KECK HIRES SPECTROSCOPY OF CANDIDATE POST–T TAURI STARS

ERIC J. BUBAR AND JEREMY R. KING
Department of Physics and Astronomy, Clemson University, Clemson, SC 29630-0978, USA; ebubar@clemson.edu, jking2@cces.clemson.edu

DAVID R. SODERBLOM
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA; soderblom@stsci.edu

CONSTANTINE P. DELIYANNIS
Department of Astronomy, Indiana University, 727 East 3rd Street, Swain Hall West 319, Bloomington, IN 47405-7105, USA; con@atena.astro.indiana.edu

AND

ANN M. BOESGAARD
Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822, USA; boes@ifa.hawaii.edu

Received 2007 April 25; accepted 2007 August 16

ABSTRACT

We use high signal-to-noise ratio (~150–450), high-resolution (R ~ 45,000) Keck HIRES spectroscopy of 13 candidate post–T Tauri stars (PTTs) to derive basic physical parameters, lithium abundances, and radial velocities. We place our stars in the M,Teff plane for use in determining approximate ages from pre-main-sequence isochrones, and we confirm these using three relative age indicators in our analysis: Li abundances, chromospheric emission, and the kinematic U,V plane. Using the three age criteria we identify five stars (HIP 54529, HIP 62758, HIP 63322, HIP 74045, and HIP 104864) as probable PTTs with ages between 10 and 100 Myr. We confirm HIP 54529 as an SB2 star and HIP 63322 as an SB1 star. We also examine irregular photometric variability of PTTs using the Hipparcos photometry annex. Two of our PTTs exhibit near-IR excesses compared to Kurucz model flux; while recent work suggests classical T Tauri stars evince similar JHK excesses presumably indicative of nonphotospheric (disk) emission, our results may be illusory artifacts of the chosen I-band normalization. The near-IR excesses we see in a literature-based sample of PTTs appear to be artifacts of previous spectral type–based T_{eff} values. Indeed, comparison of the homology of their observed and model photospheric spectral energy distributions suggests that photometric temperatures are more reliable than temperatures based on spectral standards for the cooler temperature ranges of the stars in this sample. We conclude that our age-oriented analysis is a robust means to select samples of nearby, young, isolated PTTs that otherwise masquerade as normal field stars.

Key words: stars: abundances — stars: late-type — stars: pre–main-sequence

1. INTRODUCTION

The evolution of young stars is becoming increasingly important, given the renewed interest in planet formation driven by the continuing discovery of exoplanets (e.g., Butler et al. 2006). The extremely young (<10^{7} yr) pre-main-sequence precursors to stars like our own Sun, known as T Tauri stars, are believed to possess environments conducive to planetary formation. Auspiciously, T Tauri stars have distinct observational characteristics that make them relatively easy to identify. Such characteristics include, but are not limited to, strong IR excesses, strong Hα emission, irregular variability, and high surface lithium abundances (for a recent review of T Tauri stars, see Petrov 2003 and references therein). By studying young stellar associations, T Tauri stars are fairly easily identifiable. However, the period of evolution (10^{7}–10^{8} yr) between the T Tauri and zero-age main-sequence (ZAMS) phases remains ambiguous. The late-type stars in this age range, referred to as post–T Tauri stars (PTTs), are expected to have some degree of “intermediary characteristics” between the T Tauri and main-sequence stages (Herbig 1978). Consequently, a PTT should possess, for example, relatively high measures of chromospheric emission and relatively high surface Li abundances compared to main-sequence stars of comparable mass. It may seem that finding these stars should be relatively simple. By looking near regions of T Tauri stars, we should find that some have evolved into their post–T Tauri stage. In fact, as Herbig (1978) noted nearly 30 years ago, there must be many times more PTTs than there are T Tauri stars. Yet studies of young stars which typically concentrate on regions of active star formation often fail to find the numbers of PTTs that are expected.

Several explanations that could resolve this apparent disparity are discussed in Soderblom et al. (1998), but here we concentrate on their second solution: that PTTs exist but are far from star-forming regions. To summarize their findings, Soderblom et al. (1998) showed HD 98800 to be a unique PTT system. This system of four stars was determined to be a young (~10 Myr) post–T Tauri group that is far from any region of active star formation. The orbital properties of the stars mean the system could not have been violently removed from its birthplace. It departed by a more gentle means, suggesting that it is possible that other post–T Tauri candidates evolved similarly and now exist in isolated environments.

