DISTANCE AND KINEMATICS OF THE TW HYDRAE ASSOCIATION FROM PARALLAXES

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Received 2012 June 5; accepted 2012 November 6; published 2012 December 21

ABSTRACT

From common proper motion and signatures of youth, researchers have identified about 30 members of a putative TW Hydrae Association. Only four of these had parallactic distances from Hipparcos. We have measured parallaxes and proper motions for 14 primary members. We combine these with literature values of radial velocities to show that the Galactic space motions of the stars, with the exception of TWA 9 and 22, are parallel and do not indicate convergence at a common formation point sometime in the last few million years. The space motions of TWA 9 and 22 do not agree with the others and indicate that they are not TWA members. The median parallax is 18 mas or 56 pc. We further analyze the stars’ absolute magnitudes on pre-main-sequence evolutionary tracks and find a range of ages with a median of 10.1 Myr and no correlation between age and Galactic location. The TWA stars may have formed from an extended and filamentary molecular cloud but are not necessarily precisely coeval.

Key words: open clusters and associations: individual (TW Hydrae) – stars: distances – stars: kinematics and dynamics – stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

Nearby young stars of age ~5–10 Myr provide our best opportunity to study the late stages of star and planet formation with high sensitivity and spatial resolution. During this time period, the last gas-rich disks dissipate, and the onset of the debris disk phase occurs. The star TW Hydrae sports a massive disk and was first identified as an isolated T Tauri star (Rucinski 1983) and then the first member of an association of young stars (de la Reza et al. 1989; Gregorio-Hetem et al. 1992; Kastner et al. 1997). As the nearest example of a protoplanetary disk, TW Hya has been studied at every available wavelength and spatial resolution, but to understand its disk in context, TW Hya’s age must be well determined and its disk evolution compared to other stars of similar age and mass.

Over the last decade, ~30 members of a putative TW Hydrae Association (TWA) have been identified from a combination of stellar-activity searches and space motion studies (e.g., Webb et al. 1999; Sterzik et al. 1999; Zuckerman et al. 2001; Gizis 2002; Song et al. 2003; Scholz et al. 2005; Looper et al. 2007; Shkolnik et al. 2011). Members range in spectral type from A0 to brown dwarfs and have presumed common ages ~10 Myr, as determined from Li depletion and modeling on pre-main-sequence evolutionary tracks (Barrado Y Navascués 2006). Disks in TWA range from the four accreting, gas-rich, protoplanetary ones (TWA 1, 3, 27, and 30), to seven transitional or debris disks (TWA 4B, 7, 11A, 26, 28, 31, and 32), to the majority of members that have no detectable disks at all (Weinberger et al. 2004; Low et al. 2005; Riaz & Gizis 2008; Plavchan et al. 2009; Schneider et al. 2012).

The Hipparcos mission determined distances to only four TWA members, including TW Hya itself, for an average distance of 70 pc. Although the association contains the youngest stars close to the Sun, most of its members are low-mass stars and were therefore too faint for Hipparcos. Ground-based parallaxes have been measured for two brown dwarfs in the association—TWA 27 (2M1207) (Gizis et al. 2007) and TWA 28 (SSSPM J1102) (Teixeira et al. 2008), and one additional star that may not actually be a member—TWA 22AB (Teixeira et al. 2009). This highlights the problem of determining association membership—although their proper motions are similar, as ensured by search methods, without distances and therefore true Galactic space motions TWA stars can only be presumed to be associated. Hence, various members have been suggested and then excluded by proper motion studies using varyingly restrictive conditions for membership (e.g., Makarov & Fabricius 2001; Song et al. 2003; Mamajek 2005).

Distances to a substantial number of members would aid in defining the association and estimating its age from pre-main-sequence tracks. If the kinematics allow, a cluster expansion age could also be determined. In this paper, we present parallaxes and proper motions to 14 primary stars and two visual binary companions.

2. DATA

We have observed 14 TWA primary members with the CAP-SCam instrument at the 2.5 m du Pont Telescope at Las Campanas Observatory. The instrument and basic data reduction techniques are described in Boss et al. (2009) and Anglada-Escudé et al. (2012) and only briefly summarized here. CAP-SCam utilizes a Hawaii-2RG HyViSI detector filtered to a bandpass of 100 nm centered at 865 nm with 2048 × 2048 pixels, each subtending 0′′196 on a side. The main advantage of this camera is its ability to achieve simultaneously high signal-to-noise ratio (S/N) on a bright target star and fainter astrometric reference stars. Our typical TWA sources have I ≈ 10 (see Table 1); we place these bright target stars in an independently readable subarray called the “guide window” (GW). We typically locate the GW in the center of the full field (FF) and rapidly read and reset it for integration times down to 0.2 s for a 64 × 64 pixel subarray. Simultaneously, the FF integrates for as long as necessary to obtain high S/N on many reference stars. Table 1 gives typical integration times for each target in the GW and FF, although the times were adjusted during each epoch to account for seeing and clouds.

