1983ApJ...269..229M

THE ASTROPHYSICAL JOURNAL, **269**:229–238, 1983 June 1

OBSERVATIONS OF SUSPECTED LOW-MASS POST–T TAURI STARS AND THEIR EVOLUTIONARY STATUS[1]

REINHARD MUNDT
Steward Observatory, University of Arizona
FREDERICK M. WALTER
Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards
ERIC D. FEIGELSON
Center for Space Research, Massachusetts Institute of Technology
ULRICH FINKENZELLER
Landessternwarte, Königstuhl, Heidelberg
GEORGE H. HERBIG
Lick Observatory, University of California
AND
ANDREW P. ODELL
Department of Physics and Astronomy, Northern Arizona University
Received 1982 August 4; accepted 1982 November 23

ABSTRACT

We present the results of a study of five X-ray discovered weak emission pre–main-sequence stars in the Taurus-Auriga star formation complex. All are of spectral type K7–M0, and about 1–2 mag above the main sequence. One is a double-lined spectroscopic binary, the first spectroscopic binary PMS star to be confirmed. We discuss the ages, masses, and radii of these stars as determined by photometry and spectroscopy. We investigate the difference in emission strength between these and the T Tauri stars and conclude that these "post–T Tauri" stars do indeed appear more evolved than the T Tauri stars, although there is no evidence of any significant difference in ages.

Subject headings: stars: pre–main-sequence — X-rays: sources

I. INTRODUCTION

Herbig (1978) has addressed the question of the observational absence of post–T Tauri stars. These are stars which are still contracting along the lower portions of their evolutionary tracks prior to settling down on the ZAMS, but which are not characterized by the plethora of emission lines and ultraviolet and infrared excesses of the T Tauri phase of pre–main-sequence evolution. Herbig has estimated that at 1 $M_\odot$ the T Tauri phase occupies some 5%–10% of the pre–main-sequence evolutionary time scale; hence, one should expect to see many post-T Tauri (PTT) stars, if star formation proceeds over one or more Kelvin times.

Herbig (1978) pointed out that such stars ought to be distinguished by emission characteristics intermediate between those of the T Tauri stars and stars on the ZAMS, by irregular variability at a level much reduced from that seen in the T Tauri stars, and perhaps by lower Li abundances. However, because of their more moderate characteristics, these stars are not readily detectable in objective prism surveys. Moreover, since these stars are more evolved than the T Tauri stars, they should have smaller radii and hence be intrinsically fainter than the T Tauri stars (although, as a mitigating factor, they may show less interstellar absorption, given more time to move away from the dusty regions in which they were born). Candidates for such are FK Ser and V410 Tau (Herbig 1973, 1978).

Recently, Walter and Kuhi (1981) and Feigelson and Kriss (1981) have reported X-ray detections of five stars in the Taurus-Auriga star formation complex which may represent the low-mass post–T Tauri population. These five stars are remarkably similar: all have weak Hα emission lines superposed on a normal K7–M0 IV–V spectrum, ultraviolet excesses, and strong ($L_x \sim 10^{30}$ ergs s^{-1}) X-ray emission. Rydgren, Schmelz, and Vrba (1982) show that, in this sample, two of three stars they observed have no significant infrared excesses at $\lambda \leq 3.5$ μm. All lie above the main sequence, in the lower portion of the region occupied by the T Tauri stars.

If these stars are indeed post–T Tauri (PTT), yet pre–main-sequence, then studies of the atmospheric structure may yield important clues to the nature of the T Tauri stars and the evolution of pre–main-sequence stars. We report here on optical investigations of these five stars to determine, if possible, their precise evolutionary state. The five low-mass PTT candidates

---

[1] The research reported herein is based in part upon data acquired at the Multiple Mirror Telescope Observatory (MMTO). The MMTO is a joint facility of the University of Arizona and the Smithsonian Institution.

are listed in Table 1; finding charts for the stars are presented in Figure 1 (Plate 5). Star 5 was misidentified in the finding chart published by Feigelson and Kriss (1981); P5 is actually 115″ east and 102″ south of the star marked "3" in their figure. We shall refer to these stars as P1–P5, in order of increasing right ascension.

II. INSTRUMENTS

Observations were made with the Steward Observatory 90 inch (2.3 m) echelle spectrograph, the Multiple Mirror Telescope (MMT) echelle spectrograph, with the Lick Observatory 120 inch (3 m) coudé spectrograph and 40 inch (1 m) IDS, and the McGraw-Hill Mark 2 Spectrometer. The 90″ echelle spectrograph uses IIa-O plates (baked in forming gas) behind an RCA image tube. Plates were calibrated with a spot sensitometer, using a ThAr lamp for the wavelength calibration. With these plates, about 18 echelle orders could be observed, giving a wavelength coverage of $\lambda\lambda$5700–7000, with 18 km s^{-1} resolution ($\sim$0.4 Å at Hα) over the observed wavelength region. All five stars were observed between 1981 November 15 and 17. We scanned the orders containing Hα and Li I λ6707 using the KPNO PDS machine, with a 16 μm square slit stepping by 8 μm (the plate resolution is 80 μm), as well as the interorder background to correct for scattered light, dark current, and plate fogging. The digitized intensity-transformed spectra were then smoothed with a Gaussian filter, resulting in an 18–20 km s^{-1} resolution.

The MMT echelle spectrograph with a photon counting Reticon detector was used to observe P2 between 1982 January 8 and 18. The wavelengths observed are noted in Table 2. The spectral resolution is $\sim$10 km s^{-1} (0.2 Å at 6000 Å). Details of the instrument and reduction techniques are given by Mundt and Hartmann (1983). Additional observations of star P2 were kindly carried out in 1982 April by D. Latham using the echelle spectrograph of the Mount Hopkins 60 inch (1.5 m) telescope. This spectrograph and detector are nearly identical to that on the MMT. The photographic spectra at the Lick Observatory were obtained using the 20 inch (51 cm) camera, and a Varo image intensifier, at 34 Å mm^{-1} dispersion. A rather wide slit was used for these observations, giving a 1.4 Å FWHM resolution. The radial velocities measured on these spectra were determined as in Herbig (1977). Additional spectroscopy was obtained on the McGraw-Hill 1.3 m telescope using the Mark II photon counting intensified Reticon spectrograph (Schectman and Hiltner 1976), as well as with the Image Dissector Scanner (Robinson and Wampler 1972) on the Lick Observatory 40 inch (1 m) Nickel Telescope.