Most recently, post–T Tauri search efforts have uncovered loose associations and moving groups that appear to be of post–T Tauri age (the β Pictoris moving group, the TW Hydrae association, the Tucana/Horologium association, and the AB Doradus moving group; Zuckerman & Song 2004 and references therein). In fact, HD 98800 is now believed to be a member of just such a group.
indicators, making them less robust. Analysis, as they typically decay on shorter timescales than our chosen features but choose not to include them in our age-oriented analysis. Identifying PTTs. We present our interpretations of these three features, all characteristics noted by Herbig (1978) to be useful for main sequence and/or (2) apparently evincing significant Ca emission in raw two-dimensional spectra inspected by eye. Determining approximate ages from pre-main-sequence isochrones (kinematics) for use in assigning post-AR stars. We derive qualitative age information from three diagnostics (Li abundance, chromospheric emission, and UVW kinematics) for use in assigning post-AR T Tauri candidacy. We also determine approximate ages from pre-main-sequence isochrones and masses from pre-main-sequence mass tracks, both taken from D’Antona & Mazzitelli (1997; assuming solar metallicity). For completeness, we also search for indications of irregular variability, examine IR excesses, and present equivalent widths for the H line. For the purposes of follow-up high-resolution spectroscopic programs, we flagged stars (1) residing significantly above the Hipparcos-based main sequence and/or (2) apparently evincing significant Ca H and K emission in raw two-dimensional spectra inspected by eye at the telescope as potential PTT candidates. The objects studied here are part of our ongoing survey of solar-type stars within 60 pc based on low-resolution (R ~ 2000) spectra mostly from the KPNO coude’ feed telescope. For the purpose of follow-up high-resolution spectroscopic programs, we flagged stars (1) residing significantly above the Hipparcos-based main sequence and/or (2) apparently evincing significant Ca H and K emission in raw two-dimensional spectra inspected by eye at the telescope as potential PTT candidates. Here we present high-resolution echelle spectroscopy for 13 of these stars. We derive qualitative age information from three diagnostics (Li abundance, chromospheric emission, and UVW kinematics) for use in assigning post-AR T Tauri candidacy. We also determine approximate ages from pre-main-sequence isochrones and masses from pre-main-sequence mass tracks, both taken from D’Antona & Mazzitelli (1997; assuming solar metallicity). For completeness, we also search for indications of irregular variability, examine IR excesses, and present equivalent widths for the H line. For the purposes of follow-up high-resolution spectroscopic programs, we flagged stars (1) residing significantly above the Hipparcos-based main sequence and/or (2) apparently evincing significant Ca H and K emission in raw two-dimensional spectra inspected by eye at the telescope as potential PTT candidates. Here we present high-resolution echelle spectroscopy for 13 of these stars. We derive qualitative age information from three diagnostics (Li abundance, chromospheric emission, and UVW kinematics) for use in assigning post-AR T Tauri candidacy. We also determine approximate ages from pre-main-sequence isochrones and masses from pre-main-sequence mass tracks, both taken from D’Antona & Mazzitelli (1997; assuming solar metallicity). For completeness, we also search for indications of irregular variability, examine IR excesses, and present equivalent widths for the H line. Figure 1. — Sample Keck HIRES spectra in the Li line region. The observed spectra are plotted as circles, and the varying syntheses of lithium abundances are plotted as solid lines. HIP 59152 (top) has an upper limit [log N(Li) < 0.10] on its lithium abundance, and HIP 104864 (bottom) has a clear lithium abundance determination [log N(Li) = 2.50]. The varying lithium syntheses in the positive detections each differ by a factor of 2.
2.2. Basic Physical Parameters

Temperatures were determined from photometric calibrations of Ramírez & Meléndez (2005). Both $B - V$ color indices from the Tycho catalog (Perryman et al. 1997) and $V - K_{\text{MASS}}$ indices (Cutri et al. 2003) were used to find effective temperatures. Errors for temperatures were found from the errors in the respective color indices and in the polynomial fits (Table 2 of Ramírez & Meléndez 2005). A weighted mean was taken for input into Kurucz model atmospheres. Our sample, colors, temperatures, and other data are compiled in Table 2.

Special methods had to be utilized for one of the stars in the sample (HIP 54529), as it was found to be a double-lined spectroscopic binary. Following the analysis of Boesgaard & Tripicco (1986), we performed a least-squares fit to the ratio of equivalent widths of two Fe i absorption lines ($W(6703)$ and $W(6705)$) versus effective temperature for the stars in our sample (Fig. 2). We find that the fit is given by the formula

$$\frac{W(6703)}{W(6705)} = 2.066 - 2.225 \times 10^{-4} T_{\text{eff}}.$$  

We used the equivalent widths of these lines in the primary and secondary components to determine their respective temperatures. Multiplicative correction factors to account for unequal continuum flux contributions from the components (as described in Boesgaard & Tripicco 1986) were found to be approximately unity. We report here on the analysis for only the primary component. This technique was not applied to HIP 63322 as it was not a double-lined star. The double nature of this star was revealed by asymmetry in the cross-correlation peaks of our radial velocity analysis.