We drew our sample from stars without parallaxes (thus excluding TWA 1, 4AB, 9AB, 11A, 22, 27, and 28). We observed
Table 1
Observation Log

| Target Name | Other Name | I (mag) | Ref. | Integration Times (s) | Epochs of Observation (JD) |
|-------------|------------|---------|------|-----------------------|-----------------------------|
| TWA 2       |            | 8.9     | 1.2  | 0.2                   | 2454167.7, 2454809.8, 2454818.8, 2454931.7, 2454989.5, 2454992.5, 2455222.8, 2455295.9, 2455297.9, 2455369.6 |
| TWA 5       |            | 9.3     | 5    | 0.2                   | 12 2454664.5, 2454810.8, 2454932.7, 2454990.4, 2454991.5, 2455222.9, 2455368.7, 2455579.9 |
| TWA 11C     | 2M1235-39  | 11.2    | 2    | 0.2                   | 30 2454861.8, 2454929.6, 2454989.6, 2454992.5, 2455224.8, 2455369.7 |
| TWA 12      |            | 10.5    | 5    | 0.6                   | 20 2454167.7, 2454168.1, 2454663.4, 2454809.8, 2454859.8, 2454932.7, 2454991.5, 2455222.9 |
| TWA 13      |            | 10.1    | 5    | 0.5                   | 20 2454810.8, 2454859.8, 2454930.7, 2454988.5, 2455218.8 |
| TWA 14      |            | 10.7    | 5    | 0.5                   | 20 2454810.8, 2454859.7, 2454929.8, 2454986.5, 2455218.8 |
| TWA 15      |            | 11.8/11.9 | 4 | 1.0                   | 45 2454813.8, 2454930.7, 2454990.5, 2455219.8, 2455636.8 |
| TWA 16      |            | 10.2    | 4    | 1.0                   | 30 2454861.8, 2454929.7, 2454988.5, 2454998.9, 2455219.9 |
| TWA 20      |            | 10.7    | 5    | 1.0                   | 30 2454859.8, 2454929.7, 2454987.5, 2455223.9 |
| TWA 21      |            | 9.0     | 5    | 0.2                   | 30 2454813.7, 2454929.6, 2454985.5, 2455216.8, 2455297.9, 2455370.6 |
| TWA 23      |            | 10.1    | 5    | 0.5                   | 60 2454168.7, 2454291.5, 2454661.5, 2454811.8, 2454852.8, 2454861.8, 2454989.5, 2454992.4 |
| TWA 25      |            | 9.5     | 1    | 0.3                   | 45 2454168.3, 2454291.5, 2454663.5, 2454861.8, 2454991.5, 2455299.1 |
| TWA 26      | 2M1139-31  | 15.8    | 5    | 0.3                   | 30 2454809.1, 2454930.7, 2454985.3, 2455217.8, 2455295.9, 2455584.1 |
| TWA 29      | DEN1245-44 | 18.0    | 5    | 0.5                   | 60 2454861.7, 2454990.6, 2455217.9, 2455368.7, 2455410.1 |

Note. I-band magnitudes are from (1) USNOB1.0 (Vizier I/284; Monet et al. 2003), (2) UCAC3 (Vizier I/315), (3) Reid (2003), (4) Zuckerman et al. (2001) or (5) DENIS (Vizier B/denis).
bona fide members identified in the convergent point analysis of Mamajek (2005); thus, we excluded TWA 17, 18, 19AB, and 24. Although Mamajek (2005) excludes TWA 12, we included it because of its large discrepancy between photometric (Song et al. 2003) and kinematic distance. We excluded TWA 3AB for being too bright. CAPSCam saturates in 0.2 s on I ≈ 9. We excluded TWA 6, 7, and 11B for being near very bright stars that would fall within the CAPSCam field of view because saturated images leave long-lasting after-images on the detector. We excluded TWA 8AB because the two stars, separated by 13′′, do not fit in the 64 × 64 GW. Three targets—30AB, 31, and 32—were discovered after our survey began (Looper et al. 2010; Shkolnik et al. 2011). The remaining stars were all observed with the exception of TWA 10 (Table 1). CAPSCam could in the future provide parallaxes for the remaining stars with I > 9—TWA 8AB, 10, 17, 18, 30, 31, and 32.

We can operate in a mode, called “Guide-window shutter,” (GWS) where an iris shutter opens over the FF only when the GW is integrating and closes during the initial pixel resets and during each GW read. This is done to guarantee that the images in the GW and FF sample the atmosphere identically and that no astrometric bias is introduced between them. Some of our data were taken with the shutter in this mode, but some were taken with no shutter (NS) and some in a mode where the shutter closes during the initial pixel resets but remains open during each GW read (NGWS). In principle, the best astrometric precision is obtained in GWS mode, but we operated without it in order to improve efficiency.

Flat-field images to correct for pixel-to-pixel variations either intrinsic to the detector or due to the finite opening time of the iris shutter are obtained while exposing on a quartz lamp projected on a flat-field screen.

The imaging of each astrometric field is repeated typically 15–20 times at each epoch. For each FF image, we obtain many GW images. In post-processing, these are summed and re-inserted into the FF image. For each night, one image is selected as an astrometric template of the field for that night. Sources are found automatically, and a fine centroiding algorithm is applied to produce a catalog with the sub-pixel positions of all of the objects in all of the images of the field for a given night.

Each star was observed in at least four independent epochs, with all but one star observed in five or more, i.e., dates separated by enough days that they provide independent constraints on the parallax. The dates of observation are given in Table 1. Data from all epochs are combined in an astrometric solution to derive the positions, proper motions, and parallaxes of all of the stars in each target field. The astrometric solution is an iterative process. An initial catalog of positions is generated from a chosen epoch, a transformation is applied to every other epoch’s catalog to match the initial catalog, and the apparent trajectory of each star is then fitted to a basic astrometric model. The initial catalog is updated with new positions, proper motions, and parallaxes, and a subset of well-behaved stars is selected to be used as the reference frame. The reference stars must be successfully extracted in every epoch and a subset of at least 15, and more typically 30, is chosen that shows the smallest epoch-to-epoch variation in their solutions. Over all of our target fields, these stars have typical I-band magnitudes of 13.5–17.9 with a median of 16.2. This process is then iterated a small number of times. Again, details may be found in Anglada-Escudé et al. (2012).

