The Astrophysical Journal, 512:L63–L67, 1999 February 10

DISCOVERY OF SEVEN T TAURI STARS AND A BROWN DWARF CANDIDATE IN THE NEARBY TW HYDRAE ASSOCIATION

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Received 1998 July 2; accepted 1998 December 3; published 1999 February 5

ABSTRACT

We report the discovery of five T Tauri star systems, two of which are resolved binaries, in the vicinity of the nearest known region of recent star formation: the TW Hydrae Association. The newly discovered systems display the same signatures of youth (namely high X-ray flux, large Li abundance, and strong chromospheric activity) and the same proper motion as the original five members. These similarities firmly establish the group as a bona fide T Tauri association, unique in its proximity to Earth and its complete isolation from any known molecular clouds. At an age of ∼10 Myr and a distance of ∼50 pc, the association members are excellent candidates for future studies of circumstellar disk dissipation and the formation of brown dwarfs and planets. Indeed, as an example, our speckle imaging revealed a faint, very likely companion 2″ north of CD −33° 7795 (TWA 5). Its color and brightness suggest a spectral type of ∼M8.5 which, at an age of $\sim 10^7$ yr, implies a mass $\sim 20 M_{\rm Jup}$.

Subject headings: open clusters and associations: individual (TW Hydrae) — stars: low-mass, brown dwarfs — stars: pre–main-sequence — X-rays: stars

1. INTRODUCTION

The origin of the T Tauri star TW Hya has long been a mystery to astronomers, since it is far from any known progenitor cloud. Excepting its isolation, Rucinski & Krautter (1983) noted that TW Hya has all the characteristics of a "classical" T Tauri star. Subsequent searches by de la Reza et al. (1989) and Gregorio-Hetem et al. (1992) at *IRAS* Point-Source Catalog positions revealed four other T Tauri systems in the same region of the sky and suggested that the stars might be associated. Strong X-ray fluxes seen at all five of these systems led Kastner et al. (1997) to conclude that the group does indeed form a physical association (which they dubbed the "TW Hya Association" [TWA]) at a distance of only ∼50 pc and an age ∼20 Myr. It is remarkable that the closest known region of recent star formation is only now being identified and cataloged.

The strength of the X-ray emission tabulated by Kastner et al. (1997) suggested that we might find additional TWA members at positions of X-ray–bright stars. We selected sources from the *ROSAT* All-Sky Survey within 12° of the approximate cluster center ($11^{\rm h}15^{\rm m}$, −33°) and cross-correlated their positions with stars in the Hubble Guide Star and USNO A1.0 catalogs. Since this search region passed close to another young, nearby star, HR 4796 (Jura et al. 1998; Stauffer, Hartmann, & Barrado y Navuscues 1995), we enlarged our search area to include an overlapping region of radius 8° centered on HR 4796 ($12^{\rm h}35^{\rm m}$, −40°). Throughout this Letter we consider HR 4796A and B as TWA members (see § 3). Our candidates were prioritized using X-ray flux, X-ray hardness ratios, and proper motion.

Results discussed below indicate that our search criteria were appropriate—we discovered five T Tauri systems containing a total of seven stars; all are likely TWA members. In addition, we found a $\sim 20 M_{\rm Jup}$ probable companion to CD −33°7795 (TWA 5), a previously known TWA member.

2. OBSERVATIONS

We used the Southern Proper Motion (SPM) program plates (Platais et al. 1995; Girard et al. 1998) to derive proper motions of potential TWA members. The SPM plates contain multiple images of bright stars in the TWA region, with a mean epoch difference ranging from 20 to 25 yr. Several of the brighter, previously known TWA members were measured and reduced using the standard SPM reduction procedure (e.g., Girard et al. 1998), which gives absolute proper motions accurate to about 2–5 mas $\rm yr^{-1}$ depending upon the star's magnitude. For the remainder of candidates, we used a simplified plate calibration to derive the proper motions with an accuracy of about 5–8 mas $\rm yr^{-1}$.

On 1998 February 6–7 (UT), we obtained spectra from ∼6350 to 7735 Å of approximately 50 candidate stars with the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the W. M. Keck II telescope. The 0″.7 slit yielded a measured resolution of ∼1.8 Å. Spectra were extracted and calibrated using IRAF. Seven stars, including the individual components of two double systems, show Hα emission and strong Li absorption, characteristics of T Tauri stars. We also obtained LRIS *I*-band images of the fields surrounding several TWA stars.