TABLE 1

CANDIDATE LOW-MASS POST-T TAURI STARS

Star	α (1950)	δ (1950)	Reference[a]	Alternate Designation[b]
P1..........	$4^h16^m23^s$	+28°19′29″	WK	...
P2..........	4 29 21	+17 55 24	FK	X-ray 1
P3..........	4 29 23	+18 13 54	FK	X-ray 2
P4..........	4 30 11	+24 27 59	WK	...
P5..........	5 00 2	+25 18 36	FK	X-ray 3

[a] WK = Walter and Kuhi 1981; FK = Feigelson and Kriss 1981.

[b] Notation in Rydgren, Schmelz, and Vrba 1982 and Rydgren and Vrba 1982.

III. DISCOVERY OF THE FIRST PRE–MAIN-SEQUENCE SPECTROSCOPY BINARY

During our investigations with the MMT, we discovered that P2 was a double-lined spectroscopic binary. A sequence of three MMT spectra, shown in Figure 2, clearly exhibits the double-lined nature of this system. Although it is generally assumed that pre-main-sequence stars share the same preference for duplicity and multiplicity as the main-sequence stars (Lucy and Ricco 1979), and although other low-mass PMS stars do exist in wide associations or close visual pairs (Cohen and Kuhi 1979; Herbig and Rao 1972), or are suspected of being close binaries (e.g., RY Tau; see Herbig 1977), none have been demonstrated to be spectroscopic

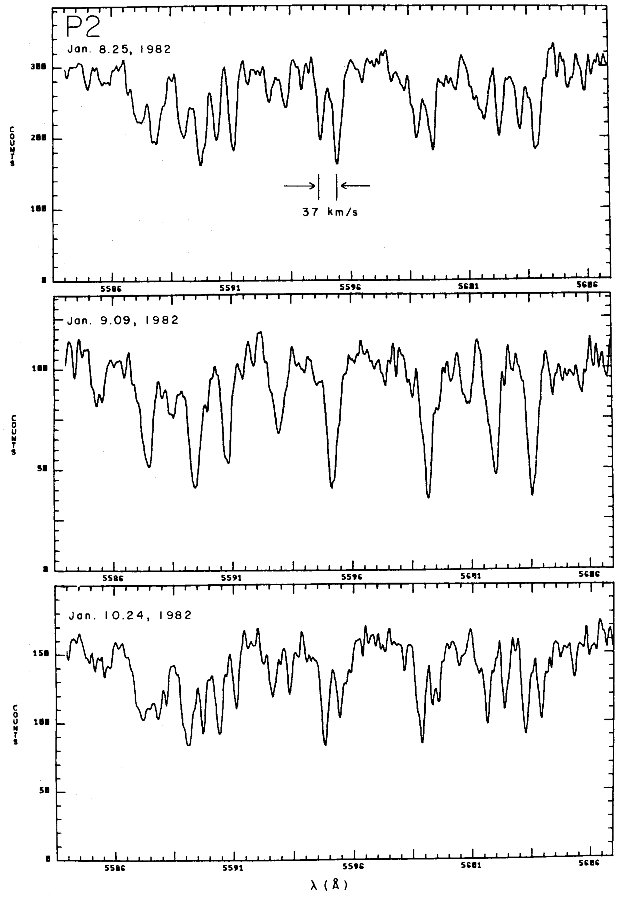

FIG. 2.—Sequence of three MMT echelle spectra with 10 km s^{-1} resolution of the binary P2. The ordinate is in detected photons per pixel (1 resolution element $\sim$6 pixels).

TABLE 2

Radial Velocity Data for P2

JD (2,444,900+)	Wavelengths (Å)	P2 A[a] n^b	P2 A[a] $\bar{v}^c$ (km/s)	P2 B n^b	P2 B $\bar{v}^c$ (km/s)	Notes
23.71	6135–6175 6400–6450	11	30.0 ± 0.5	5	4.7 ± 0.6	1
77.745	5560–5610	14	35.9 ± 0.4	10	−1.2 ± 0.5	2
78.59	5560–5610	14	18.5 ± 0.3	14	18.5 ± 0.3	2, 3
78.83	6390–6450	7	17.2 ± 0.4	7	17.2 ± 0.4	2, 3
79.735	5560–5610	13	−0.6 ± 0.3	12	36.1 ± 0.8	2
83.84	5560–5610	12	0.7 ± 0.6	12	34.2 ± 0.6	2
84.875	5560–5610	13	24.0 ± 0.6	10	10.3 ± 1.0	2, 4
85.83	5160–5205	...	34.7	...	3.1	2, 5
86.72	5175–5220	...	16.1	...	16.1	2, 5, 6
87.675	5175–5220	...	0.9	...	33.5	2, 5
162.635	5175–5220	...	11.6	...	23.3	4, 5, 7, 8
164.625	5175–5220	...	21.4	...	10.5	5, 7, 8

Notes.—(1) Observed with the Steward Observatory 90″ (2.3 m) telescope. (2) Observed with the MMT. (3) Measured close to crossover; systematic errors of ~2–4 km s^{-1} are possible due to line blending. (4) Lines not fully resolved; 2 km s^{-1} systematic errors possible. (5) Radial velocities determined by D. Latham using cross correlation with K5 star; typical errors 0.5–1.0 km s^{-1}. (6) Near crossover; lines broad but not separable; 2–4 km s^{-1} errors possible. (7) Observed with the Mount Hopkins 60″ (1.5 m) telescope echelle spectrograph. (8) Both components exhibited similar absorption line depth, leading to a 180° phase uncertainty. The velocity quoted for each component is that which gives the best orbital solution.