Our photometric temperatures can be compared to the spectroscopic values of Santos et al. (2004) for six stars in the sample (footnote a of Table 2). We find that our temperatures for warmer stars tend to agree nicely with their spectroscopic estimates but become systematically cooler (by as much as 250 K at 4600 K) with declining temperatures. We suspect the spectroscopic $T_{\text{eff}}$ values are afflicted by the effects of overexcitation seen in young cool dwarfs (Schuler et al. 2006). For this reason we have chosen to utilize photometric temperatures.

Use of Hipparcos parallaxes allowed us to calculate “physical” surface gravities using

$$\log g / g_{\odot} = \log \frac{M}{M_{\odot}} + 4 \log \frac{T_{\text{eff}}}{T_{\text{eff,\odot}}} + 0.4 V_0$$

$$+ 0.4 BC + 2 \log \pi + 0.12,$$

where $M$ is the mass in solar masses (determined from the pre-main-sequence mass tracks of D’Antona & Mazzitelli 1997), $V_0$ is the apparent magnitude, and $\pi$ is the parallax in arcseconds. The surface gravity is given in Table 2. The average uncertainty

![Fig. 2.—Equivalent width ratios of two Fe i lines (6703 and 6705) vs. photometric temperatures for the stars in our sample. The line indicates a least-squares fit to the data which was used for estimating temperatures in the primary and secondary components of the double-lined spectroscopic binary HIP 54529. This follows the method outlined by Boesgaard & Tripicco (1986).](image-url)
for the surface gravity parameter was approximately 0.20 dex. We note that mass differences (as discussed in 3.2) from using the tracks of Siess et al. (2000) and Baraffe et al. (1998) result in surface gravities that differ from our adopted ones by 0.01–0.17 dex when using the former and 0.01–0.18 dex when using the latter.

The microturbulence parameter was determined from calibrations of Allende Prieto et al. (2004). They derived a relationship for determining microturbulence as a function of effective temperature and surface gravity. The error in this parameter was determined by propagating the errors in effective temperature and \( \log g \). The average error in the microturbulence was found to be 0.01 km s\(^{-1}\). In order to examine the extent to which microturbulence would affect our lithium feature, we performed lithium synthesis for microturbulent velocities spanning 1 km s\(^{-1}\). We find this change to have very little effect on the lithium feature (\( \leq 0.01 \) dex).

Overall metallicities were kindly provided by R. Boone and are given in Table 2. These are derived based on \( \chi^2 \) fitting of low-resolution blue spectra (\( R \sim 2000 \)) with synthetic spectra of varying abundance (Boone et al. 2006). Internal 1 \( \sigma \) level uncertainties are believed to be \( \sim 0.10 \) dex.

### 2.3. Lithium Abundances

The basic physical parameters for each star were utilized to linearly interpolate model atmospheres from the Kurucz ATLAS9 atmosphere grids. These model atmospheres were then used in conjunction with the comprehensive line list from King et al. (1997) to compute synthetic spectra with various Li abundances using the most recent version of the spectral synthesis tool MOOG (Sneden 1973). The chosen models introduced an uncertainty into the lithium abundances of 0.03 dex, determined by comparing synthetic lithium synthesis for a standard Kurucz solar model and one developed using our interpolated model atmospheres. The synthetic spectra were smoothed appropriately by convolving them with Gaussians having FWHM values measured from clean, weak lines (continuum depths \( < 0.2 \)) in multiple orders for each star using the spectrum analysis tool SPECTRE (Fitzpatrick & Sneden 1987).

We positively identified lithium in 7 of the 13 stars in the sample. We derived upper limits for the other six stars. We attempted to determine equivalent width errors based on the photon noise methods of Cayrel (1988) but found 1 \( \sigma \) errors \( \leq 1.0 \) mÅ, which are significantly smaller than the uncertainty in continuum placement. In lieu of a more rigorous treatment, we chose to adopt a conservative equivalent width error estimate of 4 mÅ. To verify additional lithium syntheses for each of the stars, we translate this equivalent width uncertainty to an upper limit in lithium abundance for each star. Sample syntheses are presented in Figure 1.

Appropriate uncertainties in the lithium fits were derived by estimating the goodness of fit by means of an \( F \)-test of relative \( \chi^2 \) values and by adding in quadrature an approximate uncertainty of \( \log N/(Li) \pm 0.08 \) for a temperature uncertainty of \( \pm 100 \). The typical error in the lithium abundances is found to be \( \sim 0.06 \) dex. The synthetic lithium abundances are given, with their respective errors, in Table 2. We also plot our lithium abundances versus effective temperatures for both the stars in our sample and the stars in the \( \sim 100 \) Myr Pleiades (Fig. 3). The Pleiades data are taken from Soderblom et al. (1993), Jones et al. (1996), and King et al. (2000).

