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IDENTIFYING NEARBY, YOUNG, LATE-TYPE STARS BY MEANS OF THEIR CIRCUMSTELLAR DISKS

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ABSTRACT

It has recently been shown that a significant fraction of late-type members of nearby, very young associations (age $\lesssim$10 Myr) display excess emission at mid-IR wavelengths indicative of dusty circumstellar disks. We demonstrate that the detection of mid-IR excess emission can be utilized to identify new nearby, young, late-type stars including two definite new members ("TWA 33" and "TWA 34") of the TW Hydrae Association (TWA). Both new TWA members display mid-IR excess emission in the *Wide-field Infrared Survey Explorer* catalog and they show proper motion and youthful spectroscopic characteristics—namely, Hα emission, strong lithium absorption, and low surface gravity features consistent with known TWA members. We also detect mid-IR excess—the first unambiguous evidence of a dusty circumstellar disk—around a previously identified UV-bright, young, accreting star (2M1337) that is a likely member of the Lower-Centaurus Crux region of the Scorpius–Centaurus Complex.

Key words: brown dwarfs – circumstellar matter – open clusters and associations: individual (TW Hydrae Association) – stars: evolution – stars: low-mass – stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

Low-mass stars are the most abundant stellar constituent in our Galaxy and are likely the typical planet hosts, thanks to recent radial velocity and microlensing results (e.g., Gaudi et al. 2008). The diverse zoo of planetary systems discovered to date implies that conditions in circumstellar disks are intimately linked to the final planetary system architectures. In turn, circumstellar environments appear to be controlled by the mass of the central star they orbit (Pascucci et al. 2009, and references therein). Thus, it is of great interest to understand in detail the evolution of circumstellar material surrounding low-mass stars.

In their analysis of mid-IR excess fractions for young, nearby associations, Schneider et al. (2012) show that a significant number of M-type stars display mid-IR excess emission in stellar groups younger than ~10 Myr. Riaz et al. (2012) found a similar result in their analysis of primordial disk fractions for young clusters, namely, that disks around later-type stars remain in the primordial stage for a longer period of time than disks around stars of earlier spectral types. Based on the *Wide-field Infrared Survey Explorer* (*WISE*) channel 4 at 22 μm, for M-type members with spectral types between M0 and M6, Schneider et al. (2012) derive updated excess fractions of 45^{+15}_{-13}% for the ~5–8 Myr (Luhman & Steeghs 2004) η Cha cluster, and 21^{+12}_{-6}% for members of the TW Hydrae Association ("TWA": age ~8 Myr; Zuckerman & Song 2004). For the ~12 Myr old Beta Pictoris Moving Group (BPMG: age ~12 Myr; Zuckerman & Song 2004), no evidence was found for protoplanetary (primordial or transitional) disks. Of 20 M-type stars in the BPMG in this spectral range, only one case of marginal 22 μm excess was recovered, coming from a well-known debris disk bearing member AU Mic. This implies that M-type stars with spectral types between M0 and M6 exhibiting mid-IR excess are very likely young (age $\lesssim$ 10 Myr).

One can utilize this association of mid-IR excess and youth as a new search method for identifying nearby, young (<10 Myr), late-type stars and brown dwarfs. Low-mass stars and brown dwarfs in this age range should all show additional unambiguous indicators of youth, such as strong Hα emission, lithium absorption, low-gravity spectral features, etc. Therefore, the youth of any candidate young M-type object discovered by its excess emission at mid-IR wavelengths can be evaluated with follow-up spectroscopy.

Although several young ($\lesssim$100 Myr), nearby ($\leqslant$80 pc) moving groups were identified during the past decade (Zuckerman & Song 2004; Torres et al. 2008), these include few low-mass members (spectral types later than ~M3). This is mainly due to the fact that unambiguous identification of young M-type stars is difficult if a well-measured trigonometric parallax is missing. Some activity indicators (e.g., Hα emission, X-ray emission) cannot readily discern young ($\lesssim$100 Myr) stars from a pool of old ($\gtrsim$600 Myr) field stars (Shkolnik et al. 2009). The Li λ6708 absorption feature, an effective age indicator for young FGK-type stars in the age range of 10–100 Myr, becomes increasingly sensitive to mass and age for M-type stars. The age at which a star becomes hot enough to burn lithium in its core can be seen in the so-called lithium depletion boundary, which can affect early- to mid-M-type stars at ages as young as the BPMG (~12 Myr).