[a] Component A is defined as that with the stronger absorption lines between JD 2,444,923 and JD 2,444,988. See note 8.

[b] Number of lines measured.

[c] Heliocentric radial velocity; errors are formal standard deviations of the mean.

binaries. As such, this binary may prove a boon for studies of stellar formation in the presence of a close companion.

We present the heliocentric radial velocity observations in Table 2. The data were collected with three telescopes and using two reduction techniques. The majority of the observations involved direct measurements of both blended (but symmetrical) and unblended lines. To permit usage of the blended lines, we measured the center of gravity wavelengths of these lines in the spectra of 61 Cyg A and B, which are of similar spectral type to P2 (see below). These comparison spectra were obtained in 1981 June using an identical setup. Fairly accurate wavelengths could be determined for the blended lines, as 61 Cyg A and B are high quality radial velocity standards in the Mount Wilson Radial Velocity Catalog. In this way we could measure between 8 and 14 lines in each spectrum. No systematic differences were measured between the radial velocities determined using the blended and unblended lines. The remaining observations and data reductions were made by D. Latham in the region of the Mg *b* band, using a cross correlation of the stellar spectrum against that of a K5 template to determine the radial velocities (cf. Latham 1982 for details).

The best orbital parameters are given in Table 3; the velocity curves are shown in Figure 3. The $3^{\rm d}.9063 \pm 0^{\rm d}.0006$ orbital period is similar within the errors to the $4^{\rm d}.05 \pm 0^{\rm d}.2$ photometric period observed for this system by Rydgren and Vrba (1983*a*). The orbit is circular, and the mass ratio is unity.

TABLE 3

Orbital Elements of P2

Element	Value
P	$3^{\rm d}.9063 \pm 0^{\rm d}.0006$
T_0[a]	$2{,}444{,}923^{\rm d}.157 \pm 0^{\rm d}.015$
e	0.01 ± 0.02
V_0	17.85 ± 0.3 km s^{-1}
$K_{\rm A}$	18.0 ± 0.3 km s^{-1}
$K_{\rm B}$	17.3 ± 0.9 km s^{-1}

[a] Conjunction with A in front of B.

The two components appear to be of similar spectral type, K7–M0 Ve. We will discuss this and the color indices in § V. However, during ten of the twelve observations, one star (component A) showed ~15% deeper absorption lines than did the B component. On the last two observations, the line strengths were similar. Two stars of the same mass, on the same isochrone, should have similar radii, and similar luminosities. If the difference in line strengths is attributable to different stellar luminosities, then the radius of the A component is ~7% larger than that of the B component. This is unlikely, since it requires that the stars not be exactly coeval, and poses the interesting question of how to form a non-coeval close binary. An alternative, and more likely, explanation hinges on the photometric variability observed by Rydgren and Vrba (1983*a*). This is interpreted as due to strong stellar activity, with spots and plage regions

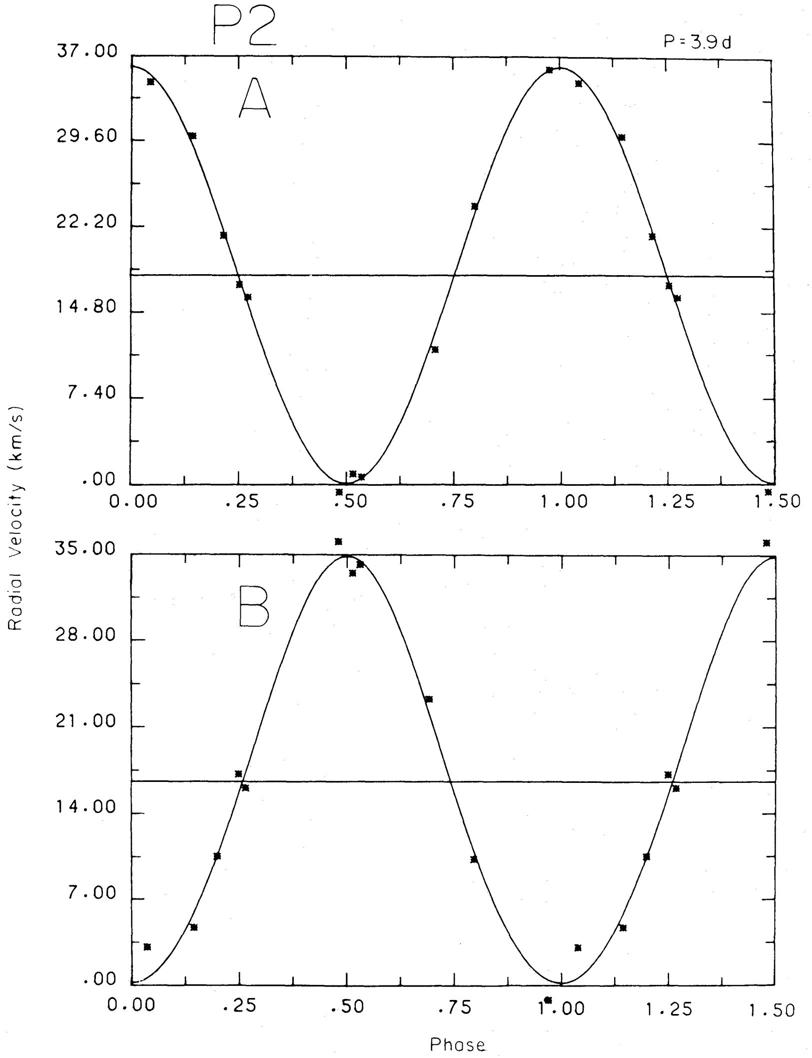

FIG. 3.—Radial velocity curve of P2

concentrated upon one side of one or both of the components. Strong plage activity can fill in photospheric absorption lines (cf. Giampapa, Worden, and Gilliam 1979). If this is the case, then star B would be the active star. The observation of equal line strengths during the latter observations is consistent with this scenario: the activity level must have decreased. There is no evidence in these data for phase related variations in line depths.