### 2.4. Radial Velocities and UVW Kinematics

Radial velocities were derived via cross-correlation analysis using the IRAF packages \texttt{fxcor} and \texttt{rvcor}. We used HIP 90485 as our template spectrum and adopted its CORAVEL radial velocity of \( -17.4 \pm 0.2 \) km s\(^{-1}\) (Nordström et al. 2004). Whenever possible, we compared our radial velocities with precise determinations from the literature. In all cases, our velocities matched within the adopted errors. These radial velocities and errors are shown in Table 3. The quoted errors are the internal uncertainties from fitting the cross-correlation functions. Total radial velocity uncertainties are larger than the cross-correlation fitting uncertainties inasmuch as \( \sim 2 \) km s\(^{-1}\) intranight telluric line shifts are observed.

The cross-correlation peaks used in the radial velocity determinations confirmed that both HIP 54529 and HIP 63322 were members of binary systems. This was readily apparent in the double-lined spectrum of HIP 54529, but HIP 63322 showed no indication of double lines. The asymmetry of the radial velocity cross-correlation peaks showed this star’s binary nature.

Space motions were derived with an updated version of the code used by Johnson & Soderblom (1987), which accounts for covariances. The required inputs, \( UVW \) kinematics, and uncertainties are given in Table 3.

### 3. RESULTS AND DISCUSSION

#### 3.1. Post–T Tauri Status Evaluation

We utilize three different indicators to assess the evolutionary classification of our stars (summarized in Table 4). First is the lithium abundance. We plot in Figure 3 our derived lithium abundances against effective temperatures for each star and lithium abundances in the Pleiades from King et al. (2000); they utilized temperatures and lithium abundances derived from both \( B - V \) and \( V - I \) color indices, which we averaged to find a single temperature and abundance. Those stars with abundances that place them in the observed lithium abundance trend of the Pleiades are qualitatively classified as likely being young. Those stars which have measurable Li yet lie below the Li trend of the Pleiades have inconclusive results about youth. Finally, those stars which have no measurable lithium (i.e., upper limits) are stipulated to most likely be older stars and unlikely post–T Tauri candidates.
Chromospheric activity also provides a useful estimate of youth. In Figure 4 we plot the chromospheric activity index log \( R'_{\text{HK}} \) (from the recent chromospheric Ca ii H and K survey of nearby \( |d| \leq 60 \) pc late-F through early-K dwarfs of D. Soderblom) versus color index for each of our stars. We separate this plot into four distinct activity levels, following the work of Henry et al. (1996) and Gray et al. (2003). We classify those stars with log \( R'_{\text{HK}} \) greater than \(-4.75 \) as either active or very active and, therefore, young targets. It can be noted in Figure 4 that many of the stars have activities resting in the inactive zone yet are still near the active part. While it is unlikely that activity variations are entirely due to stellar variability, we note that activity can be at least partially diminished by various effects (i.e., Maunder minimum phases). With this in mind, we label these stars with inconclusive ages based on chromospheric emission. Those stars which rest in the very inactive category are classified as unlikely to be young.

Third, we utilize \( UVW \) kinematics to discern additional qualitative age information. We plot our stars in the \( U-V \) plane (Fig. 5) for comparison with locations of both early-type groups (young main-sequence stars of spectral types B–F) and late-type groups (a mixture of young and old main-sequence stars of spectral type F–M) in Figures 8 and 10 of Skuljan et al. (1999). When a star clearly resides outside of any structures depicted as being young, it is classified as likely being older. In doing so, we identify several potential members (HIP 47007, HIP 47202, and HIP 104903) of the alleged Wolf 630 moving group of Eggen (1969). Youth is difficult to confirm from kinematics alone; therefore, the \( U-V \) plane was primarily used to exclude older objects. While no conclusive results can be determined, the \( UVW \) kinematics did provide a useful criterion for confirming stars with lower lithium abundance and lower activity as being old.

We considered the above three criteria in interpreting evolutionary status from the H-R diagram. In order to describe a star as being young, we require (1) a measurable lithium abundance at least as high as that observed in the Pleiades, (2) classification of chromospheric activity as either very active or active, and