Speckle observations at the NASA Infrared Telescope Facility (IRTF) 3 m telescope were conducted 1998 February 18–20 (UT) at 2.2 μm to search for close companions to the newly discovered systems as well as four of the original TWA members and HR 4796B. These diffraction-limited observations resolved the known binary stars Hen 600 (separation = 1″.44 ± 0″.01, P.A. = 215°.4 ± 1°.0) and CD −29°8887 (separation = 0″.56 ± 0″.01, P.A. = 29°.5 ± 1°.0). One new object was discovered, a faint companion to TWA 5 (see § 3). Otherwise, these observations preclude the presence of any unseen companions down to a typical $\Delta K = 4$ mag over the separation range from 0″.2 to 1″.0 as derived by determining the maximum amplitudes of cosine waves that could be hidden in the noise of the power spectra (see Ghez, Neugebauer, & Matthews 1993; Henry 1991). To search for wider companions (∼1″–3″), individual images were aligned on the brightest speckle and summed; these shift-and-add data are sensitive to a limiting $\Delta K \sim 6$ mag.

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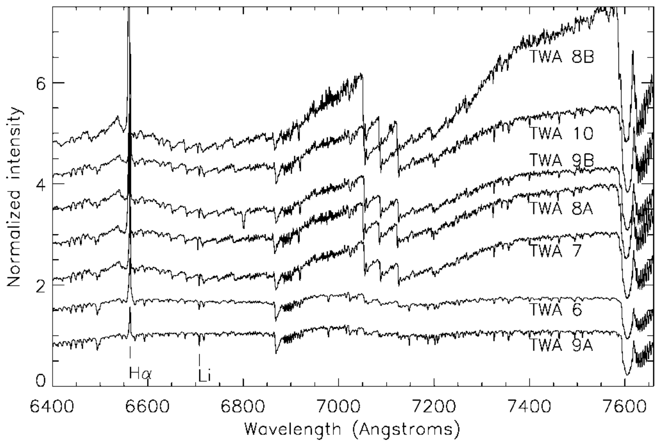

FIG. 1*a*

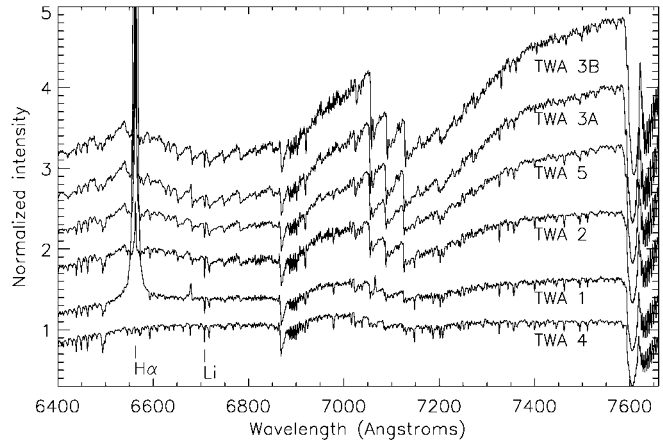

FIG. 1*b*

FIG. 1.—LRIS spectra of (*a*) the seven new and (*b*) six of the original members of the TW Hya Association. In each plot, stars are ordered by spectral type, with the earliest types at the bottom. The Hα lines overlap and are confused, but their EWs can be found in Table 1 as can the derived spectral types. Hα (emission—λ6563) and Li I (absorption—λ6708), both indicators of youth, are prominent in the spectra.

3. RESULTS AND DISCUSSION

LRIS spectra of the seven newly discovered young stars and six of the previously known TWA members are shown in Figures 1*a* and 1*b*. All of the stars show the Li I λ6708 line in strong absorption with equivalent widths (EWs) ranging from ∼0.36 to 0.57 Å (Table 1). The strengths of the Li lines are typical of T Tauri stars and distinctly above that found for Pleiades stars at $\sim 10^8$ yr (e.g., Martín 1997). Each star, except HD 98800, has Hα in strong emission. Following the spectroscopic T Tauri classification scheme of Martín (1998), nine of the 13 are classified as true T Tauri stars, while the remaining four fall slightly (but within the 50 mÅ uncertainty) below the