The photometric period indicates that at least one component is rotating synchronously. It is likely that both are, since they are convective stars in a short period orbit (cf. Scharlemann 1981).

From the period and K velocities, $a \sin i = 1.4\ R_\odot$; Kepler's law yields $(M_1 + M_2)\sin^3 i = 0.002\ M_\odot$. Using the visual magnitude and the A_v we compute (see § V), we can place the stars on convective tracks (Cohen and Kuhi 1979), and we find that $M_1 = M_2 \sim 0.6\ M_\odot$. Assuming these masses we calculate $i = 7^\circ\!.2$ and $a = 11\ R_\odot$. For stellar radii of $\sim 1.9\ R_\odot$, from the Barnes-Evans (1976) relation, and assuming synchronous and co-aligned rotation, $V \sin i \sim 3$ km s^{-1}, which is consistent with our upper limits of $V \sin i < 10$ km s^{-1}.

IV. ON THE PRE–MAIN-SEQUENCE NATURE OF THESE STARS

There are a number of indications that these five stars are indeed pre–main-sequence objects. The first is the spatial argument, presented by Walter and Kuhi (1981), that these five stars are located in the ~ 12 deg^2 of the sky observed with the *Einstein Observatory* in the Taurus-Auriga star formation complex. Similar stars have not been found in other directions; in fact, the likelihood of detecting a serendipitous stellar X-ray source in a randomly chosen square degree of sky is much lower than $\sim \frac{1}{2}$ per deg^2 observed here, by roughly an order of magnitude. Feigelson and Kriss (1981) point out, as well, that these stars are preferentially located near dark clouds (see Fig. 1), which argues further for their physical association with the Taurus-Auriga star formation complex.

We have measured the heliocentric radial velocity of the Li λ6707 and other absorption lines for each star (see Table 4). In each case the radial velocity of the stellar absorption lines (and the systemic velocity of P2) is identical within the errors with the radial velocities of the molecular clouds which they abut. This is compelling evidence that these stars are associated with the molecular clouds. We therefore assign to each star a distance of 160 pc. At this distance, these stars are well above the main sequence. All five stars display strong Li I λ6707 absorption (see Table 4) with equivalent widths of ~0.7 Å. The Li surface abundance is anticorrelated with stellar age in convective stars (cf. Duncan 1981). These five stars display Li equivalent widths comparable in strength to those of T Tauri stars of similar spectral type (D. Duncan 1982, private communication) and hence must be of nearly comparable ages. We have derived Li abundances for these stars following Duncan (1981), using a model atmosphere for a K7 V star (Eriksson, Gustafsson, and Bell 1983). The resultant log n(Li)'s, given in Table 4, are consistent with the undepleted, cosmic value of log $n(\mathrm{Li}) = 3.0 \pm 0.5$. Hence, these five stars cannot be older than the low-mass T Tauri stars by more than one or two pre-main-sequence Li destruction time scales. The Li destruction time scale for pre-main-sequence K7 stars is not known. However, a crude upper limit may be calculated from the observations of Mundt and Bastian (1981), who obtained upper limits of log $n(\mathrm{Li}) \lesssim 0.6$ for three Pleiades dMe stars which may be pre-main-sequence. Assuming a stellar contraction age of 2×10^8 yr (Stauffer 1980), this limits the Li decay time to $< 4 \times 10^7$ yr for an initial log $n(\mathrm{Li}) = 3.0$. A similar value is derived by an (unjustified and questionable) extrapolation of the decay time determined by Duncan (1981) for G dwarfs to lower mass stars. In sum, the Li data, while confirming the youth of these stars and fixing their ages at less than a few times 10^7 yr, cannot be used to search for age differences between these and the T Tauri stars.

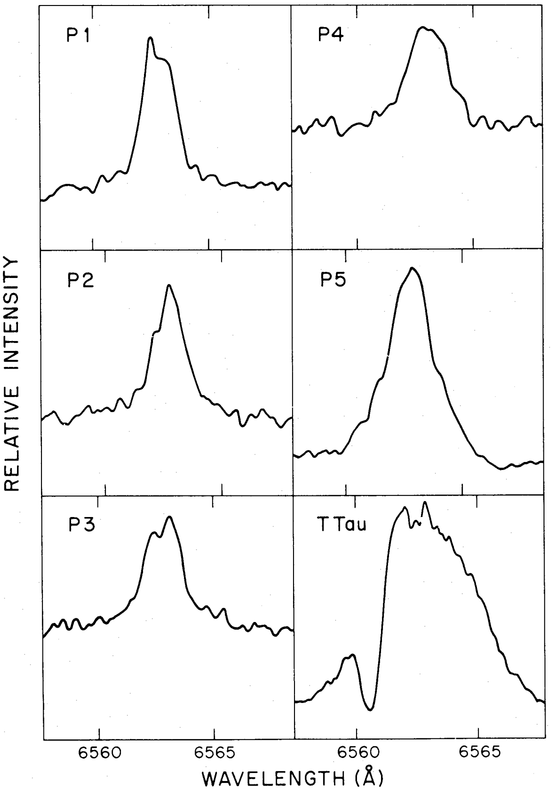

FIG. 4.—Hα line profiles of the five post-T Tauri stars, with T Tau itself included for comparison ($\Delta V = 20$ km s^{-1}).

