is not completely clear. The leading candidates for these systematic differences are the unaccounted expansion of the subgroups, and the probable presence of unresolved spatial and kinematic substructure within the subgroups. For robustness, we include all available radial-velocity measurements in the derivation of UVW vectors.

For each of the 21 stars in our high-Li and moderate-Li samples, we derive moving cluster parallaxes using the HD 141569 and US velocity vectors (Table 4). The formalism for this is

\begin{equation}
\sigma = \frac{A \mu_v}{v \sin(\lambda)},
\end{equation}

where $\sigma$ is the parallax, $A$ is 4.74 km yr$^{-1}$ (the ratio of one AU in km to a Julian Year in s), $\mu_v$ is the parallel component of proper motion (proper motion in the direction of the convergent point), $v$ is the velocity of the group in km s$^{-1}$, and $\lambda$ is the angular separation between the star and the convergent point (Equation 1, Mamajek 2005). An additionally useful parameter, the comovement probability, can also be calculated. Comovement probability is defined as $1 - P_{\perp}$, where $P_{\perp}$ is the likelihood that the star’s proper motion is entirely perpendicular to the direction of the convergent point; the projection of proper motion in this direction is denoted as $\mu_{\parallel}$, and a $\mu_{\perp}$ close to 0 is indicative of comovement.

4. RESULTS

4.1. Distances, Comovement Probabilities, and Membership

The spatial proximity of our youthful sample stars to US and UCL (Figure 5) suggests that these objects are not likely to be kinematically related to the farther away HD 141569 system. It is important to stress at this juncture that derived comovement probabilities are not absolute probabilities per se; their derivation depends directly on the velocity model assumed as a priori. We do know with certainty that the stars in our sample are young (by virtue of their high Li abundances) and that they are moreover in projected proximity to other stars known to be young, nearby, and comoving (Figure 1). Thus there is a strong “prior” favoring the velocity models that we have chosen to test. Still, the comovement probabilities reported in Table 4 should be regarded as measures of consistency with the assumed velocity models, and not proof of membership. We therefore adopt the very simple criterion of spatial proximity to a group in application of velocity modeling, and report the resulting distances and comovement probabilities for objects when tested against the velocity vectors of US and UCL. Parallax distances and comovement probabilities calculated as previously described (Section 3.4) are reported in Table 4.

Based on two simple criteria, youth determined via measurement of the $\lambda6707$ line and spatial position, objects 2, 6, 7, 8, 9, 11, 13, 15, and 21 lie within the US “box” as defined by de Zeeuw et al. (1999). Similarly, stars 4, 5, 14, 17, and 20 appear to be UCL members. These “spatial matches” are summarized in Column 3 of Table 5. Due to the similarities of velocity vectors in the Ophiucus–Sco–Cen region, it is unsurprising that in some cases, objects we deem US or UCL members have higher comovement probabilities when tested against the velocity vector of the other group. Factors which create blurring of kinematic boundaries include internal velocity dispersions inherent to a given moving group and observational uncertainties, which then propagate into the convergent-point solution. We thus take ($\ell, b$) position as the strongest indicator of group membership and then examine comovement probabilities as a supplement. Outside of the US box, stars 3, 12, and 18 have high comovement probabilities with US. We would present stars 12 and 18 with some caution as US members, as they are within a few degrees of the most extended, already known US members. Object 3 is almost 10$^\circ$ away from the southermost US stars and thus its association with US is also dubious. For these three objects, we tentatively suggest US membership and denote their membership in Table 5 as “US?” In two cases, we note objects with low comovement probabilities with their spatially matched groups: objects 1 and 19 do not have velocities consistent with US and are spatially inconsistent with being UCL members. Object 15, while spatially coincident with US, has low enough comovement probability to be a suspect. Finally, stars 10 and 16 have high comovement probabilities with US, but appear to be too far away in ($\ell, b$)-space to be considered part of US. These remaining five objects we classify as being of “Indeterminate” membership. In summary, the total number of new US members presented here is eight, and five new members of UCL are also identified.

4.2. Space Motions

To illustrate kinematic association in a familiar way, we could utilize the transformation matrices of Johnson & Soderblom (1987) to calculate UVW space motions for the sample stars. UVW motions, however, depend on distance, a quantity we have
obtained via assumption of comovement with a given \( U VW \) vector. The resulting \( U VW \) plot is thus degenerate and does not provide additional criteria by which we can further examine association.