Some young M-type stars have been identified, though they are either comoving companions of earlier spectral types or in a group of very young ($\lesssim$10 Myr) stars that are relatively confined to a small region of the sky (e.g., TWA and the subregions of the Scorpius–Centaurus Complex). With a well-measured trigonometric parallax, one can find a young M-type field star (e.g., AP Col; Riedel et al. 2011); however, a systematic search for young M-type stars needs to wait for the next generation of parallax missions, such as *Gaia*, *Pan-STARRS*, etc. Using the fact that random field M-type stars with mid-IR excess are extremely rare, one can search for $\lesssim$10 Myr M-type stars in the solar neighborhood with *WISE* data. These additional youngest M-type post-T Tauri stars can give an important clue to the mass function of young nearby stellar associations.

The TWA is one of the nearest (d ~ 30–90 pc) star-forming regions. Its proximity, in combination with its young age make it an ideal area for the study of stellar, planetary, and circumstellar

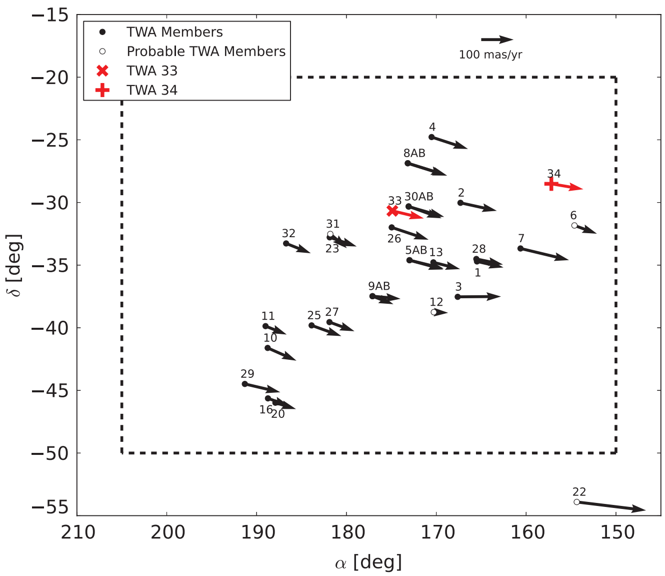

Figure 1. Location of TWA 33 and TWA 34 alongside other TWA members. Probable members (6, 12, 22, and 31; Schneider et al. 2012) are displayed as open circles. Arrows indicate the direction and magnitude of the measured proper motions for each member. The large dashed box indicates the search area defined in Section 2.

(A color version of this figure is available in the online journal.)

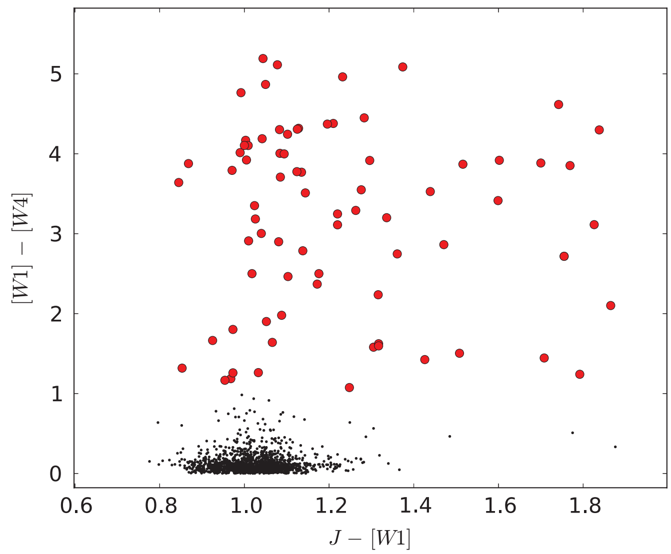

Figure 2. $J - W1$ vs. $W1 - W4$ color–color diagram showing our excess candidate selection. Seventy-six excess candidates are shown as large red symbols, while small black symbols represent non-excess candidates (see Section 2).