TABLE 1
PROPERTIES OF THE TWA STARS

TWA Number	Common Name	R.A. (J2000)	Decl. (J2000)	Spectral Type	EW Hα (Å)	EW Li λ6708 (Å)	J	H	K	PM R.A. (mas yr^{-1})	PM Decl. (mas yr^{-1})	log L_X/L_{bol}
New Members												
6[a]	…	10 18 28.8	−31 50 02	K7	−4.65	0.56	8.79	8.17	7.97	−60	−20	−2.92
7	…	10 42 30.3	−33 40 17	M1	−4.95	0.44	7.78	7.13	6.89	−120	−27	−3.24
8A	…	11 32 41.5	−26 51 55	M2	−7.34	0.53	8.37	7.72	7.44	…	…	−2.99
8B	…	11 32 41.4	−26 52 08	M5	−16.5	0.56	9.91	9.36	9.01	…	…	…
9A[b]	CD −36°7429	11 48 24.2	−37 28 49	K5	−2.35	0.46	8.60	7.95	7.68	−54.1	−20.0	−3.02
9B[b]	…	−6″	+0″	M1	−5.01	0.48	10.06	9.41	9.14	…	…	…
10	…	12 35 04.3	−41 36 39	M2.5	−8.39	0.46	9.17	8.55	8.19	−67	−43	−3.09
Previously Known Members												
1	TW Hya	11 01 51.9	−34 42 17	K7	−220	0.39	8.46	7.65	7.37	−66.9	−12.4	−2.86
2A	CD −29°8887	11 09 13.9	−30 01 39	M0.5	−1.89	0.49	7.85	…	7.18	−90	−20	−3.35
2B	…	+0″.3	+0″.5	M2	…	…	9.09	…	7.99	…	…	…
3A[a]	Hen 600A	11 10 28.0	−37 31 53	M3	−21.8	0.53	8.22	7.60	7.28	−112	−11	−3.30
3B	Hen 600B	−0″.8	−1″.2	M3.5	−7.14	0.54	8.63	8.07	7.80	…	…	…
4	HD 98800	11 22 05.3	−24 46 40	K5	0	0.36	6.44	5.82	5.65	−85.5	−33.4	−3.44
5A[a]	CD −33°7795	11 31 55.4	−34 36 27	M1.5	−13.4	0.57	7.71	7.06	6.83	−86	−21	−2.95
5B[c]	…	+0″.1	+1″.9	M8.5	…	…	I = 15.8[d]	12.1	11.5	…	…	…
11A[c]	HR 4796A	12 36 01.3	−39 52 09	A0	…	…	5.80	5.80	5.80	−67.1	−55.9	…
11B[c]	HR 4796B	−5″.3	−5″.5	M2.5	−3.5	0.55	9.32	8.57	8.36	…	…	−3.30[e]

NOTE.—TWA numbers are ordered by right ascension, beginning with the first five known members from Kastner et al. (1997), followed by the new members presented in this Letter. Spectral types are assigned utilizing our LRIS spectra and standards from Montes & Martín (1998). EWs of Hα and Li were derived from our LRIS spectra except for HR 4796A and B—data from Stauffer et al. (1995) and Jura et al. (1998), respectively. The listed EW of the Li line represents a Gaussian fit to the red side of the line to avoid contribution from a nearby, blended Fe line. The uncertainty in the Li EW is typically ∼50 mÅ. Near-IR photometry is from the IRTF, except TW Hya, HD 98800, and HR 4796, whose values are from Rucinski & Krautter (1983), Zuckerman & Becklin (1993), and Jura et al. (1993), respectively. IRTF J and H uncertainties are typically ± 0.1 mag; K-band speckle uncertainties are ±0.07 mag. Proper motions (PMs) are derived from the SPM database, except those with *Hipparcos* measurements which are denoted by PM's quoted to the nearest tenth. L_X/L_{bol} is derived from the *ROSAT* All-Sky Survey and the J- band magnitudes. All components of multiple systems are assumed to contribute to the X-ray flux, hence L_{bol} represents the total system flux. The exceptions are HR 4796 (see note e) and TWA 8 (where the X-rays appear to originate from the primary).

[a] TWA 6, TWA 5A, and Hen 600A are possible spectroscopic binaries (Webb et al. 1999b). Parameters listed are the total of the unresolved systems.

[b] TWA 9 was independently discovered by Jensen et al. (1998).

[c] HR 4796 was previously known to be a young star system, but not known as a TWA member. TWA 5B is a new member.