As an additional check on the application of each velocity model, given an assumed velocity vector, radial velocities for each object can be predicted based on their proper motions and positions. We find good consistency between the predicted radial velocities and those measured, when comparing measured radial velocity to predicted radial velocity, for whichever velocity model we naively expect to be applied for a given simple spatial proximity to a given moving group. Illustrating the radial velocity structure of the sample in context with nearby groups can be a measurement-based, assumption-free way of analyzing space motions. In the selection criteria we constrained proper motions to agree with those of HD 141569 within a wide range of values, which includes proper motions generally observed in US. Measured radial velocities and projected radial velocities for the US velocity vector are plotted as a function of Galactic longitude in Figure 6. Most notably, the entire high-Li sample agrees well with the predicted radial velocities of US within \( \sim 2–3\sigma \). The farthest outlying points are from the moderate-Li sample.

### 4.3. \( H–R \) Diagram

In Figure 7, we show the placement of the sample stars on three \( H–R \) diagrams to illustrate shifts in \( M_K_s \) magnitude due to changes in distance. Absolute magnitudes were calculated from the observed 2MASS \( K_s \) magnitudes (Table 2) and one of the three distances. Uncertainties in \( M_K_s \) are the propagated errors of the 2MASS photometry together with the formal errors in distance. The uncertainty in \( T_{\text{eff}} \) is taken to be two spectral subtypes (see Section 3.1). To derive the ages of our sample stars we also show the pre-main-sequence (PMS) evolutionary tracks of Baraffe et al. (1998) and D’Antona & Mazzitelli (1997).

In the upper panel, we illustrate placement of the sample on the \( H–R \) diagram when we apply the distance to every individual object of the HD 141569 system. The isochronal ages inferred for most stars in our sample using the HD 141569 mean distance are in general older (\( \sim 30–100 \) Myr) than what would be expected for the stars based on their lithium abundances and...
comovement with the HD 141569 system (age $\pm 3$ Myr). In concert with the lack of spatial proximity, we further rule out the potential for a coeval, coherent moving group near HD 141569.

In contrast, the inferred ages using the US mean distance ($\sim 145$ pc, effectively equivalent to that of UCL, $\sim 142$ pc) are entirely consistent with the expectation of $\lesssim 30$ Myr as imposed by the Li EW measurements. All stars appear on or above the 30 Myr isochrone, save objects 10 and 16, which, despite their high comovement probabilities with US, do not appear to be in close-enough spatial proximity to be members of that moving group. In the third H–R diagram, applied distances are determined by the velocity model, US or UCL, that provides the highest comovement probability with a given object. This particular representation is not only mostly consistent with the age range expected from Li i presence, but it also "correctly" places the higher mass objects closer to the zero-age main sequence (ZAMS); particularly, objects 10, 16, and 17 have derived distances that make them appear to be ZAMS stars rather than anomalous objects far above or below the theoretical isochrones.

Scatter in an H–R diagram generally can be attributed to many factors: the radial extent of a young association (Mamajek 2005, e.g., TW Hydra $\sim 55$ pc), observational errors, or even the choice of evolutionary tracks can generate shifts and enhance spread in isochronal age of a sample expected to be coeval. Using the D’Antona & Mazzitelli (1997) evolutionary models, our sample stars all appear to have isochronal ages $\lesssim 10$ Myr.

In general, these tracks appear to be shifted by $\sim 400$ K to higher temperatures with respect to the Baraffe et al. (1998) tracks. For an illustration of these track-based discrepancies, see Simon et al. (2000). In spite of obstacles posed by apparently discrepant H–R diagrams, we can say with confidence based on Li i presence that these objects are indeed young, $\lesssim 30$ Myr. The H–R diagram, when applying high comovement probability derived distances, provides a higher degree of confidence in adopting these distances, as the ages are indeed as expected from Li measurements.