(A color version of this figure is available in the online journal.)

disk evolution. It has also been shown to be useful as a testbed for the evaluation and implementation of new techniques to identify young stars (e.g., UV-excess; Rodriguez et al. 2011; Shkolnik et al. 2011). For the above reasons, we have chosen to examine the TWA in a pilot study to find young, M-type stars by their mid-IR excess emission.

2. SEARCH METHOD

First, we define a search area around known TWA members in decimal degrees for right ascension (R.A.) and declination (decl., Figure 1):

$$150.0 < \text{R.A.} < 205.0$$

$$-50.0 < \text{decl.} < -25.0.$$

We cross-match all Two Micron All Sky Survey (2MASS) sources in this region with *WISE* using a source matching radius of 5″, restricting our search to those matches that are well detected (i.e., not upper limits) in all 2MASS and *WISE* bands, and require the *WISE* extended source flag to be less than 2 (i.e., not associated with a 2MASS extended source catalog object). Then, we make the following magnitude cut in 2MASS J magnitude in an attempt to exclude extragalactic sources, and we restrict various 2MASS/*WISE* colors to be those of M-type objects. 2MASS/*WISE* color selection criteria for M-type objects were determined by examining the colors of known M-type members of the β Pic, η Cha, and TWA:

$$J < 14.0 \text{ (mag)}$$
$$0.5 < J - H < 0.75 \text{ (mag)}$$
$$0.2 < H - K_S < 0.5 \text{ (mag)}$$
$$0.8 < J - K_S < 1.2 \text{ (mag)}$$
$$0.75 < J - W1 < 2.0 \text{ (mag)}.$$

The resulting list is replete with spurious detections in *WISE* channel 4 (for example, sources with S/N $\geqslant 5$, but no obvious source visible in $W4$ images). To address this issue, we make a *WISE* channel 4 magnitude cut in such a way as to detect an M-type star at $>5\sigma$ based on a typical uncertainty for a detectable faint source of ∼1.0 mJy. Using the zero-point flux from Jarrett et al. (2011), we find a source with a flux of 5.0 mJy in *WISE* channel 4 corresponds to a magnitude of ∼8.1 mag. Therefore, we keep as candidates all sources with a measured *WISE* channel 4 magnitude less than 8.1 mag.

As stated previously, candidates are required to have detections in *WISE* channel 4. This refers to the $W4$ magnitude measured with profile-fitting photometry provided in the *WISE* catalog. The *WISE* catalog also provides a $W4$ magnitude as determined via aperture photometry, which can be found in the "long form" version of the *WISE* All-Sky Source Catalog. In addition to the requirement that all candidates were well detected in the profile-fitting photometry, we require candidates to be well detected (i.e., not an upper limit) as determined by their magnitude measured via aperture photometry. By carefully eye-checking a selection of sources, it was found that those with an upper limit in *WISE* channel 4 determined by aperture photometry, even when the profile-fitting magnitude indicates a good detection, are spurious detections. By forcing point-spread function (PSF) fitting and aperture photometric results to be similar, approximately half of all remaining candidates were discarded in this way.

WISE channel 1 and *WISE* channel 4 magnitudes are then used to select objects with mid-IR excess. As seen in Figure 2 of Schneider et al. (2012), a typical $W1-W4$ color for an M-type non-excess star is between 0 and 1. Objects having colors in the following range are selected as excess candidates:

$$W1 - W4 > 1.0 \text{ (mag)}.$$

Mid-IR excess candidate selection is displayed in Figure 2.

A total of 76 M-type mid-IR excess candidates were found in the TWA search area defined above. These were then further examined by checking the corresponding *WISE* images of each candidate for any evidence of contamination, spurious