All five stars display prominent Hα emission (see Table 4 and Figure 4). With the exception of P5, all have emission equivalent widths of a few Å. P5 appears

TABLE 4

PHYSICAL PARAMETERS

Star	Spectral Type	$R/R_\odot$	$V \sin i$ (km s^{-1})	Age (10^6 yr)	W(Li) (mÅ)	log n(Li)[a]	V_{abs}[b] (km s^{-1})	V_{Li}[c] (km s^{-1})	$V_{\mathrm{H\alpha}}$[d] (km s^{-1})	V_{cloud}[e] (km s^{-1})	$W_{\lambda(\mathrm{H\alpha})}$[f] (Å)	FWHM$_{\mathrm{H\alpha}}$ (Å)
P1......	K7 V	2.0	<15	2	790 ± 80	3.2 ± 0.1	12 ± 4	18.9 ± 3	4.0 ± 2	16.1 ± 0.1	3.4 ± 0.5	1.7
P2 A[g] ..	K7–M0 V	1.9	<10	3	750 ± 100	3.1 ± 0.2	30.0 ± 0.5	30.7 ± 2	6.4 ± 2	19.5 ± 0.1	3.2 ± 0.6	1.6
P2 B[g] ..	K7–M0 V	1.9	<10	3			4.7 ± 0.6	3.9 ± 2				
P3......	K7–M0 V	2.8	20–25	1	670 ± 60	3.0 ± 0.1	18 ± 4	19.1 ± 2	11.4 ± 3	19.5 ± 0.1	3.0 ± 1.0	1.8
P4......	K7–M0 V	2.3	25–30	1.5	620 ± 60	2.9 ± 0.1	19 ± 4	16.7 ± 3	17.2 ± 2	18.2 ± 0.1	2.4 ± 0.8	1.9
P5[h].....	K7–M0 V	1.9	<15	<4	690 ± 80	3.0 ± 0.1	... 13 ± 4	22.0 ± 2 ...	12.6 ± 2 5 ± 4	18 ± 0.5	8.8 ± 3.9[i]	2.0

[a] Li abundance, based on log n (all atoms) = 12, and an unpublished model atmosphere for $T_e = 4000$ K, log $g = 4.5$ (Eriksson, Gustafsson, and Bell 1983).

[b] Based on 34 Å mm^{-1} image tube coudé spectra.

[c] $\lambda_0(\mathrm{Li}) = 6707.785 \pm 0.03$ Å (Herbig 1977).

[d] Radial velocity measured using the center of gravity of the top half of the Hα emission line.

[e] From Dieter 1975.

[f] Errors are formal standard deviations from all measurements.

[g] Velocities measured on JD 2,444,923.71 (see Table 2 for ephemeris).

[h] A possible radial velocity variable; the two observations are presented.

[i] Variable, between 5 and 15 Å in seven observations.

more active with W_λ(Hα) between 5 and 14Å. We display the Hα profiles of these five stars in Figure 4, along with the Hα profile of T Tau for comparison (obtained at marginally higher resolution with the Mount Hopkins 60 inch [1.5 m] telescope). In contrast to T Tau and many other T Tauri stars, these five stars show relatively symmetric and narrow line profiles. The mean FWHM of the Hα emission lines is ~1.8 Å. For comparison, an average of 40 K5–M1 T Tauri stars in Taurus-Auriga (from Cohen and Kuhi 1979) has a Hα equivalent width of 57 Å; the FWHM of the Hα line in 15 of these stars is 5.3 Å (Mundt 1983*a*, *b*; Ulrich and Knapp 1982). Clearly these five stars are less active than the average T Tauri star. It is interesting to compare them to the dMe stars in the Pleiades, which have not yet reached the ZAMS (but see also Stauffer 1982), and which have contraction ages of $\sim 2 \times 10^8$ yr (Stauffer 1980). Fifteen of these stars have an average W_λ(Hα) of 2.2 Å (Stauffer 1980; Mundt and Bastian 1981), with an average FWHM of 1.8 Å in a sample of six stars (Mundt 1983*b*). Clearly these suspected PTT stars show Hα emission characteristics more like the young dMe stars than the T Tauri stars.

Another common indication of youth is stellar variability. T Tauri stars exhibit variability by up to a few magnitudes on almost all conceivable time scales (cf. Herbig and Rao 1972; Mundt and Giampapa 1982). Robinson and Kraft (1974) find that several young K and M dwarfs in the Pleiades are variable at low levels on time scales of a few days, while similar stars in the Hyades are not. BY Dra stars (cf. Bopp 1980), which are considered young stars because of their rapid rotation, show photometric periodicities attributed to rotational modulation of an inhomogeneous photosphere. Meys, Alphenaar, and van Leeuwen (1982) have recently identified a large number of rapidly rotating, BY Draconis-like stars in the Pleiades. One might expect these five stars to show variability at some intermediate level, yet these stars clearly cannot be as variable as the T Tauri stars, since they are not cataloged as variables, with the exception of P5, which is HV 6869 (Hoffleit 1935) and exhibits an amplitude $\Delta m_{\rm pg} \simeq 0^{\rm m}\!.5$. (However, other PMS stars likely to be in a similar evolutionary state, like V410 Tau and FK Ser (Herbig 1978), are variable.) Our investigation of this aspect of the PTT stars has taken two directions: examination of short time scale variability and searches in plate stacks for longer term changes.

Photometric *UBVRI* data on these stars are presented in Table 5. These data so indicated are from Rydgren, Schmelz, and Vrba (1982); other data were kindly obtained for us by Dr. W. Wisniewski using the University of Arizona 61 inch (1.5 m) telescope. Only P1 shows photometric and color variabilities at levels of 0.2 mag in these data. Rydgren and Vrba (1983*a*) have detected periodic light variations in P2 and P3 with, respectively, amplitudes of 0.1 and 0.2 mag, which they interpret as BY Draconis-like rotational modulation due to an asymmetric spot distribution.