[d] I-band measurement for TWA 5B is from LRIS imaging data. The presence of the bright, nearby primary induces an uncertainty of ∼±0.4 mag.

[e] Pointed *ROSAT* observations indicate the X-rays are emitted by the B component of the HR 4796 system Jura et al. (1998).

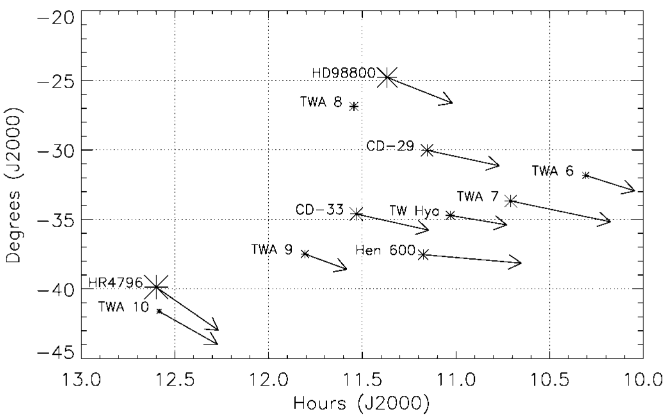

FIG. 2.—Positions and motions of the TW Hya Association stars. Coordinates are equinox 2000. Vectors show the observed proper motion extrapolated over a period of 200,000 yr. Proper motion has not yet been measured for TWA 8. Solar reflex motion is responsible for a substantial portion of the observed proper motion. Assuming a mean distance of 50 pc for the association, a typical correction for the Sun's motion relative to the LSR is $+55$ mas yr^{-1} in right ascension and $+20$ mas yr^{-1} in declination. However, at this distance, a substantial uncertainty is introduced when making these corrections (Hoff et al. 1998). The symbol size represents the *J*-band flux.

Li EW strength threshold into the "post–T Tauri" regime. Of those classified as T Tauri stars, three have Hα emission above the threshold (Martín 1997) for "classical" as opposed to "weak-lined" T Tauri stars. This evolutionary state agrees with a cluster age of ~10 Myr as discussed below.

Each of the newly discovered systems, along with the original five members, were strongly detected in the *ROSAT* All-Sky Survey. The X-ray luminosities normalized to the total stellar luminosities are listed in Table 1. All five new systems display a similarly large L_X/L_{bol} consistent with Kastner et al.'s age determination ($20 \pm 10 \times 10^6$ yr), placing them at a seldom-studied evolutionary state: the transition between the T Tauri and the post–T Tauri phase.

Hipparcos observed four TWA members (HD 98800, TW Hya, TWA 9, and HR 4796), providing accurate parallactic distances and proper motions. The *Hipparcos* distances to TW Hya and HD 98800, 56 and 47 pc respectively, are in excellent agreement with the estimates of Kastner et al. (1997); TWA 9 and HR 4796 are at 50 and 67 pc, respectively. Proper motions of other members were extracted from the SPM database (see Table 1 and Fig. 2). While there is some dispersion, the proper motion among the TWA members is fairly uniform. Whether or not the motions are consistent with a common origin is controversial (Jensen, Cohen, & Neuhäuser 1998; Soderblom et al. 1998; Hoff, Pfau, & Henning 1998). We defer discussion to a second paper in which we use echelle radial velocities to demonstrate common space motions for TWA members (Webb, Reid, & Zuckerman 1999b).

Given that we searched only in a limited solid angle of sky, one might ask whether a comparable spectroscopic survey of X-ray–bright stars, but in a very different direction, would reveal many nearby stars of comparable young age. We think this is unlikely and that the TWA represents a true localized association. Support for this assertion is threefold:

First, consider the population of nearby (less than 70 pc) stars with T Tauri or A star characteristics that are far from dark clouds and that exhibit substantial excess IR emission (defined here as a ratio of excess far-IR luminosity divided by total bolometric luminosity of 10^{-3} or greater). Many stars that appear to fulfil all of these criteria have been shown to be peculiar post–main-sequence stars (e.g., Zuckerman, Kim & Liu 1995; Fekel et al. 1996; Webb et al. 1999a). Indeed, we know of only six stars that satisfy the preceding criteria—four of the six are in the TWA (HD 98800, TW Hya, Hen 600, and HR 4796). The other two are β Pic and 49 Cet. This concentration points to the vicinity of TW Hya as special. Similarly, Jensen et al. (1998) note an excess of young, low-velocity stars in the vicinity of TW Hya.