### Table 4
**Summary of Age-Oriented Analysis Results**

| HIP   | \( \log N(\text{Li}) \) | \( \log R'_{\text{HK}} \) | Kinematics | H-R Diagram | Status        | Ages\(^a\) (Myr) | \( \delta(\text{age}) \) |
|-------|-------------------|-----------------|------------|-------------|---------------|----------------|----------------|
| 47007 | Yes               | No              | No         | No          | Post-ZAMS     | ...            | ...            |
| 47202 | ?                 | No              | No         | No          | Post-ZAMS     | ...            | ...            |
| 54529A | Yes\(^c\)        | ?               | ?          | Yes         | PTTs          | 25\(\pm\)5.5 | -3.16          |
| 59152 | No                | Yes             | ?          | ?           | ZAMS or older | ...            | ...            |
| 63258 | No                | Yes             | ?          | ?           | PTTs or ZAMS  | 47\(\pm\)10 | -6.93          |
| 63322 | Yes               | Yes             | ?          | Yes         | PTTs          | 36\(\pm\)8 | -3.38          |
| 74045 | Yes               | No              | ?          | Yes         | ZAMS          | ...            | ...            |
| 87380 | No                | No              | ?          | No          | Post-ZAMS     | ...            | ...            |
| 90004 | No                | No              | ?          | No          | Post-ZAMS     | ...            | ...            |
| 90485 | No                | No              | No         | No          | Post-ZAMS     | ...            | ...            |
| 104864 | Yes              | Yes             | ?          | No          | PTTs or ZAMS  | 29\(\pm\)7 | ...            |
| 104903 | Yes             | Yes             | ?          | No          | Post-ZAMS     | ...            | ...            |
| 114007 | No              | No              | No         | No          | ZAMS or older | ...            | ...            |

\( ^a \) Ages are derived based on the assumption of solar metallicity.

\( ^b \) The quantity \( \delta(\text{age}) \) gives the difference between ages assuming solar metallicity and ages which account for the subsolar metallicities. We utilized the online tools of Siess et al. (2000) to interpolate between solar \((Z = 0.02)\) and subsolar \((Z = 0.01)\) stellar ages to obtain our metallicity-sensitive ages. The negative sign indicates that metallicity sensitive ages are younger.

\( ^c \) We compare the levels of \( H_\alpha \) emission of this star with several other stars in the sample in Fig. 7. This star is seen to have emission levels similar to those of one of the more chromospherically active stars in the sample; thus, we label it as "active."
nonmembership in "old" structures in the $U$-$V$ plane. The stars which satisfied these criteria are deemed to likely be young stars, and mass and age estimates are determined from pre-main-sequence mass tracks and isochrones of D’Antona & Mazzitelli (1997). The lithium, chromospheric emission, and kinematic criteria suggest that some of our objects (HIP 90004, HIP 90485, HIP 104903, HIP 47007, and HIP 47202) are post-ZAMS. Ages are not derived for these stars, as we have successfully eliminated them from consideration as post-$Y$ T Tauri candidates.

### 3.2. Ages

Ages were derived in the standard manner from the most recent pre-main-sequence isochrones of D’Antona & Mazzitelli (1997). Examining the positions of our stars in the H-R diagram, we found them to lie above or very near the main sequence. We take an age of 100 Myr as indicative of membership on the ZAMS, which is confirmed by the coincidence of single Pleiades stars from King et al. (2000) with the 100 Myr isochrone.

Figure 6 contains our PTT candidates, the D’Antona isochrones for ages of 10, 20, 30, 50, and 100 Myr, and the mass tracks from D’Antona & Mazzitelli (1997). Errors from convection treatments and opacity effects are not considered. We also examined derived ages and masses using tracks from both Baraffe et al. (1998) and Siess et al. (2000) to determine the consistency of our derived ages. The isochrones all give similar ages within the error bars. The mass tracks from Baraffe et al. (1998) are shifted to lower $T_{\text{eff}}$, resulting in higher mass estimates, particularly for the lower mass stars. Mass differences appear to be as great as $0.07 M_\odot$ around $0.80 M_\odot$ and diminish to $0.02 M_\odot$ at a mass of $1.05 M_\odot$. The mass estimates from the Siess et al. (2000) tracks agree well with those from D’Antona & Mazzitelli (1997).

### 3.3. Individual Stars

We present results for each of the stars in the sample. The stars we classify as post-$T$ Tauri are given in bold.

**HIP 47007/HD 82943.**—The HIP 47007 lithium abundance $[\log N(\text{Li}) = 2.33]$ lies a factor of 5–6 below the Pleiades distribution; the abundance is more consistent with the older
lack of evidence of youth from activity and kinematics and the presence of very little lithium make it unlikely to be a good post-T Tauri candidate.

**HIP 62758/HD 111813**.—This star has a near-Pleiades lithium abundance of \( \log N(\text{Li}) = 1.67 \); its chromospheric emission (\( R'_{\text{HK}} = -4.32 \)) places it in the active category. These two findings suggest possible youth not inconsistent with its location in the \( U-V \) plane. Using the H-R diagram we derive an age of \( 47 \pm 10 \) Myr and a mass of \( 0.78 \pm 0.02 \, M_\odot \). Recognizing that, within the errors, this star is nearly on the ZAMS, we classify it as a PTT or ZAMS star.