### 2.1. Zero-point Parallax Correction

The motion of the target star is measured with respect to background stars, which are not truly stationary and which all have parallactic motions given by Earth’s motion and therefore move in the same direction. This introduces a small bias, so the average parallax of the reference stars must be removed to find the absolute parallax.

If all the stars in the field had perfectly known distances and that information was inserted a priori, the parallax zero-point correction would always be a positive number. Note, however, that some zero-point corrections in Table 2 are negative. Because we do not know the distances a priori, in the astrometric solution, the parallaxes for all objects are initialized to zero. In the iterations that follow, each individual parallax and proper motion is adjusted. While the mean parallax measurement over all the stars after the first iteration should still be approximately zero, the mean parallax of a subset of them, i.e., those used as reference stars, can be either positive or negative due to statistical fluctuations. At any epoch, the position of a star has centoring uncertainties, and for distant stars, proper motion will take out all apparent motion of the star, leaving positional residuals that are both positive and negative. Therefore, although the true parallax to every star must be positive, we allow the fit parallaxes to take on positive and negative values. The quality of the final astrometric solution as measured by the residuals on

| Target | πel | μRA cos Decl. rel | μDecl. rel | Zero Point | πabs |
|--------|-----|-------------------|------------|------------|------|
| TWA 2  | 21.76 ± 1.26 | −80.8 ± 0.9 | −18.6 ± 0.9 | 0.28 ± 0.30 | 21.48 ± 1.30 |
| TWA 5  | 20.07 ± 0.67 | −75.7 ± 1.0 | −21.1 ± 4.4 | 0.10 ± 0.19 | 19.97 ± 0.70 |
| TWA 11C| 14.55 ± 0.38 | −45.0 ± 0.8 | −26.1 ± 1.2 | 0.06 ± 0.34 | 14.49 ± 0.51 |
| TWA 12 | 15.43 ± 0.59 | −54.4 ± 1.1 | −16.4 ± 1.4 | −0.16 ± 0.37 | 15.59 ± 0.70 |
| TWA 13A (NW) | 17.89 ± 0.68 | −57.7 ± 1.7 | −13.6 ± 0.9 | −0.09 ± 0.23 | 17.98 ± 0.72 |
| TWA 13B (SE) | 16.66 ± 0.70 | −59.3 ± 2.6 | −12.2 ± 2.1 | −0.09 ± 0.23 | 16.75 ± 0.74 |
| TWA 14 | 10.15 ± 1.19 | −36.3 ± 2.7 | −4.4 ± 3.3 | −0.27 ± 0.21 | 10.42 ± 1.21 |
| TWA 15A (NE) | 8.27 ± 1.61 | −28.8 ± 1.6 | −11.5 ± 1.2 | −0.30 ± 0.13 | 8.57 ± 1.62 |
| TWA 15B (SW) | 8.80 ± 1.72 | −27.8 ± 2.3 | −11.0 ± 2.3 | −0.30 ± 0.13 | 9.10 ± 1.72 |
| TWA 16 | 13.04 ± 0.49 | −41.4 ± 1.7 | −26.9 ± 4.3 | 0.28 ± 0.12 | 12.76 ± 0.50 |
| TWA 20 | 12.85 ± 0.59 | −44.3 ± 1.2 | −22.9 ± 2.5 | −0.08 ± 0.15 | 12.93 ± 0.61 |
| TWA 21 | 18.20 ± 0.46 | −56.4 ± 0.9 | 4.8 ± 1.2 | −0.05 ± 0.17 | 18.25 ± 0.49 |
| TWA 23 | 18.41 ± 0.33 | −63.8 ± 0.6 | −27.2 ± 1.5 | −0.14 ± 0.35 | 18.55 ± 0.48 |
| TWA 25 | 18.39 ± 1.23 | −68.7 ± 1.2 | −28.3 ± 1.2 | −0.09 ± 0.14 | 18.48 ± 1.24 |
| TWA 26 | 23.38 ± 2.54 | −81.2 ± 3.9 | −27.7 ± 2.1 | −0.44 ± 0.46 | 23.82 ± 2.58 |
| TWA 29 | 12.61 ± 2.06 | −40.3 ± 11.7 | −20.3 ± 17.0 | −0.05 ± 0.18 | 12.66 ± 2.07 |
all the stars is independent of the value of the mean zero-point parallax and will not be adjusted in subsequent iterations.

To find the zero point for each field, we estimate a photometric distance to the brightest reference stars by fitting a Kurucz stellar model to cataloged USNO-B1 – B2, R2, and I (Monet et al. 2003) and 2MASS – J, H, and Ks (Skrutskie et al. 2006) photometry and assuming each star is a dwarf. Giant stars are then easily recognizable because they appear to be so close that they should have detectable parallaxes, and we refit them as giants. Dwarf stars with fit $T_{\text{eff}} < 3800$ K are not considered because the stellar models are less reliable. We average the difference between our astrometrically determined (even if they are not statistically significant) and photometric parallaxes to find the average bias and its uncertainty and subtract it from our relative parallaxes and propagate the uncertainty. A comparison of our parallaxes determined this way to literature values is given in Anglada-Escudé et al. (2012).