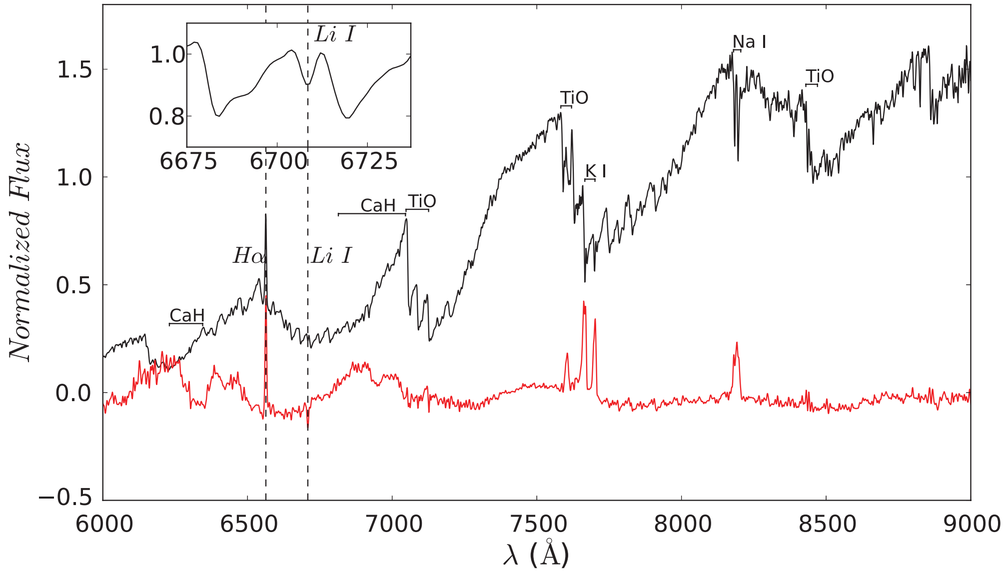

Figure 3. Portion of the optical spectrum of TWA 33. Major atomic and molecular features have been labeled. The inset shows its lithium absorption feature, and has been normalized to the continuum. The red line is the spectrum of TWA 33 divided by the combined spectra of old disk stars GJ 299 and GJ 551, highlighting the various gravity sensitive features.

(A color version of this figure is available in the online journal.)

detections in *WISE* channel 4 (S/N $\geqslant$ 5, but no obvious source visible in W4 images), or an extended shape indicative of an extragalactic nature. After the *WISE* image screening, 51 candidates remained. This list was then cross-matched with SIMBAD. Twelve sources were found to be either extragalactic or pulsating variable stars.

One object (2MASS 13373839−4736297) is a known young M-dwarf first discovered by Rodriguez et al. (2011) in their search for young stars utilizing UV-excess. Rodriguez et al. (2011) show that this star, with an estimated spectral type of M3.5 and distance of 126 pc, shows youthful characteristics in its spectrum. They measure an Hα equivalent width of 13.7 Å in emission, and an Li λ6708 equivalent width of 308 mÅ. This object is likely a member of Lower-Centaurus Crux (LCC) region ($d \sim 95$ pc, age $\sim$ 10 Myr; Song et al. 2012) of the Scorpius–Centaurus Association, based on its estimated distance and proper motion. This is the first evidence for mid-IR excess for this star, which shows that our search method is likely to be useful for other areas of the sky, such as the subregions of the Scorpius–Centaurus Complex.

Six confirmed TWA members were recovered (TWA 3A, 27, 28, 30A, 31, and 32). The lone late-type (M4), mid-IR excess TWA member not returned with our search method was TWA 30B. This object did not meet our selection criteria because its photospheric emission is heavily obscured up to at least *WISE* channel 2, likely due to its edge-on disk geometry (Looper et al. 2010a; Schneider et al. 2012).

For the remaining 32 candidates, we cross-match their positions with the PPMXL catalog of positions and proper motions (Roeser et al. 2010) to inspect for any candidates that have measured proper motions consistent with that of known TWA members. To select the best candidates, we require that the total proper motion magnitude and direction be within 1σ of the average of confirmed TWA members. Thirty of the candidates show inconsistent proper motions. The last two remaining candidates (2MASS 11393382−3040002 and 2MASS 10284580−2830374), with proper motions consistent with known members of TWA (see Figure 1), are discussed in detail in the following section.