4.4. Is HD 141569 Related to US?

HD 141569 is an apparently isolated system located within tens of degrees (and parsecs) of known sites of recent (< 5 Myr) and ongoing star formation, all apparently associated with the Sco–Cen star forming complex (Preibisch & Mamajek 2008), which appears contiguous with the Aquila Rift regions (Dame et al. 1987, $\ell \simeq 30^\circ$). HD 141569 appears to agree with the projected velocity model of US (see Figure 6), but we can rule out the possibility of HD 141569 originating or being kinematically associated with US. The hypothesis that HD 141569 could have been ejected at high velocity from a known high density stellar nursery can be strongly discounted on two grounds. First, HD 141569 has two low-mass companions at wide separation ($\sim 10^3$ AU, with likely orbital motion of $\sim 1$ km s$^{-1}$). A velocity kick of more than 2–3 km s$^{-1}$ to either A or B+C would have likely disintegrated the system.

Figure 7. H–R diagram for sample stars with the PMS tracks of Baraffe et al. (1998) overplotted. Isochrones shown are (from top to bottom) 1, 3, 10, 20, 30, and 100 Myr. Also shown is the 100 Myr isochrone of D’Antona & Mazzitelli (1997) extending to higher masses. This isochrone and the 10 Myr isochrone are highlighted for reference. The upper panel shows the stars using $M_{K_s}$ derived from the distance to HD 141569 from the second Hipparcos data release, 116 ± 8 pc (van Leeuwen 2007). In the middle panel, we apply the mean distance to US, 145 ± 2 pc (de Zeeuw et al. 1999). The lower panel was generated using distances derived from the US velocity model (see the text). The sample’s isochronal age appears consistent with the high lithium abundances which indicate ages $\lesssim 30$ Myr (see Figure 4). (A color version of this figure is available in the online journal.)
A low-velocity ejection (< 2–3 km s\(^{-1}\)) would have placed the birth site within less than 10–15 pc (< 5°–7°), but no such known young clusters or molecular clouds appear there.

Position and velocity information for these nearby groups were entered into an orbit code which employs the epicyclic approximation. The separations between these groups and HD 141569 were evaluated during the past 10 Myr; combined distance and velocity vector uncertainties result in less than 15 pc uncertainties over this time frame. Presently, HD 141569 is \(\sim 55\) pc away from the center of US, and was only slightly closer at its minimum separation of \(\sim 53\) pc (\(\sim 2.7\) Myr ago). In UVW, the only substantial difference is in the W component of velocity—while US has negligible vertical motion with respect to the Local Standard of Rest (Mamajek 2008), HD 141569 is moving northward out of the disk at \(\sim 5\) km s\(^{-1}\). This anomalous W component of motion is discrepant with any known molecular cloud or star-forming region near HD 141569. Further, given the kinematic data and the isochronal age of HD 141569 (4–5 Myr), it appears that HD 141569 could not have formed from any of the known sites of recent star formation in its vicinity.

The list of excluded birth sites includes US, UCL, Lower Centaurus Crux (LCC), and the Ophiuchus, Corona Australis, and Lupus clouds.

Combining the kinematics, position, and age data, we conclude that the HD 141569 triple system was likely formed in the Lupus clouds. The list of excluded birth sites includes US, UCL, Lower Centaurus Crux (LCC), and the Ophiuchus, Corona Australis, and Lupus clouds.

5. SUMMARY AND CONCLUSIONS

We have identified a group of 21 PMS stars within 30° of HD 141569 on the basis of strong Li absorption and, in nine of those 21 cases, by He in emission. These stars were selected through a joint catalog search for X-ray sources with spatial and proper-motion characteristics similar to those of HD 141569, a B9.5Ve star at 116 pc that harbors a circumstellar disk and for which two low-mass companions had previously been identified (Weinberger et al. 2000). For these 21 stars, we have applied a moving cluster parallax technique to proper-motion data from the literature.

Table 5 outlines our final membership assessments; we present eight potential new members of US and five new potential members of UCL. These stars possess lithium presence consistent with youth and furthermore, appear youthful on the H–R diagram. Primarily we utilize spatial position as the principal criterion for determining membership and supplement that with comovement probabilities from the moving cluster parallax derivation. Additionally, we examine the motion of the HD 141569 system away from the Galactic midplane over its lifetime. The system, surprisingly, appears to have formed in isolation, well outside of presently known star-forming regions and molecular clouds.

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