In principle, this zero-point correction could be done for the proper motions as well, but the reference stars do not generally have cataloged proper motions to use in measuring their bias. Instead, we estimate our bias directly by comparing the proper motions of the TWA stars themselves as computed from our astrometry with their cataloged values in UCAC3 (Zacharias et al. 2009). Given that the brightnesses and spectral types of the reference stars have approximately the same distribution for all our targets, which are also in the same general direction in the Galaxy, we can then find a correction of our CAPSCam proper motions to absolute proper motions. Leaving out TWA 13 and 15, which are visual binary stars whose proper motions in the UCAC3 are suspect, 10 of our 14 stars have UCAC3 proper motions. CAPSCam-determined proper motions are indeed well correlated with the UCAC3 values, with a mean offset of $-8.8 \pm 5.5$ mas yr$^{-1}$ in R.A. and $1.1 \pm 5.1$ mas yr$^{-1}$ in decl. (Figure 1). We correct these biases to find the proper motions of TWA sources without UCAC3 measurements, i.e., TWA 13AB, 15AB, 26, and 29.

3. RESULTS

The results of our parallax survey are presented in Table 2, including the relative proper motions and parallaxes from the iterative solution, as well as the estimates of the zero-point parallax in each field and the resulting absolute parallaxes.

Two targets, TWA 13 and TWA 15, are visual binaries for which we obtained independent astrometry for the two stars in each system. Their solutions agree within their uncertainties.

3.1. Notes on Individual Sources

3.1.1. TWA 5

TWA 5 (i.e., TWA 5A) has a companion brown dwarf (BD) TWA 5B (Webb et al. 1999). It is visible in CAPSCam images taken during good seeing (Figure 2), but the BD is faint enough and widely separated enough that it does not contribute to the PSF centroiding of the primary star.

We measure the location of 5B in the 2009 April 11 and 2009 June 9 epochs, both of which had excellent seeing of $\sim 0'\!07$. Because we were integrating on TWA 5A in the GW at 0.2 s and the reference FF for 30 s or 12 s, respectively, we have 2250 (720) GW images to use for “lucky imaging” to select the best few hundred images on each date. For each epoch, we shift and add these on the brightest pixel to form a final image with high quality—FWHM of $0'\!54$ on April 11 and $0'\!60$ on June 9. In these images, we measure the separation and position angles (P.A.s) of the brown dwarf 5B with respect to 5A. The location of 5A is well determined by the shift-and-add process.
To find the TWA 5B centroid, we examine individually the flux in slices of each row and column around its location. In each slice, we subtract a smooth continuum from the bright star, and then fit the peak produced by 5B with a Gaussian. We then average the individual slice locations weighted by the height of the Gaussian in each slice to produce separate centroids in R.A. and decl. Unfortunately, TWA 5B falls nearly on top of a diffraction spike that limits our ability to accurately centroid. The average separation on the two dates is 2′′00 ± 0′′10.