3. SPECTROSCOPIC FOLLOW-UP AND MEMBERSHIP EVALUATION

To check for the expected signatures of youth for an M-type TWA member, candidates 2M1139 and 2M1028 were followed up spectroscopically with the Wide Field Spectrograph (WiFeS; Dopita et al. 2007) on the 2.3 m telescope located at the Siding Spring Observatory. 2M1139 was observed on 2012 May 30 and 2M1028 was observed on 2012 August 3. The spectra were obtained with the B_{3000} and R_{3000} gratings that cover the wavelength ranges 3400–6000 Å and 5600–9500 Å, respectively, with a resolution of $R \sim 3000$. A portion of each spectrum containing the Hα emission line and the Li λ6708 absorption line is shown in Figure 3 (2M1139) and Figure 4 (2M1028). 2M1139 closely resembles the average combined spectrum of old field dwarfs GJ 299 (M4.5) and GJ 551 (M6), while 2M1028 most closely resembles GJ 551. A comparison of each candidate TWA member with these spectra shows a considerable weakening of MgH, CaH, CaOH, K I and Na I features compared to old field dwarfs with similar TiO band strengths (Figures 3 and 4). As seen in Table 1, each candidate shows moderate Hα emission and strong lithium absorption.

Lawson et al. (2009) show that indices derived from spectroscopic features that are sensitive to a star's surface gravity can be used to distinguish relative age differences of nearby clusters and moving groups. In particular, for stars of spectral type M3 and later, the Na I λ8183/8195 doublet index shows a distinct difference between field dwarfs (strong absorption), young stars ($\lesssim$12 Myr, reduced absorption), and giants, in which the feature is mostly absent. We measure an Na I index for both candidates, and, using their *R*–*I* colors from our flux-calibrated spectra, compare their values with the Na I index–color relations for various stellar groups from Lawson et al. (2009) in Figure 5. *VRI* colors (in the Johnson–Cousins system) were computed from our flux-calibrated spectrum for each candidate, and are listed in Table 1. We estimate the photometry is accurate to within ±0.01–0.02 mag. As seen in the figure, the Na I index of each candidate suggests a low surface gravity, and an age similar to TWA. This low-gravity feature, along with the measured

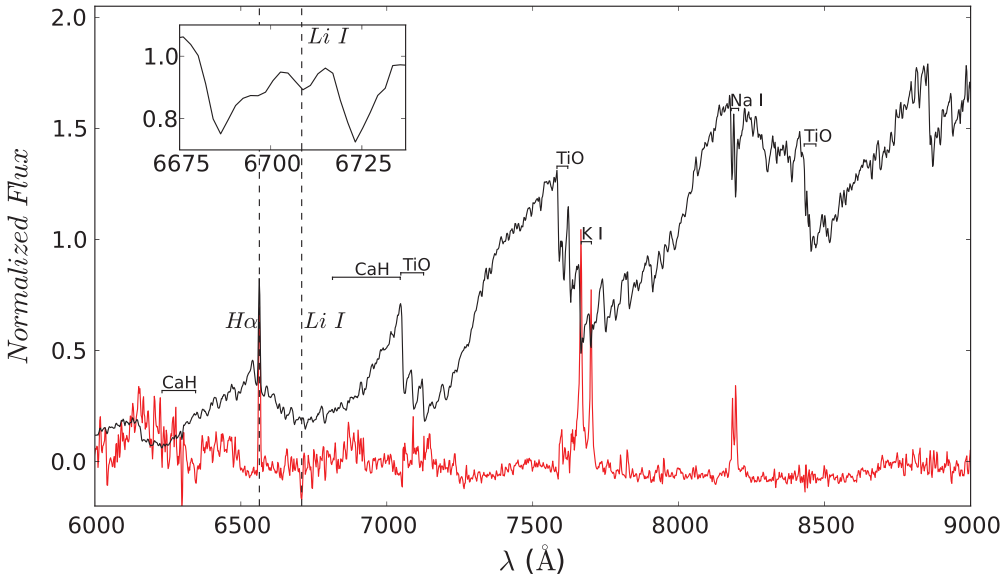

Figure 4. Portion of the optical spectrum of TWA 34, displayed in the same manner as in Figure 3. The red line is the spectrum of TWA 34 divided by the spectrum of GJ 551.