Second, surveys of X-ray–bright stars in other regions well separated from known dark clouds do not produce a similar number of T Tauri stars. In our LRIS survey, 12 of our targets were late-type stars (spectral types K5 or later), and five of these have T Tauri spectral characteristics. We consider only late-type stars because the Li depletion time is short and there is a clear distinction in Li EW between T Tauri (10 Myr) and Pleiades (120 Myr) age stars. Magnani and colleagues have searched for T Tauri stars toward three widely separated trans-

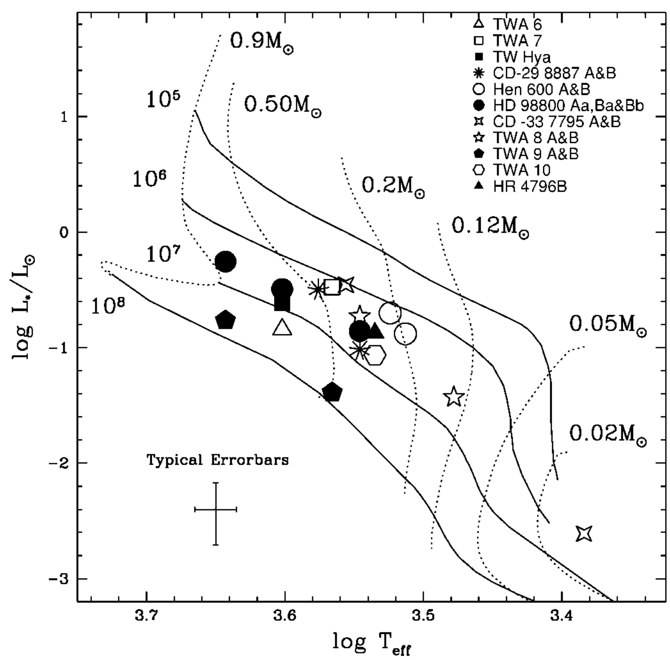

FIG. 3.—TW Hya Association stars plotted on an H-R diagram along with the PMS tracks of D'Antona & Mazzitelli (1997). All stars are assumed to be at 50 pc except those with measured *Hipparcos* parallaxes, which appear as filled symbols (TW Hya, HD 98800, HR 4796B, and TWA 9A and B). The vertical error bars represent a conservative uncertainty of ± 15 pc in distance (given that the four TWA members with *Hipparcos* distances lie between 47 and 67 pc from Earth). Horizontal bars represent the typical classification uncertainty of 1 spectral subclass or about ± 150 K. HD 98800A is a known single-line spectroscopic binary, and the fainter companion should have little effect on the derived luminosity and temperature. Preliminary results from HIRES spectra indicate that Hen 600A, TWA 5A, and TWA 6 may be spectroscopic binaries (Webb et al. 1999b). The indicated positions represent the combined system parameters; the primary effect of an unresolved companion is a slight increase in observed luminosity. Placement of TWA 2B is based purely on ΔK magnitude and the color-spectral type relations of Kirkpatrick & McCarthy (1994). TWA 5B's temperature is from its $I-K$ color, and its luminosity is from its K magnitude and the bolometric correction (BC_J = 2.05 extrapolated to K) adopted by Luhman et al. (1997). Due to contamination from the primary and the uncertainty in the temperature scale, the representative error bars should be approximately doubled in size for TWA 5B. Other bolometric luminosities are based on measured or published J magnitudes (the band that is least likely to be affected by nonphotospheric excesses) and the bolometric corrections compiled in Hartigan et al. (1994). The temperature scale for M dwarfs is highly uncertain. Here we use are the spectral types derived in this Letter and the temperature scale of Luhman & Rieke (1998).