We use 2MASS sources in the larger astrometric frame to solve for any P.A. offset between CAPSCam and the 2MASS reference frame and find offsets of 0°.17 and 0°.22 on the two dates.
| Star     | $\pi$ (mas) | $\sigma\pi$ (mas) | $\mu$ R.A. cos Dec (mas yr$^{-1}$) | $\sigma\mu$ R.A. (mas yr$^{-1}$) | $\mu$ Decl. (mas yr$^{-1}$) | $\sigma\mu$ Decl. (mas yr$^{-1}$) | RV (km s$^{-1}$) | $\sigma$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$^{-1}$) |
|---------|------------|-------------------|-----------------------------------|----------------------------------|-----------------------------|-----------------------------------|----------------|-------------------------|----------------|-------------------------|----------------|-------------------------|----------------|-------------------------|
| 1       | 18.6$^a$   | 2.1               | -70.2                             | -13.7                            | 2.5                         | 1.1                               | 12.7$^b$     | 0.2                     | -11.9         | 1.8                     | -18.0         | 0.7                     | -5.2           | 1.0                     |
| 2       | 21.5       | 1.3               | -91.1                             | -21.0                            | 0.8                         | 0.8                               | 11.0$^b$     | 0.1                     | -13.8         | 1.1                     | -17.8         | 0.4                     | -6.3           | 0.5                     |
| 3       | 22.3$^c$   | 2.3               | -91.7                             | -28.2                            | 1.5                         | 2.4                               | 9.2$^b$      | 1.0                     | -13.0         | 1.8                     | -17.2         | 0.9                     | -6.0           | 1.0                     |
| 5       | 20.0       | 0.7               | -82.6                             | -22.6                            | 0.8                         | 1.0                               | 13.3$^c$     | 2.0                     | -11.8         | 0.8                     | -20.7         | 1.8                     | -4.8           | 0.9                     |
| 9A      | 21.4$^d$   | 2.5               | -53.1                             | -20.0                            | 1.9                         | 3.4                               | 9.5$^b$      | 0.4                     | -5.7          | 1.3                     | -14.4         | 0.7                     | -2.9           | 0.9                     |
| 11A     | 13.7$^e$   | 0.3               | -53.3                             | -21.2                            | 3.0                         | 4.0                               | 6.9$^d$      | 1.0                     | -10.8         | 1.1                     | -17.3         | 1.1                     | -5.2           | 1.3                     |
| 11C     | 14.5       | 0.5               | -45.1                             | -20.1                            | 2.4                         | 2.3                               | 9$^g$        | 1.0                     | -6.8          | 0.9                     | -16.8         | 1.0                     | -3.4           | 0.8                     |
| 12      | 15.6       | 0.7               | -68.3                             | -12.1                            | 2.7                         | 1.5                               | 13.1$^c$     | 1.6                     | -13.4         | 1.2                     | -20.1         | 1.5                     | -5.6           | 0.8                     |
| 13A     | 18.0       | 0.7               | -66.4                             | -12.5                            | 2.4                         | 1.8                               | 11.7$^b$     | 0.6                     | -11.4         | 0.9                     | -17.6         | 0.6                     | -3.9           | 0.6                     |
| 13B     | 16.8       | 0.7               | -68.0                             | -11.0                            | 3.1                         | 2.7                               | 12.6$^b$     | 0.5                     | -12.8         | 1.1                     | -18.9         | 0.7                     | -4.0           | 0.8                     |
| 14      | 10.4       | 1.2               | -44.1                             | -8.1                             | 1.4                         | 1.3                               | 15.8$^c$     | 2.0                     | -11.7         | 2.2                     | -21.9         | 2.0                     | -6.8           | 1.2                     |
| 15A     | 9.1        | 1.7               | -37.5                             | -10.4                            | 2.4                         | 2.0                               | 11.2$^d$     | 2.0                     | -10.3         | 3.6                     | -20.4         | 2.7                     | -3.7           | 1.5                     |
| 15B     | 8.6        | 1.6               | -36.5                             | -9.9                             | 2.9                         | 2.8                               | 10.0$^e$     | 1.7                     | -11.4         | 3.8                     | -19.8         | 2.6                     | -4.1           | 1.9                     |
| 16      | 12.8       | 0.5               | -49.2                             | -21.2                            | 1.6                         | 0.8                               | 9$^g$        | 0.4                     | -9.7          | 0.8                     | -18.6         | 0.6                     | -6.0           | 0.4                     |
| 20      | 12.9       | 0.6               | -64.4                             | -28.6                            | 3.1                         | 1.0                               | 8.1$^f$      | 4.0                     | -14.2         | 2.3                     | -21.0         | 3.4                     | -9.5           | 1.3                     |
| 21      | 18.2       | 0.5               | -61.9                             | -15.0                            | 1.2                         | 1.4                               | 17.5$^c$     | 0.8                     | -12.0         | 0.5                     | -20.2         | 0.8                     | -4.9           | 0.4                     |
| 22      | 57.0$^b$   | 0.7               | -175.8                            | -21.3                            | 0.8                         | 0.8                               | 14.8$^b$     | 2.1                     | -8.0          | 0.4                     | -17.1         | 2.0                     | -9.0           | 0.1                     |
| 23      | 18.6       | 0.5               | -72.7                             | -29.3                            | 0.9                         | 0.9                               | 8.5$^c$      | 1.2                     | -10.6         | 0.6                     | -18.2         | 1.0                     | -5.4           | 0.6                     |
| 25      | 18.5       | 0.7               | -74.0                             | -27.7                            | 0.8                         | 0.8                               | 9.2$^d$      | 2.1                     | -10.7         | 1.4                     | -18.7         | 1.9                     | -5.6           | 1.0                     |
| 26      | 23.8       | 2.6               | -89.9                             | -26.5                            | 4.2                         | 2.6                               | 11.6$^d$     | 2.0                     | -10.7         | 2.0                     | -18.8         | 1.9                     | -3.8           | 1.3                     |
| 27      | 19.0$^f$   | 0.4               | -62.7                             | -22.8                            | 1.7                         | 2.8                               | 11.2$^d$     | 2.0                     | -9.1          | 0.6                     | -16.6         | 1.8                     | -6.7           | 1.0                     |

Notes. Parallaxes are from this work unless otherwise noted in footnotes. Sources of RVs are given in footnotes.

$^a$ Hipparcos—van Leeuwen (2007).
$^b$ Torres et al. (2003).
$^c$ Shkolnik et al. (2011).
$^d$ Bright Star Catalog V50.
$^e$ Assume same RV as for HR 4796B from Stauffer et al. (1995).
$^f$ Reid (2003).
$^g$ Song et al. (2003).
$^h$ Teixeira et al. (2009).
$^i$ Mohanty et al. (2003).
$^j$ Weighted average of Biller & Close (2007), Gizis et al. (2007), and Ducourant et al. (2008).
distance of 69.0 ± 2.4 pc indeed agrees well with the Hipparcos distance to HR 4796A of 72.8 pc ± 1.7 pc (van Leeuwen 2007).

3.1.3. TWA 16

Zuckerman et al. (2001) reported that TWA 16 was a close visual binary with separation ≈ 0.6′′ and flux ratio ≈ 0.9. The CAPSCam images reveal an elongated source in all epochs and resolve two sources during the observations with the best seeing (Figure 3). The pipeline does not identify two sources there, however, so the measured parallax and proper motion are for the photocenter of the system. For the 2009 June 8 data, which had the best seeing, we used “lucky imaging” to select the best few hundred GW images. We shift and added these on the brightest star, as determined in Section 4.1. There is no apparent correlation between age and location.