Feigelson and Kriss (1981) searched the Harvard plate stacks for evidence of variability of P2, P3, and P5 and concluded that P5 was constant to within 0.5 mag, and P2 and P3 did not vary by more than 0.3 mag. We have repeated this procedure for all five stars with the plate stacks of the Landessternwarte Heidelberg (Gaida, Krautter, and Zekl 1979), using plates from the 40 cm Bruce twin astrograph. The plates date from ~1900 to the present, with 70% obtained prior to 1930. Between 8 and 15 plates were available for each star. Magnitude estimates were made against the comparison stars used by Badalian (1962) and Kholopov (1951). Stars P1, P3, and P5 exhibit no variability above $m_{\rm pg} \sim 0.3$ mag in these data. P2 shows marginal variability at the 0.3–0.5 mag level, and P4 is definitely variable, with a range of at least 0.5 mag and perhaps as much as a full magnitude. We note that P1 and P3 have been used as comparison stars by Badalian (1962) and Kholopov (1951).

Thus at least some of these stars do vary at low levels, as do the BY Dra and dMe stars, but they do not exhibit the large scale variability of the T Tauri stars, except perhaps in the case of P4. This strengthens the argument that these stars are young, but we cannot clearly distinguish them from the T Tauri stars, since

TABLE 5

COLOR DATA

Star	Data	V	$U-B$	$B-V$	$V-R$	$R-I$	A_v[a]	NOTE
P1	1982 Feb 20	13.50	1.40	1.55	1.58	1.30	1.3	
	1982 Feb 21	13.24	1.20	1.53	1.46	1.35	...	
P2	1980 Dec 15	12.15	1.17	1.37	...	...	0.4	1
	1981 Dec 30	12.15	1.16	1.41	1.21	1.04	...	
P3	1980 Dec 15	12.21	1.09	1.38	...	...	0.5	1
	1981 Dec 30	12.15	1.06	1.40	1.21	1.09	...	
P4	1982 Feb 20	12.26	1.14	1.46	1.26	0.95	0.3	
	1982 Feb 21	12.28	1.06	1.38	1.24	1.01	...	
P5	1981 Mar 10	13.17	1.28	1.53	1.38	1.17	0.8	1

NOTE.—(1) From Rydgren, Schmelz, and Vrba 1982; $V-R$ and $R-I$ colors for P5 have been transformed to the Johnson 1966 system using the transforms in Bessel 1979.

[a] From $R-I$ excess based on TiO band depth (Stauffer 1980).

there are T Tauri stars which exhibit only small amounts of variability for extended intervals (e.g., T Tauri itself).

Kraft (1967) and Skumanich (1972) showed that stellar rotation and age are correlated, with young stars rotating relatively rapidly. Vogel and Kuhi (1981) showed that low-mass T Tauri stars exhibit rotational velocities $V \sin i$ generally less than ~ 30 km s^{-1}. This is confirmed by Giampapa, Mundt, and Soderblom (1983), who observed a sample of 30 T Tauri stars and found the bulk exhibited 10 km s^{-1} $\leq V \sin i \leq$ 25 km s^{-1}, with the remaining 30% of the sample falling below the lower limit of $V \sin i \sim 10$ km s^{-1}. Post–T Tauri stars should show similar rotational velocities, if they are of comparable ages. Absorption line widths indicate that P3 and P4 are rotating with $V \sin i$ of $\sim$20–25 and $\sim$25–30 km s^{-1}, respectively. From the stellar radii and inclination deduced for the two components of the binary P2, assuming synchronous rotation, $V \sim 22$ km s^{-1}. Upper limits for the other stars are given in Table 4.

Finally, the X-ray flux from these stars is comparable to that from the chromospherically least active T Tauri stars and chromospherically most active main-sequence stars (Walter and Kuhi 1981). The X-ray fluxes from P2 and P3 indicate that these stars obey the coronal rotation-activity relation for K dwarfs (Walter 1982). Using this relation, X-ray fluxes from the other three stars indicate that they also rotate in about 4 days, which is consistent with the observed measures of $V \sin i$.

All these observations are consistent with the notion that these stars are pre–main-sequence stars. They are not as active as the T Tauri stars, being more like the dMe stars in certain aspects. They can be interpreted as an evolutionary successors of the T Tauri stars. However, it is also possible that these stars are merely dormant T Tauri stars, between periods of strong activity.

V. PHYSICAL CHARACTERISTICS OF THESE STARS

In the following discussion we have attempted to use all the color data and spectral information at hand to deduce the radii, masses, and ages of these stars. However, reliable estimation of these parameters is hampered by the lack of a reliable extinction determination from the broad-band colors, due to apparent intrinsic color excesses in these stars, insufficient knowledge of the intrinsic colors of pre–main-sequence stars, and the lack of long-wavelength IR magnitude for many of these stars. We have investigated two color diagrams ($U-B$, $B-V$, and $V-R$ vs. $R-I$) for these stars and find that their locations cannot be explained simply by reddening of a main-sequence star or subgiant. Since color excesses due to stellar activity are strongest in the blue, we have based our extinction measurements upon the $R-I$ indices. We determined the intrinsic $R-I$ colors from the correlation of Johnson's (1966) $R-I$ colors with the TiO band strength near $\lambda\lambda 6200$ (Stauffer 1980). The computed values of A_v, given in Table 5, are $\sim$0.3–0.8 mag, except for P1, which appears to suffer more than a magnitude of extinction.

The reliability of these A_v values depends to some extent upon the applicability of the correlation between TiO band strength and $R-I$ colors among pre–main-sequence stars. It is worth noting that these $R-I$ colors suggest spectral types of K7–M0 for P2–P5, while the coudé spectra suggest systematically earlier K7 spectral types. The latter may be attributable to the reduced surface gravity, relative to a dwarf, of these stars. Adoption of the earlier spectral types would increase the values of A_v in Table 5 by 20% to 50% ($\sim$0.2 mag).

Based on these values for A_v, all the stars show significant color excesses, of $\sim$0.2–0.5 mag in $U-B$, $\sim$0.1–0.2 mag in $B-V$, and $\sim$0.2 mag in $V-R$. We estimate radii using the Barnes-Evans (1976) relation and the $V-R$ color after correcting for A_v and the $V-R$ color excess. We have also placed the stars in the H-R diagram, using isochrones of Cohen and Kuhi (1979, Fig. 7) to estimate ages, masses, and provide another estimate of the stellar radius. In placing the stars in the H-R diagram, we have assumed that the bolometric corrections are similar to those of main-sequence stars.