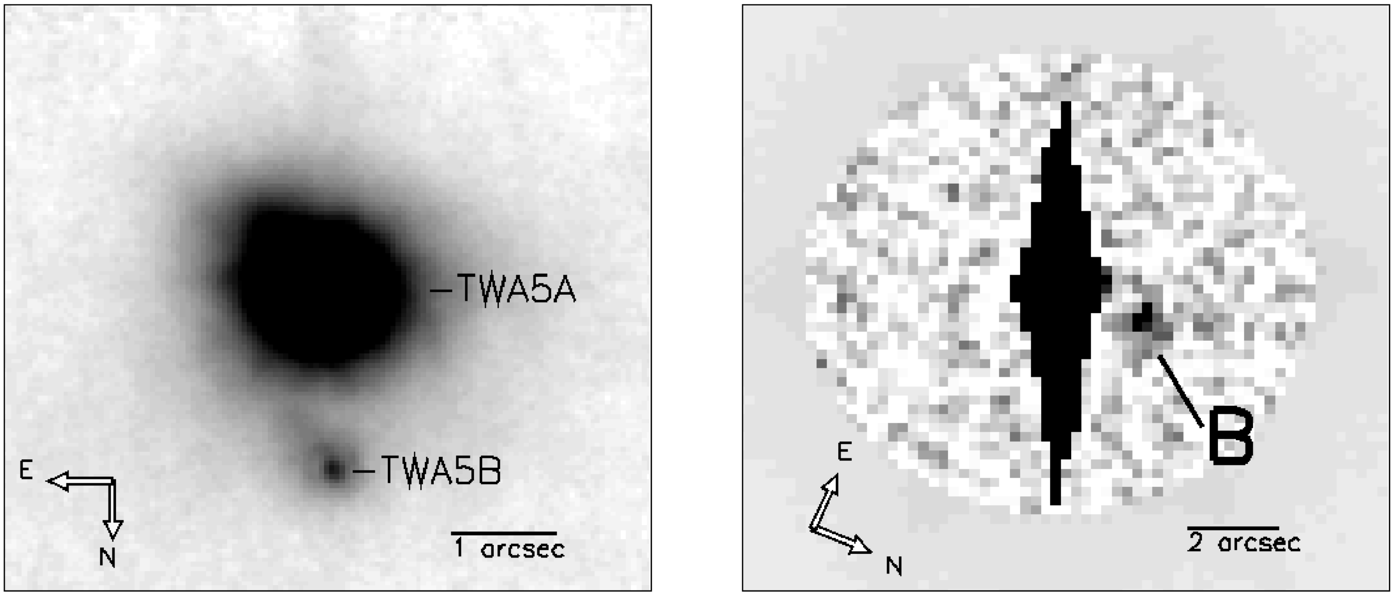

FIG. 4.—*Left:* Shift-and-add IRTF K-band image showing TWA 5A ($K = 6.83$) and TWA 5B ($K = 11.5$). The pixel scale is 0″.053 pixel^{-1}, and the measured separation is $X = +1.77$ pixels (0″.1) and $Y = -35.67$ pixels (-1″.9). *Right:* LRIS I-band image of TWA 5. A Gaussian fit to the wings of the saturated primary has been subtracted out to a radius of 5″ revealing the B component. Saturated pixels and bleeding to adjacent pixels have not been removed. The scale is 0″.22 pixel^{-1}.

lucent clouds: MBM 40 (Magnani et al. 1996) and MBM 7 and 55 (Hearty et al. 1999), which are located at $|b| \sim 40°$. Their target list consisted of X-ray–bright *ROSAT* stars; they list 42 with spectral type similar to the TWA members. None showed substantial lithium absorption, in vivid contrast to results of our LRIS survey near TW Hya. Also, in 1998 September we surveyed 11 late K- and M-type, X-ray–bright field stars, many of which are listed in Fleming (1998), with the Kast spectrograph on the 3 m Shane telescope at Lick Observatory. None showed any detectable Li with an upper limit of ∼50 mÅ.

And third, if T Tauri stars are truly widely distributed in the solar neighborhood, then we would anticipate seeing many X-ray–bright post–T Tauri stars in the 10–100 × 10^6 yr age range. As we mention below, our LRIS data show no evidence of such a population. Together these characteristics are adequate to firmly establish the stars in Table 1 as a physical association.

In Figure 3, we use the photometry obtained at the IRTF (assuming a distance of 50 pc for those stars without measured parallax) and the spectral types derived from the LRIS spectra to place the TWA members on the pre–main-sequence (PMS) tracks of D'Antona & Mazzitelli (1997). All of the stars, with the possible exception of TWA 9, are clearly above the zero-age main sequence and, within the uncertainties, are consistent with a cluster age of $\sim 10^7$ yr. TWA 9A and B are likely younger than they appear on Figure 3 (∼70 Myr). With EWs of ∼500 mÅ, their Li lines are much stronger than any similar stars in the Pleiades (e.g., Martín 1997). Possible explanations for their apparent greater ages include derived spectral types that are too hot, larger-than-expected errors in the photometry, circumstellar extinction, or an error in the *Hipparcos* distance (the ∼20 pc required to put TWA 9 on the 10^7 yr isochrone is a 3 σ deviation).