4. DISCUSSION

4.1. Pre-main-sequence Track Ages

We determine absolute magnitudes using our parallaxes and 2MASS apparent magnitudes. We also correct for binarity for six sources. TWA 2 is a visual binary with Δmag ≈ 1 (Webb et al. 1999). TWA 5A (see Section 3.1.1) is a close (speckle/AO resolved) binary with Δmag ≈ 1.1 (Konopacky et al. 2007). TWA 14 is an approximately equal brightness SB (Jayawardhana et al. 2006 and E. L. Shkolnik 2011, private communication). TWA 16 is a visual binary with a flux ratio of 0.9 (Zuckerman et al. 2001). TWA 20 is a SB for which we assume the components are equal brightness (Jayawardhana et al. 2006). TWA 23 is a SB with equal brightness components (Shkolnik et al. 2011). No attempt has been made to correct for extinction, which is small in the near-infrared due to the closeness of the stars and the absence of edge-on optically thick circumstellar disks in our sample. The tabulated uncertainties in absolute magnitude include the photometric uncertainty in the 2MASS H-band measurement and the parallax uncertainty.

We obtain effective temperatures by converting literature spectral types to temperature using the intermediate scale of Luhman (1999) for the M-type stars and tabulated values in Hartigan et al. (1994) for the earlier type stars. These are all given in Table 3. Most of the spectral types come from recent compilations that use the TiO band or other spectral index fitting and should be mutually consistent and good to ≈ 75 K. TWA 25 has no published spectral type; to obtain its temperature, we fit a Kurucz model to its photometry. TWA 29 (DEN1245) is the latest spectral type object for which we measured a parallax; it sits near the M–L transition. The spectral type to effective temperature conversion is not well known for such objects, and we approximate it to be at 2250 K. Finally, we must note that historical optical and new infrared spectral types for TW Hya do not agree (Webb et al. 1999; Vacca & Sandell 2011). TW Hya’s optical spectrum has been typed as K7V, 4000 K, but the Vacca & Sandell (2011) determination of 3400 K is likely to be too cool (N. Calvet 2012, private communication); we have chosen an intermediate value of the $T_{\text{eff}}$ of 3615 K.

Theoretical isochrones overplotted with the data for all stars with parallaxes (literature as well as this work) are shown in Figure 4. We have chosen the Baraffe et al. (1998) tracks with $Y = 0.775$, mixing length parameter 1 for $m < 0.6 \, M_\odot$ and $Y = 0.282$, and mixing length 1.9 for $m \geq 0.6 \, M_\odot$, based on their relative success in reproducing multiple star coevality (White et al. 1999). The combination of the isochrones with different helium abundances creates a small temperature discontinuity at 3500–3700 K, which is unfortunately the temperature range of many of our stars (Table 3), but we interpolate over this region anyway. We use the DUSTY isochrones (Chabrier et al. 2000) for the stars with $T_{\text{eff}} < 2900$ K. We interpolate the combined theoretical tracks to estimate the ages of all the stars at their nominal positions in absolute-magnitude–$T_{\text{eff}}$ space. The median age is 10.1 Myr. Individual ages are also given in Table 3, along with all the data plotted on the tracks. Because of the abundance of stars with $T_{\text{eff}} \approx 3600$ K, Figure 5 shows a zoomed view of this part of the diagram. From the parallax uncertainty alone, the typical age uncertainty on each star is 3 Myr. An age of 10 Myr is consistent with previous estimates, as summarized in Fernández et al. (2008).

4.2. Galactic Space Motion and Membership

For the analysis of the kinematics of the group, we use all stars with known proper motions (from UCAC3 if available), parallaxes, and radial velocities. These are given along with...
Figure 7. Three-dimensional space motion of the TWA stars with measured parallaxes and radial velocities in Galactic coordinates. Black dots show the present locations of the stars and the colored points show the motion in 200,000 yr timesteps for 15 Myr. The parallel velocities mean that the stars are never much closer together than they are at present. This plot excludes TWA 9A and 22.

Figure 8. Age histogram of the TWA stars with parallaxes, excluding 9AB and 22, which have kinematics inconsistent with membership, and 29, which has a highly uncertain $T_{\text{eff}}$ and therefore uncertain age. The bin size is 3 Myr, which is the median uncertainty in the individual ages based on the uncertainties in their absolute magnitudes (i.e., parallaxes). The best-fit Gaussian to the age distribution is overplotted with the dashed line and has a mean of 9 Myr and standard deviation of 6.8 Myr. The width of the age distribution exceeds what would be expected for a population of stars formed in a single burst.

The present average distance from their mean location for the stars in Table 4, excluding 9A and 22, is 20.4 pc. The present-day locations of the TWA stars with measured parallaxes and radial velocities are shown in Figure 6. The velocities are nearly parallel, as shown in Figure 7. The nominal closest approach of all the stars is 2 Myr ago, but has a mean distance of 19.2 pc from the center, meaning that there is no time in the past when the stars were significantly more concentrated than they are today. At the mean age of 10 Myr established in Section 4.1, the mean distance from the center is 34 pc.

Figure 8 displays a histogram of the ages excluding 9AB, 22, and 29. There is a tail of stars to apparently larger ages while

the calculated UVWs in Table 4. Uncertainties in all three quantities are propagated into the final velocity uncertainties. We also use positions from the 2MASS catalog (Skrutskie et al. 2006). We then compute the mean velocity of the entire TWA association. The uncertainty weighted average velocities in Table 4 are $[-10.1, -17.9, -8.0] \pm [0.2, 0.2, 0.1]$ km s$^{-1}$. Two stars have velocities more than $3\sigma$ from the mean of the association in at least two directions: TWA 9A and TWA 22. TWA 22 was already suspected not to be a member by Mamajek (2005) and Teixeira et al. (2009), based on similar velocity arguments. However, TWA 9A is a “classical” member used to define the convergent point in the Mamajek analysis. Given its discrepant age in Table 3, as well as its discrepant velocity, we conclude that it is not a member or that its Hipparcos distance is underestimated. The new average velocities after excluding these two stars are $[-10.9, -18.2, -5.3] \pm [0.2, 0.2, 0.2]$ km s$^{-1}$. The standard deviation of the total velocities is 2.0 km s$^{-1}$, and the rms deviation in the total velocity from the mean total velocity is 1.9 km s$^{-1}$. These are considerably lower dispersions than obtained when photometric distances are used (Fernández et al. 2008).