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Table 1
Properties

Parameter	Value		Ref.
	TWA 33 (2M1139)	TWA 34 (2M1028)	
α (J2000)	11:39:33.83	10:28:45.80	1
δ (J2000)	−30:40:00.3	−28:30:37.4	1
μ_α	-88.7 ± 6.1 (mas yr^{-1})	-65.5 ± 4.1 (mas yr^{-1})	2
μ_δ	-25.9 ± 6.1 (mas yr^{-1})	-11.1 ± 4.1 (mas yr^{-1})	2
Optical SpT	M4.7 ± 0.5	M4.9 ± 0.5	3
Distance[a]	41 ± 8 pc	50 ± 10 pc	3
Distance[b]	42 ± 4 pc	49 ± 4 pc	3
$V-R$	1.37 ± 0.03 (mag)	1.65 ± 0.03 (mag)	3
$R-I$	1.80 ± 0.03 (mag)	1.97 ± 0.03 (mag)	3
J	9.985 ± 0.021 (mag)	10.953 ± 0.027 (mag)	1
H	9.414 ± 0.023 (mag)	10.410 ± 0.024 (mag)	1
K_S	9.118 ± 0.023 (mag)	10.026 ± 0.022 (mag)	1
$W1$	8.765 ± 0.022 (mag)	9.592 ± 0.023 (mag)	4
$W2$	8.404 ± 0.019 (mag)	9.116 ± 0.020 (mag)	4
$W3$	7.135 ± 0.017 (mag)	8.243 ± 0.020 (mag)	4
$W4$	5.518 ± 0.038 (mag)	6.845 ± 0.075 (mag)	4
Li EW	470 mÅ	370 mÅ	3
Hα EW	−5.8 Å	−9.6 Å	3
Na I index	1.14 ± 0.02	1.12 ± 0.02	3
NUV		22.325 ± 0.397 (mag)	5

Notes.
[a] Photometric distance using empirical TWA isochrone.
[b] Kinematic distance assuming TWA membership.
References. (1) 2MASS catalog (Cutri et al. 2003); (2) PPMXL catalog (Roeser et al. 2010); (3) This work; (4) *WISE* All-Sky Source Catalog (Cutri et al. 2012); (5) *GALEX* catalog.

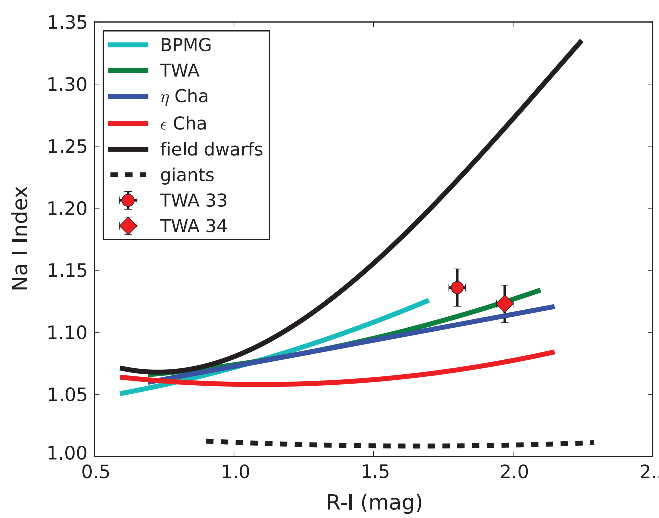

Figure 5. Na I index trends for various stellar groups from Lawson et al. (2009). The location of TWA 33 and TWA 34 suggests a low surface gravity, consistent with other TWA members. Ages of these groups are as follows: Beta Pictoris Moving Group ∼ 12 Myr, TWA ∼ 8 Myr, η Cha ∼ 5–8 Myr, and ϵ Cha ∼ 6–7 Myr.

(A color version of this figure is available in the online journal.)

equivalent widths of the Hα emission and lithium absorption lines, given in Table 1, confirm the youth of both candidates.

As mentioned in Schneider et al. (2012), for most cases, the determining factor between membership in TWA and the further away, LCC region of the Scorpius–Centaurus Complex is distance, with a possible boundary between the two regions occurring near 100 pc. We estimate the distance to each candidate TWA members in two ways. First, we calculate a photometric distance using our measured spectral type in combination with an empirical isochrone for known TWA members. We estimate a spectral type of M4.7 ± 0.5 for 2M1139 and M4.9 ± 0.5 for 2M1028 using the TiO5 index as described in Reid et al. (1995). Placing these candidates on the empirical TWA isochrone, we estimate an absolute K magnitude of ∼6.0 mag and ∼6.5 mag for 2M1139 and 2M1028, respectively. From these absolute magnitudes, we calculate a photometric distance of ∼41 pc for 2M1139 and ∼50 pc for 2M1028. Uncertainties using this method are typically ∼20%.