P1.—This is the faintest of the five stars, with $m_v \sim 13.3$ mag. The spectral type is $\sim$K4 Ve from the coudé spectra, and K7 from the spectrophotometry. The depth of the TiO band indicates $(R-I) \lesssim 0.85$ (K7 if on the main sequence, slightly earlier if above the main sequence), and $A_v \sim 1.3$ mag. This large value of A_v indicates that this star is presumably not entirely clear of the nearby dark cloud and accounts for the low apparent luminosity. This star has an intrinsic $E(U-B) \sim 0.5$ mag, assuming K7 main-sequence colors. The stellar radius, using the Barnes-Evans relation with $V-R$ corrected for the intrinsic excess, is $\sim 2.0\ R_\odot$.

P2.—This is the binary discussed in § III. The spectral type of each star is K7–M0. The TiO bands indicate $A_v \sim 0.4$ mag and an intrinsic $E(U-B)$ of $\sim$0.25 mag. The stellar radii are $\sim 1.9\ R_\odot$. Rydgren, Schmelz, and Vrba (1982) find no significant IR excess for $\lambda \leq 3.5\ \mu$m, and by inference little hot circumstellar dust around this star. Orbital parameters have been discussed in § III.

P3.—The spectral type of this star is K7–M0, with $A_v \sim 0.5$ mag. The intrinsic color excesses are nearly identical to those of P1. This star has a $3^{d}.63$ photometric period (Rydgren and Vrba 1983*a*); our measurement of $V \sin i$ gives $R > 1.6\ R_\odot$. The radius from the Barnes-Evans relation is $\sim 2.8\ R_\odot$, which yields $V \sim 40$ km s^{-1}. Rydgren, Schmelz, and Vrba (1982) find no IR excess for $\lambda \leq 3.5\ \mu$m in this star.

P4.—The spectral type is K7–M0; $A_v = 0.3$ mag. The colors are similar to P2. The stellar radius is $\sim 2.3\ R_\odot$.

P5.—This star has the strongest Hα line of this sample and may be more T Tauri-like than the others. Rydgren and Vrba (1983*a*) report evidence for emission from circumstellar dust. The spectral type is also K7–M0, $A_v \sim 0.8$ mag. The stellar radius is $\sim 1.9\ R_\odot$. We note that the radial velocities determined from different spectral features on two coudé and echelle plates differ significantly (see Table 4); this star may also be a member of a close binary system.

By placing these stars on an H-R diagram with evolutionary tracks and isochrones, we can estimate other stellar parameters. Since they are all of approximately the same spectral type, these stars are all of mass $\sim 0.6\ M_\odot$, except that P1 may be ~ 0.1–$0.2\ M_\odot$ more massive if it really is of an earlier spectral type. The stellar ages, inferred using the isochrones published by Cohen and Kuhi (1979, Fig. 7) range from $\sim 1 \times 10^6$ yr for the largest stars (P3, P4) to $\sim 3 \times 10^6$ yr for P2 and P5. P1 is $\sim 2 \times 10^6$ yr old. The radii inferred from the locations in the H-R diagram are consistent with the radii inferred above using the Barnes-Evans relation.

Were it not for their bright coronae, these particular stars would likely remain undiscovered. All five were detected as serendipitous X-ray sources with the *Einstein Observatory*, at X-ray luminosities of $\sim 10^{30}$ ergs s^{-1}. This bright coronal and chromospheric emission provides further clues to the nature of these stars. The observed X-ray surface fluxes in these stars are comparable to those of the most active main sequence and evolved late-type stars (Walter and Bowyer 1981; Walter 1982). In fact, there is no significant difference between the X-ray fluxes and spectra of the T Tauri stars, rapidly rotating late-type main-sequence stars, and these five stars. It is likely that the coronae of these five stars are solar-like, in that they are small relative to the stellar radius, as suggested for the T Tauri stars (Walter and Kuhi 1981), and confined by magnetic flux tubes. This contention is supported because the X-ray surface flux for the two stars with measured rotational periods (P2, P3) falls on the K star $L_x/L_{\rm bol}$-Ω relation (Walter 1982).

The Hα line, when compared to the lines in T Tauri and dMe stars, also reveals insights into the nature of these stars. The Hα line in three of these stars tends to be blueshifted relative to the photospheric absorption lines by some 10 km s^{-1} (see Table 4). There is no shift in P4, and in the binary P2 the emission may arise on the B component (the same component hypothesized to have the strong veiling in § III). In addition, all the Hα lines are narrow (see § IV) relative to the Hα lines of many T Tauri stars. A likely interpretation is that the Hα emission arises in a compact, chromosphere-like region, and that in the three stars with blueshifted emission we are seeing the effect of a stellar wind with the receding part of the emission occulted by the star. Such a blueshift is not observed in dMe stars (M. Giampapa and L. Hartmann, private communication). In T Tauri stars the Hα emission is likely to arise in a large expanding envelope. The weak and narrow Hα lines in these five stars suggest that mass loss rates in these stars is far lower than those in T Tauri stars and that these stars are indeed intermediate in character between the T Tauri and dMe stars.

VI. ON THE EVOLUTIONARY STATUS OF THE SUSPECTED POST–T TAURI STARS

The data we have presented argues strongly that these five stars show characteristics intermediate between the T Tauri stars and the dMe stars. In fact, they display all the characteristics laid out by Herbig (1978) (see § I) for the post–T Tauri stars. However, we are unable to demonstrate conclusively that these stars are significantly older than the T Tauri stars. Thus it is not clear whether these are true post–T Tauri stars, or whether they are bonafide T Tauri stars undergoing a long hiatus in their activity.