**HIP 63322/BD +39 2587**.—We find an appreciable abundance of lithium in this star [\( \log N(\text{Li}) = 1.60 \)]. Its chromospheric emission ties for the highest of any of the stars in the sample (\( R'_{\text{HK}} = -4.12 \)). Its location near the Pleiades branch (Saffe et al. 2005) in the kinematic plane is consistent with youth. The age (\( 45 \pm 13 \) Myr) derived from its location in the H-R diagram, coupled with the significant Li and chromospheric emission, leads us to label this star as post–T Tauri. We find a rough estimate of the mass, assuming it was a single star, of \( 0.77 \pm 0.03 \, M_\odot \). We also note again that the line profiles and cross-correlation peaks exhibit a notable asymmetry, indicative of this star being a spectroscopic binary.

**HIP 74045/HD 135363**.—HIP 74045 is the only broad-lined star of the sample, suggesting a moderate projected rotation (\( \sim 15 \) km s\(^{-1} \)) consistent with youth. The substantial lithium abundance [\( \log N(\text{Li}) = 1.96 \)] lying in the midst of the Pleiades’s distribution is also suggestive of youth. The chromospheric emission (\( R'_{\text{HK}} = -4.17 \)) places this star in the very active category. Finally, this object does not reside in any older \( U-V \) kinematic plane structures. Its location in the H-R diagram confirms youth and a PTT classification with an age of \( 36 \pm 14 \) Myr and a mass of \( 0.78 \pm 0.01 \, M_\odot \).

**HIP 87330/HD 162020**.—Our upper limit to the lithium abundance of HIP 87330 [\( \log N(\text{Li}) < -0.30 \)] lies a factor of 10 below the Pleiades trend, suggesting a post-ZAMS age. However, the chromospheric emission index (\( R'_{\text{HK}} = -4.12 \)) taken from Saffe et al. (2005) is the highest in the sample. The kinematics of the star yield inconclusive results. With the lack of correlation between the low lithium abundance and high chromospheric emission, we hesitate to make any definitive conclusions on the nature of this star.

**HIP 90004/HD 168746**.—This star has an upper limit to its lithium abundance of \( \log N(\text{Li}) < 0.90 \). The chromospheric emission index (\( R'_{\text{HK}} = 5.11 \)) is the lowest in the sample. While its position in the \( U-V \) plane is inconclusive, the low lithium upper limit, extremely low emission index, and H-R diagram position imply that this star is post-ZAMS.

**HIP 90485/HD 169830**.—We set an upper limit on this star of \( \log N(\text{Li}) < 1.5 \). The chromospheric emission is also extremely low (\( R'_{\text{HK}} = -4.93 \)). Although the position in the \( U-V \) kinematic plane is inconclusive, the low lithium upper limit coupled with the low emission index clearly indicate that this star’s location above the main sequence on the H-R diagram is due to its status as a post-ZAMS star.

**HIP 104864/HD 202116**.—This star shows a high lithium abundance of \( \log N(\text{Li}) = 2.50 \), which lies just below the Pleiades trend. The emission index of \( R'_{\text{HK}} = -4.37 \) places this star in the active category. The \( U-V \) kinematics do not place this star within any old moving group structures. While these three indications imply youth for the star, the position in the H-R diagram shows that, within the errors, this star could reside on the main sequence. We derive an age of \( 29 \pm 21 \) Myr and a mass of \( 1.03 \pm 0.02 \, M_\odot \). While this age makes the star a post–T Tauri candidate, its location...
in the H-R diagram shows that a ZAMS classification remains plausible.

**HIP 104903/HD 202206.**—This star exhibits a low Li abundance \(\log N(\text{Li}) = 1.10\), placing it well below the Pleiades distribution. The chromospheric emission of \(R'_{\text{HK}} = 4.81\) places it in the inactive category, implying a slightly older star. Indeed, the position in the \(U-V\) plane leads to classification of this star as a potential member of the alleged 5 Gyr Wolf 630 moving group of Eggen (1969). Its position in the H-R diagram indicates that the star is post-ZAMS.

**HIP 114007/BD +07 5930.**—The star has an upper limit lithium abundance of \(\log N(\text{Li}) < 0.30\) and an extremely low chromospheric emission index \(R'_{\text{HK}} = 4.74\). The object’s position in the kinematic plane is inconclusive. The low lithium upper limit and the low chromospheric emission, coupled with the position on the H-R diagram, lead to this star’s classification as ZAMS or older.

### 3.4. Irregular Variability

We used the *Hipparcos* Epoch Photometry Annex to examine photometric variability in the five PTT candidates. This tool provided all the photometric measurements from the *Hipparcos* mission for the stars in our sample. We used these to construct histograms of the reduced \(\chi^2(\chi^2_{\text{red}})\) and the real dispersion \(\sigma_{\text{real}}\) of the \(V\) magnitudes about their average. We calculated the difference in the observed and expected variances as the real variance.