We also estimate the kinematic distance by obtaining a kinematic parallax following the method described in Mamajek (2005). The mean velocity of TWA was calculated using parameters of confirmed members from Schneider et al. (2012).

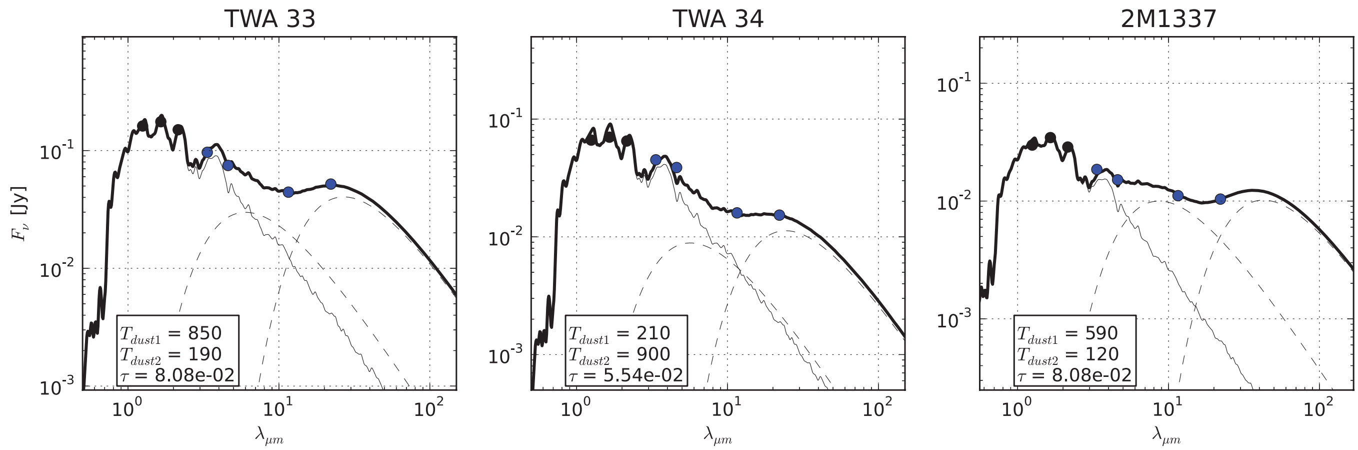

Figure 6. Spectral energy distributions of TWA 33, TWA 34, and 2M1337 showing their mid-IR excess emission. The solid circles are photometric measurements from 2MASS and *WISE*. The thin black curve is an atmospheric model (Hauschildt et al. 1999) fit to the 2MASS data. The dashed lines are single temperature blackbody dust fits to the excess emission with the dust temperatures (in K) as specified in the plot. The thick curve is the spectral model + blackbody dust fit. τ = infrared luminosity $= L_{\rm IR}/L_{\rm bol}$.

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The adopted TWA space velocity is $(U, V, W) = (-10.8, -18.1, -4.4)$ km s^{-1}. As with TWA 30A and TWA 30B, which have sky positions and proper motions similar to that of 2M1139 (see Figure 1), we find that almost all space motion is directed toward the TWA convergent point (Looper et al. 2010a, 2010b). From this motion, we calculate a kinematic parallax of 23.6 $\pm$ 1.8 mas, corresponding to a distance of 42 $\pm$ 3 pc. For 2M1028, we calculate a kinematic parallax of 20.3 $\pm$ 1.7 mas, which corresponds to a distance of 49 $\pm$ 4 pc. Both estimates are in excellent agreement with our calculated photometric distances. These distance estimates put each candidate well on the TWA side of the $\sim$100 pc dividing line between TWA and the LCC.

Rodriguez et al. (2011) and Shkolnik et al. (2011) show that UV-excess is an effective tool for identifying young, M-type objects. We searched for any evidence of UV-excess using the *Galaxy Evolution Explorer* (*GALEX*; Martin et al. 2005) and found that 2M1139 has not been covered in the most recent data release. 2M1028 was detected by *GALEX*, with a near ultraviolet (NUV) magnitude of 22.325 $\pm$ 0.397 mag. With a 2MASS $J - K$ color of 0.93 mag, and an NUV$-J$ color of 11.37 mag, we note that this object would pass the selection criteria outlined in Rodriguez et al. (2011) for young stars candidates, namely, NUV $- J \leqslant 10.20(J - K) + 2.2$, indicative of a young age.