The uncertainties on the mean velocities above are computed assuming the stellar velocity distribution is Gaussian, i.e., standard deviation of velocities divided by the square-root of the number of stars. However, a K-S test reveals that the velocities are neither Gaussianly distributed nor are they uniformly distributed between their minimum and maximum values.

To trace the stars back in time, we take their present positions and three-dimensional space velocities and compute their locations in Galactic coordinates for timesteps back every 100,000 years. To treat the distance and velocity uncertainties properly, we do this in a Monte Carlo for 10,000 trials, selecting each star’s distance and velocity in each direction randomly in each trial but distributed assuming the uncertainties for each individual star are Gaussian. Then, the centroid 3D location of the stars at each time is computed as well as the average distance of the stars from this centroid. The time of best convergence is defined to be when the average distance is minimized. We tested that the Galactic potential does not significantly affect the motions over the short timescale of 10 Myr.
there are no stars with inferred ages less than 3 Myr. The best Gaussian fit to the age distribution has a mean of 9.5 Myr and standard deviation of 5.7 Myr. To assess the reliability of these values for such a small sample, we repeated the histogram fit in a Monte Carlo. In each trial, the age of each star was drawn from a Gaussian distribution based on that individual’s star mean age and absolute magnitude uncertainty on the Baraffe et al. (1998) tracks. The typical age uncertainty on each star is 3 Myr. The mean age over all the trials was 8.7 Myr and the width of the age distribution over all the trials was 6.5 Myr. Thus, the age histogram is robust against the individual age uncertainties, and the width of the distribution compared to the typical age uncertainty indicates that there is a real spread in derived ages.

5. CONCLUSIONS

The identification of TWA members has largely been based on youth plus similarity to the young star TW Hya in terms of location on the sky, proper motion, and radial velocity. Coevality was thought to follow under the assumption that these stars with similar motions formed from the same raw material at the same time. With parallaxes to 14 primary stars identified as TWA members, we have greatly expanded the knowledge of the kinematics of these young stars. We find that although they do share a common space motion, the stars do not appear to have formed in a concentrated volume with a well-defined expansion velocity. The TWA stars appear to have formed over a larger volume than they presently occupy.

Nor do the stars appear to be completely co-eval, as the stars studied here have ages that range from 3 to 23 Myr as derived from their locations on pre-main-sequence tracks. Although uncertainties in the distance and the effective temperatures allow for several Myr of uncertainty in individual ages, it would be extremely difficult to force them all to a common age. This apparent age spread could be due to a real difference in the times of formation of the stars or it could be due to the lasting effects of episodic accretion (Baraffe et al. 2009).

The spatial distribution of these nominal TWA stars of 40–60 pc is largely filamentary in nature, which naturally leads to some conclusions about their provenance. Perhaps the stars formed in an extended wisp of a molecular cloud, probably one related to the Scorpius–Centaurus complex that is nearby on the sky but 80 pc farther away. The Galactic V and W velocities of TWA are very similar to the older Upper Centaurus Lupus (UCL) and Lower Centaurus Crux (LCC) subgroups of Sco-Cen (Chen et al. 2011) at ages of 15–17 Myr (Mamajek et al. 2002). TWA is located near LCC in Galactic coordinates but their separation in distance, age, and velocity distinguish the two groups. Fernández et al. (2008) showed that TWA was ∼45 pc from LCC 8 Myr ago and could have been subjected to 0.5 supernovae Myr⁻¹. Multiple supernova shocks could have triggered star formation in dense parts of the filamentary progenitor TWA cloud over a few million years and not in a regular progression from one side to the other. Ortega et al. (2009) also suggest that stellar winds and supernovae from LCC and UCL could compress gas in the region of TWA, although the mechanism for an extended time of star formation is less clear in this case.

The Las Campanas Observatory staff and operators of the du Pont telescope, particularly Oscar Duhalde, Javier Fuentes, Herman Oliveras, Patricio Pinto, and Andrés Rivera, made the CAPSCam observations smooth and efficient. Rebecca Rattray made helpful analyses of portions of these TWA data during an undergraduate internship at DTM in 2009. CAPSCam was built with support from the NSF ATI program and Carnegie Institution of Washington. We acknowledge support for the observing by the NASA Astrobiology Institute under cooperative agreement NNA09DA81A. This work makes use of the Simbad database and Vizier catalogue access tool, CDS, Strasbourg, France, and the 2MASS survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