For comparison, we performed the same analysis on a sample of the 25 best solar analog candidates from Tables 5–7 of Cayrel de Strobel (1996). These analogs provide a solid baseline of inactive stars that are presumably not subject to irregular variability. In addition, we performed this analysis for 15 classical T Tauri stars from the emission-line star catalog of Herbig & Bell with available *Hipparcos* data. The solar analogs and T Tauri stars provide the context of a large range of anticipated variability to fit our PTTs into. We also included 41 post–T Tauri aged stars taken from the literature (Mamajek et al. 2002) to increase the PTT sample size and compare with our candidates. The \(\chi^2_{\text{red}}\) and \(\sigma_{\text{real}}\) values can be seen in Figure 8.

The T Tauri stars clearly show random variability. The majority have both \(\chi^2_{\text{red}}\) values and real dispersions nearly an order of magnitude greater than the PTTs and solar analogs.

\[ \text{VizieR Online Data Catalog, 5073 (G. H. Herbig & K. R. Bell, 1995).} \]
Fig. 9.—SEDs for the two PTTs (HIP 63322 and HIP 74045) that show an IR excess in the $J$, $H$, and $K$ bands. The excess appears clearly when the Kurucz fluxes are normalized to the Cousins $I$ band (solid line). The excess, however, is essentially nonexistent when Kurucz fluxes are normalized to the 2MASS $J$ band (dotted line). Errors are no greater than the size of the points.

Fig. 10.—Kurucz model atmosphere flux curves and photometric data for a selection of our stars and for a sample of solar analogs. The top two rows show the stars in our sample, and the bottom row provides curves for a sample of solar analogs. Each plot is labeled with the HIP number of the corresponding star, and the Kurucz fluxes are normalized to the $I_C$ band. Note the apparent excess in the $JHK$ bands in the PTTs (HIP 63322 and HIP 74045).
The majority of the solar analogs cluster around $\chi^2_\nu = 1$. This shows that the analogs tend to have magnitudes close to their average, i.e., that they are much less variable. Furthermore, the dispersion histogram also shows that the analogs stay clustered close to their average magnitudes, with the typical dispersion $\sigma_{\text{real}} \leq 0.01$ mag.

The $\chi^2_\nu$ and $\sigma_{\text{real}}$ of our post–T Tauri candidates fit nicely in the range exhibited in the literature sample, between $\chi^2_\nu$ values of 1 and 4, lending further credence to their selection as candidates. Also, note that the dispersions of the post–T Tauri magnitudes are both lower and less widespread than those of the T Tauri stars. They are not as variable as their precursors. Examining the overall picture, note that both $\chi^2_\nu$ and $\sigma_{\text{real}}$ are intermediate between the values exhibited by T Tauri stars and solar analogs, as expected.

We performed a Kolmogorov-Smirnov (K-S) test of the distributions to quantitatively explore the differences between the histogram distributions. The K-S test comparing the distributions of both the real dispersion ($\sigma_{\text{real}}$ and $\chi^2_\nu$) values for T Tauri stars and our PTTs revealed that the two samples were not drawn from the same distribution. Comparing the PTT sample from the literature with the PTTs of this paper, we found them to be drawn from a similar distribution. Finally, the K-S test for our PTTs and solar analogs revealed that the two cumulative samples were drawn from different distributions. The K-S tests then solidify our PTT classifications to the extent that they confirm that PTTs have an intermediate degree of irregular variability between T Tauri stars and solar analogs, as anticipated.

3.5. IR Excess

For the sake of completeness we conducted a search for any irregularities in the PTT spectral energy distributions (SEDs), traced by Johnson $BVI_C$ photometry, 2MASS $JHK_s$ photometry, and $IRAS$ and Spitzer photometry when available. Considering the proximity of these stars (within 60 pc of the Sun), we did not anticipate that they would be affected by interstellar reddening. However, to determine the extent to which reddening may have an effect, we created a reddening-sensitive Johnson-band color-color diagram of $(J - K)$ versus $(V - K)$, following Carney (1983). The stars in our sample were clearly seen to lie along a trend of unreddened, single stars of the Hyades. This implies that they are not susceptible to interstellar reddening.

After establishing that reddening corrections were unnecessary, we converted the relevant magnitudes to flux densities (in janskys) for comparison with Kurucz model photospheric fluxes.

Fig. 11.—Kurucz model atmosphere flux curves and photometric data for a sample of PTTs taken from the literature. HIP numbers are given in each of the plots. We present this figure to demonstrate that PTTs appear to demonstrate many variations of excess. In some cases the excesses are similar to those of our candidates (HIP 62445), although temperature differences may suggest a different conclusion (Fig. 12).
(Castelli & Kurucz 2003), normalized at $I_C$. We chose to normalize to the $I_C$ magnitudes. Two of the five PTTs we identified showed significant near-IR excesses (HIP 63322 and HIP 74045). However, we reserve judgment on the authenticity of the observed excess in these two cases because using a $J$-band normalization yields no sign of excess in any of the stars (Fig. 9). Indeed, in contrast to the results of Cieza et al. (2005) on $JHK$ excesses in classical T Tauri stars, we find that a $J$-band normalization slightly improves the fit to the SED at other wavelengths.