The combination of position, proper motion, spectral signatures of youth, distance estimates, mid-IR excess, and, in the case of 2M1028, UV-excess, lead us to the conclusion that 2MASS 1139 and 2M1028 are indeed authentic members of the TWA. Following the naming convention for TWA members, we designate 2M1139 TWA 33 and 2M1028 TWA 34. The properties of TWA 33 and TWA 34 are summarized in Table 1. Figure 6 includes a spectral energy distribution (SED) that shows the mid-IR excess emission of each new member. Also shown is the SED of a likely LCC member 2M1337, first identified as a young star by Rodriguez et al. (2011), the infrared excess of which was discovered in our search.

4. DISCUSSION

We note that, at the age of TWA or younger, use of mid-IR excess as a search method is highly effective for TWA members with spectral types of M4 or later. Including TWA 33 and TWA 34, there are 16 TWA members with spectral types in this range. Fourteen of these were individually detected with *WISE* (TWA 3B and 5B are too close to their primary members to be resolved individually). Nine of these 14 members show significant mid-IR excess emission, eight of which were found with our search method. The discovery of TWA 33 and TWA 34 demonstrates the effectiveness of using mid-IR excess as a tool to identify nearby, young, late-type stars. These stars show many signatures of youth expected for a TWA member, such as Hα emission, lithium absorption, and low surface gravity spectral features. Using two different methods, we estimate a distance of $\lesssim$50 pc for both stars, consistent with their TWA membership. We also rediscovered the young, likely LCC member 2M1337, first identified as a young star by Rodriguez et al. (2011), and found evidence for the presence of a circumstellar disk around this star.

Considering the high fraction of late-type mid-IR excess stars from TWA and the slightly younger η Cha Association (45% for M-type members; Schneider et al. 2012), we believe that mid-IR excess can be a useful tool in identifying more young, nearby, late-type stars and brown dwarfs. One can expand our search for these objects to other areas of interest, such as the subregions of the Scorpius–Centaurus Association, or even the entire sky.

An interesting conjecture is whether there is a higher fraction of mid-IR excess stars among the latest M spectral types (M6 or later). For the six known TWA members with spectral type later than M6, three—TWA 27, 30A, and 32—were detected individually by *WISE* to have excess emission in channel 4. TWA 5B, an M8 dwarf companion to TWA 5A, is too close to its primary to be resolved. TWA 26 and TWA 29 have only upper limits in *WISE* channel 4, so no strong conclusions regarding mid-IR excess can be deduced from *WISE* for these members, though TWA 26 shows no excess at 24 μm via *Spitzer* MIPS (Schneider et al. 2012). In summary, all *WISE* detectable late M-type TWA members show mid-IR excess emission at the W4 band. To date, no members of the η Cha cluster have been found with spectral types later than M6, though searches have been performed (Lyo et al. 2006). The BPMG has two known late-type members (excluding giant planet β Pictoris b), HR 7329B (M7.5; Lowrance et al. 2008) and 2MASS 0608$-$27 (M8.5; Rice et al. 2010). HR 7329B is too close to its host star to be resolved individually with *WISE*, and 2MASS 0608$-$27 has an upper limit in *WISE* channel 4. So, at this point, only TWA has a reasonable number of latest M-type members to check the conjecture of even more prolonged disks among the latest M-type stars. Future missions, such as *Gaia*, which should discover more late-type members of these nearby associations, will allow us to test the hypothesis that primordial disks have longer lifetimes around later-spectral types in this spectral type range.

While we have shown that mid-IR excess emission can be a useful tool for identifying nearby, young, late-type stars and brown dwarfs, caution must be taken when considering association properties, such as disk fraction and mass function. Any objects found with this method will surely bias the measure of disk frequency for a particular group of stars, so we do not update the excess fraction for TWA here. If the hypothesis of longer disk lifetimes around later spectral types is true, then any objects found with this method would bias any estimate of the mass function as well. While the question of whether or not there is a higher fraction of mid-IR excess for the latest spectral types is an interesting one, it cannot be answered with objects found with the search method described in this paper.

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