REFERENCES

Anglada-Escudé, G., Boss, A. P., Weinberger, A. J., et al. 2012, ApJ, 746, 37
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403
Baraffe, I., Chabrier, G., & Gallardo, J. 2000, ApJL, 702, 27
Barrado Y Navascués, D. 2006, A&A, 459, 511
Billers, B. A., & Close, L. M. 2007, ApJL, 669, 41
Bonnefoy, M., Chauffin, G., Dumas, C., et al. 2009, A&A, 506, 799
Boss, A. P., Weinberger, A. J., Anglada-Escudé, G., et al. 2009, PASP, 121, 1218
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, ApJ, 542, 464
Chen, C. H., Mamajek, E. E., Bitner, M. A., et al. 2011, ApJ, 738, 122
de la Reza, R., Torres, C. A. O., Quast, G., Castilho, B. V., & Vieira, G. L. 1989, ApJL, 343, 61
Ducourant, C., Teixeira, R., Chauffin, G., et al. 2008, A&A, 477, L1
Fernández, D., Figueras, F., & Torra, J. 2008, A&A, 480, 735
Gizis, J. E. 2002, ApJ, 575, 484
Gizis, J. E., Jao, W.-C., Subasavage, J. P., & Henry, T. J. 2007, ApJL, 669, 45
Gregorio-Hetem, J., Lepine, J. R. D., Quast, G. R., Torres, C. A. O., & de la Reza, R. 1992, AJ, 103, 549
Hartigan, P., Strom, K. M., & Strom, S. E. 1994, ApJ, 427, 961
Jayawardhana, R. C., Coffey, J., Scholz, A., Brandeker, A., & van Kerkwijk, M. H. 2006, ApJ, 648, 1206
Kastner, J. H., Zuckerman, B., & Bessell, M. 2008, A&A, 491, 829
Kastner, J. H., Zuckerman, B., Weintraub, D. A., & Forveille, T. 1997, Sci, 277, 67
Konopacky, Q. M., Ghez, A. M., Duchêne, G., McCabe, C., & Macintosh, B. A. 2007, AJ, 133, 2008
Looper, D. L., Burgasser, A. J., Kirkpatrick, J. D., & Swift, B. J. 2007, ApJL, 669, 97
Looper, D. L., Mohanty, S., Bochanski, J. J., et al. 2010, ApJ, 714, 45
Low, F. J., Smith, P. S., Werner, M., et al. 2005, ApJ, 631, 1170
Luhman, K. L. 1999, ApJ, 525, 466
Makarov, V. V., & Fabricius, C. 2001, A&A, 368, 866
Mamajek, E. E. 2005, ApJ, 634, 1385
Mamajek, E. E., Meyer, M. R., & Liebert, J. 2002, AJ, 124, 1670
Mohanty, S., Jayawardhana, R., & Barrado Y Navascués, D. 2003, ApJL, 593, 109
Mohanty, S., Jayawardhana, R., Huelamo, N., & Mamajek, E. 2007, ApJ, 657, 1064
Monei, D. G., Levine, S. E., Canzian, B., et al. 2003, AJ, 125, 984
Neuhauser, R., Schmidt, T. O. B., Hambaryan, V. V., & Vogt, N. 2010, A&A, 516, 112
Ortega, V. G., Jilinski, E., de la Reza, R., & Bazzanella, B. 2009, AJ, 137, 3922
Plavchan, P., Werner, M. W., Chen, C. H., et al. 2009, ApJ, 698, 1068
Prato, L., Ghez, A. M., Pitta, R. K., et al. 2001, ApJ, 549, 590
Reid, N. 2003, MNRAS, 342, 837
Riaz, B., & Gizis, J. E. 2008, ApJL, 678, 1584
Rucinski, S. M., & Krautter, J. 1989, A&A, 121, 217
Schaefer, A., Melis, C., & Song, I. 2012, ApJ, 754, 39
Scholz, R.-D., McCaughrean, M. J., Zinnecker, H., & Lodieu, N. 2005, A&A, 430, L49
Shkolnik, E. L., Liu, M. C., Reid, I. N., Dupuy, T., & Weinberger, A. J. 2011, ApJ, 727, 6
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Soderblom, D. R., King, J. R., Siess, L., et al. 1998, ApJ, 498, 385
Song, I., Bessell, M. S., & Zuckerman, B. 2002, A&A, 385, 862
Song, I., Zuckerman, B., & M. S. 2003, ApJ, 599, 342
Stauffer, J. R., Hartmann, L. W., & Barrado Y Navascués, D. 1995, ApJ, 454, 919
Sterzik, M. F., Alcalá, J. M., Covino, E., & Petr, M. G. 1999, A&A, 346, L41
Teixeira, R., Ducourant, C., Chauffin, G., et al. 2009, A&A, 503, 281
Teixeira, R., Ducourant, C., Chauvin, G., et al. 2008, A&A, 489, 825
Torres, C., Quast, G., Melo, C., & Sterzik, M. 2008, in ASP Monograph Publ. 5, Handbook of Star Forming Regions, Vol. II: The Southern Sky, ed. B. Reipurth (San Francisco, CA: ASP), 757
Torres, C. A. O., Quast, G. R., da Silva, L., et al. 2006, A&A, 460, 695
Torres, G., Guenther, E. W., Marschall, L. A., et al. 2003, AJ, 125, 825
Vacca, W. D., & Sandell, G. 2011, ApJ, 732, 8
van Leeuwen, F. 2007, in Hipparcos, The New Reduction of the Raw Data, Astrophysics and Space Science Library, (Berlin: Springer), 350

Webb, R. A., Zuckerman, B., Platais, I., et al. 1999, ApJL, 512, 63
Weinberger, A. J., Becklin, E. E., Zuckerman, B., & Song, I. 2004, AJ, 127, 2246
White, R. J., Ghez, A. M., Reid, I. N., & Schultz, G. 1999, ApJ, 520, 811
Zacharias, N., Finch, C., Girard, T., et al. 2009, VizieR On-line Data Catalog, 1315, 0
Zuckerman, B., & Song, I. 2004, ARA&A, 42, 685
Zuckerman, B., Webb, R. A., Schwartz, M., & Becklin, E. E. 2001, ApJL, 549, 233