In order to examine the likelihood that a PTT would exhibit a near-IR excess, we performed the same analysis on a literature sample of 16 PTTs (Mamajek et al. 2002) utilizing spectral-type-based $T_{\text{eff}}$ values. The sample analyzed showed that excess was present in approximately 50% of the stars analyzed. To further examine our methodology, we analyzed a sample of presumably unremarkable solar analogs to confirm that no spurious effects were present. None of the solar analogs analyzed exhibited any form of IR excess. In Figures 10 and 11 we present SEDs for our stars, as well as a sample of solar analogs and literature PTTs. The observed SEDs of many objects in the literature sample of PTTs seemed to match the morphology of our post–T Tauri candidates of lower $T_{\text{eff}}$, thus, we calculated photometric temperatures for each of the literature stars and performed a Kurucz model flux fit using these photometric temperatures. The model fluxes characterized by photometric temperatures fit the observed SEDs better than those characterized by the literature-based effective temperature values (Fig. 12), which are 250–1000 K higher. This indicates that photometric temperatures may be more reliable than those determined from spectral-type calibrations for the cooler pre-main-sequence stars or that the log $g$-based decrements used by Mamajek et al. (2002) are too small.

### 3.6. H$\alpha$ Equivalent Widths

H$\alpha$ emission provides a strong indication of youth in a star. However, if we consider H$\alpha$ emission relative to our other indicators of youth, it has the smallest decay time. So, while high levels of emission imply youth, low levels of emission (or high levels of absorption) do not necessarily discredit youth. For completeness, measurements of the equivalent widths of the H$\alpha$ feature for each of the stars in the sample are presented in Table 5, since these line strengths are often used in classifying classical T Tauri stars.

We note that the binary star HIP 63322 exhibits a P Cygni profile in the H$\alpha$ region, a feature that is common in many classical
T Tauri stars; however, the equivalent width is too low to suggest such a classification. The blueshifted absorption feature can be attributed to a strong stellar wind; however, a small redshifted absorption feature also appears to be present. Data with the H$\alpha$ line centered away from the edge of the CCD are needed to examine this feature and determine whether it is “real.” If it represents actual absorption, this could be indicative of infall onto one of the members of the system, making this a particularly interesting example of a post–T Tauri system.

4. SUMMARY

We have utilized an age-oriented analysis to identify five isolated post–T Tauri candidates (HIP 54529, HIP 62758, HIP 63322, HIP 74045, and HIP 104864) and analyzed their irregular variability and SEDs. The irregular variability of our candidates, and PTTs in general, appears to be intermediate in nature to T Tauri and solar analog variability. Two of the five candidates (HIP 63322 and HIP 74040) exhibit near-IR excesses when normalized to $I_C$, although this same excess is nonexistent with a $J$-band normalization. Subsequent study must be undertaken to determine the nature and validity of these excesses. In our SED analysis, we also find that model fluxes based on photometric temperatures appear to match observed SEDs better than model fluxes using temperatures based on spectral standards. Also of note is the binarity of two of our PTTs: HIP 54529 and HIP 63322 are found to be spectroscopic binaries.

Our combination of H-R diagram positions and various qualitative indicators of youth (including lithium abundances, chromospheric emission, and kinematics) appears to be a robust means to select samples of nearby, young, isolated PTTs that would otherwise masquerade as normal field stars. The method we have developed will be applied to larger samples of stars to further enhance the population of known PTTs.

We thank Robbie Boone for the use of his metallicity determinations. We also wish to thank the anonymous referee, whose comments helped to improve and clarify the paper. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This publication also makes use of data products from the Two Micron All Sky 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. J. R. K. and E. J. B. gratefully acknowledge support for this work from NSF grants AST 00-86576 and AST 02-39518. E. J. B. would also like to acknowledge support from the South Carolina Space Grant Consortium.

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TABLE 5

| HIP  | Hα Equivalent Width (Å) |
|------|--------------------------|
| 47007 | 1.1368                   |
| 47202 | 1.0342                   |
| 54529 | 0.1703                   |
| 59152 | 0.9546                   |
| 62758 | 0.8549                   |
| 63322 | 0.2521                   |
| 74045 | 0.2115                   |
| 87330 | 0.6016                   |
| 90004 | 1.0409                   |
| 90485 | 1.1310                   |
| 104864| 0.9736                   |
| 104903| 1.0233                   |
| 114007| 0.8626                   |

a The Hα features for these stars are plotted in Fig. 7.