The age of the TWA is moderately well-constrained. Detailed study of HD 98800 yields 10^{+10}_{-5} Myr (Soderblom et al. 1998) and of HR 4796 gives 8–10 Myr (Stauffer et al. 1995; Jura et al. 1998). Our data are consistent with these estimates: the TWA stars appear nearly along the same isochrone (∼8 Myr; Fig. 3), although the distance uncertainty adds substantial scatter. The high ratio of X-ray to total luminosity is characteristic of stars evolved beyond the early T Tauri phase, suggesting an age of 10–100 Myr. And the spectral characteristics indicate that, within the errors of our measurements and the classification scheme, all members are likely weak-lined or classical T Tauri stars. In our sample of ∼45 other X-ray–bright stars in this region, *none* displayed significant Li I absorption that would fill in the "post–T Tauri star gap" noted by, e.g., Martín (1997). This implies that the TWA stars are not the young tail of a large population of post–T Tauri stars, but rather a distinct group of old T Tauri stars with an age less than a few times 10^7 yr.

A probable companion to TWA 5 was found ∼2″ north of the primary in shift-and-add processing of the IRTF speckle data (Fig. 4). The primary and companion differ in magnitude by $\Delta K = 4.7 \pm 0.1$. The companion was also revealed in our LRIS I-band images following a deconvolution of the primary's point-spread function (PSF) with the IRAF DAOPHOT package. Scaling a PSF from a field star and fitting the wings of the (saturated) primary indicates $\Delta I = 6.9 \pm 0.4$ mag. The measured ΔI, ΔK, and $I-K$ color (Table 1) suggest a spectral type of M8–M8.5, according to the color relations of Kirkpatrick & McCarthy (1994).

The companion is shown as a four-pointed star in Figure 3. The tracks indicate a mass of about $20M_{\rm Jup}$; this estimate is largely insensitive to variations in luminosity (i.e., distance and/or age). The major uncertainty is the photometric error associated with the I-band deconvolution and the temperature scale for young, late-M stars. However, the steepness of $I-K$ color for late-M stars constrains the uncertainty to within ∼1.5 subclasses. Uncertainties in the spectral-type to temperature conversion are discussed in Luhman, Liebert, & Reike (1997) and Lowrance et al. (1999). Although there is no proper motion confirmation of companionship, the small separation at relatively high Galactic latitude and the fact that TWA 5B appears to be coeval with the primary imply that it is likely a physical companion (see also Lowrance et al. 1999).

Given the rarity of young isolated stars in other parts of the sky, we believe that HR 4796A and B are TWA members despite their position on the edge of the cluster both in direction (∼18° from the cluster center) and in distance (67 pc; ∼15 pc further than the mean distance). The X-ray emission from HR 4796, which is emitted by the "B" component (Jura et al. 1998), is consistent with that of the other members. Thus, in every respect—age, Li abundance, kinematics, and X-ray brightness—HR 4796B appears very similar to the other TWA stars.

4. SUMMARY

Eleven young star systems, totaling at least 19 stars and a brown dwarf, are now known in the vicinity of the isolated, classical T Tauri star TW Hya. Given the youth of each of the members, the far-infrared excess emission at four of the TWA systems, and the common motions demonstrated in Webb et al. (1999b), it is very unlikely that this group of young stars is anything but a bona fide association of T Tauri stars with a common origin. This uniquely close group of young stars is an ideal laboratory to study star and planetary formation processes.

Primary funding for this research is provided by NSF grant 9417156 to UCLA. The SPM program is supported by grants from the NSF. IRTF data was funded through NASA grant NAGW-4770 under the Origins of Solar Systems program. This research has made use of the Simbad database operated at CDS, Strasbourg, France. Most of the data presented herein were obtained at the W. M. Keck Observatory, made possible by the generous financial support of the W. M. Keck Foundation and operated as a scientific partnership among Caltech, the University of California, and NASA. We thank J. Kastner for helpful discussions, the referee for helpful comments, and J. Lee, T. Girard, and M. Hazen for assistance with plate archives.

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