In order to compare the underlying stellar luminosity of these suspected post–T Tauri stars and T Tauri stars, we plot $m_v - A_v$ in Figure 5 for these stars and the T Tauri stars in Taurus-Auriga observed by Cohen and Kuhi (1979). At a given spectral type, differences in $m_v - A_v$ should indicate differences in stellar radius. The more evolved stars would be expected to have smaller radii and $m_v - A_v$, provided that pre-main-sequence stars of the same spectral type have nearly the same effective temperature and that all the stars have dust with similar absorption properties. The suspected PTT stars do not lie below the T Tauri stars but do fall toward the lower end of the distribution. We conclude that these suspected PTT stars appear to be neither significantly smaller nor older than all the T Tauri stars.

The significance of this result is open to question,

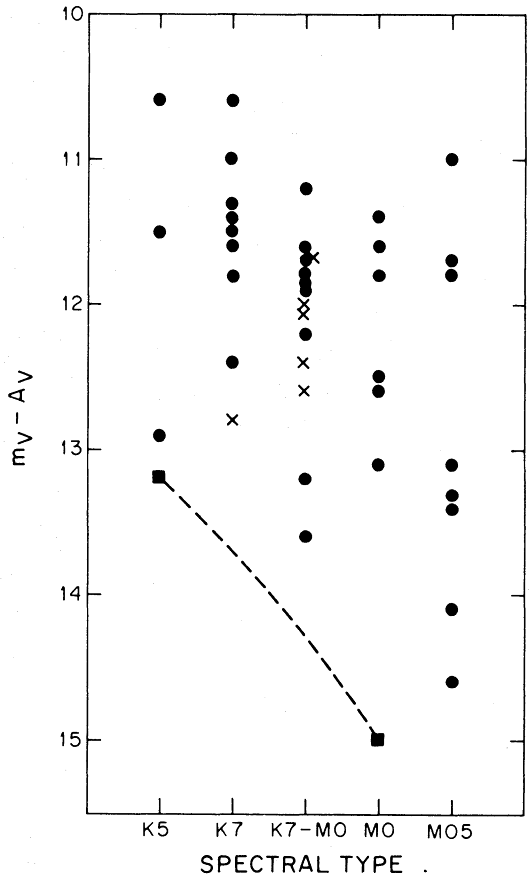

FIG. 5.—Visual magnitude ($m_v - A_v$) for the T Tauri and post–T Tauri stars in the Taurus-Auriga dark cloud complex. At a given spectral type, $m_v - A_v$ should scale with the stellar radius. The post–T Tauri stars (×) tend to fall at the low end of the distribution of the T Tauri stars (·) observed by Cohen and Kuhi 1979 but are not significantly smaller (hence closer to the ZAMS) than the T Tauri stars.

as the Herbig and Rao (1972) and Cohen and Kuhi (1979) samples may not be complete for the fainter stars. However, a number of lines of evidence indicate that the fraction of post–T Tauri stars is fairly well known, in which case their systematically low $m_v - A_v$ may be significant. Cohen and Kuhi (1979) found that the ratio of weak or nonemission Taurus association members, essentially the ratio of post–T Tauri to T Tauri stars, is $\sim$0.2. Jones and Herbig (1979), in a proper motion survey which avoided spectroscopic selection effects which tend to bias results toward the emission-line objects, deduced a similar ratio of 0.26 ± 0.1. The ~ 12 deg^2 of the Taurus-Auriga T association surveyed in X-rays includes 28 stars in the Herbig-Rao (1972) catalog. One is a hot member of the Orion population (AB Aur), two are of type m, one is unclassified, and the remaining 24 are T Tauri stars. Including the stars of type m with the T Tauri stars, we find that $n(\text{PTT})/n(\text{T Tau}) = 5/26 = 0.19$, which is in good agreement with the other results. This confirms earlier conclusions that there are indeed few post–T Tauri stars in Taurus-Auriga. Assuming that the two groups have similar distributions of A_v, this suggests that the post–T Tauri stars do tend to have smaller radii on the whole than the T Tauri stars.

Additionally, these five weak emission PMS stars apparently do not rotate significantly slower than other PMS stars, with $P \sim 4^d$ (Rydgren and Vrba 1983*a*) and $V_{\text{rot}} \sim 20$–30 km s^{-1}. Hence, the emission characteristics cannot depend solely on the stellar rotation rate. One must look elsewhere for the difference between the T Tauri stars and these suspected PTT stars.

The main difference between these suspected PTT stars and the T Tauri stars appears to be in their apparent lack of significant amounts of circumstellar gas and dust. This may be the result of lower mass loss rates among these stars, since high mass loss T Tauri stars are expected to have, and indeed exhibit, numerous strong emission lines (e.g., Kuhi 1964; Mundt 1983*a*). This then redirects the question of where these weak emission PMS stars fall on an evolutionary sequence to the question of why they show low mass loss.

Mundt (1983*a*) has observed indications for strong variations in the properties of T Tauri winds. It may be that episodes of high mass loss rates are superposed upon episodes of lesser activity. This suggests the hypothesis that these suspected PTT stars may some day turn back on and acquire true T Tauri characteristics. Another alternative is that these particular stars may never have had the high activity levels exhibited by the T Tauri stars, perhaps as a result of the environment wherein they were formed. In any event, at this epoch these five stars, along with stars like V410 Tau and FK Ser, do appear to be more evolved than the T Tauri stars and appear to be examples of the elusive post–T Tauri stars.

These stars may not be the oldest of the Taurus population. The difficulty in picking out older, less active stars is aggravated above and beyond the difficulty of finding stars like these PTT stars. Older stars would have smaller radii, and hence would be less luminous by perhaps 1–2 mag. Because L_x/L_{bol} decreases linearly with the stellar angular velocity, at least for ages up to $\sim 10^9$ yr (Walter 1982), such stars should still be bright X-ray sources. Presumably X-ray surveys would be the best way to find them, but the same X-ray observations quoted here can be used to place limits on the numbers of such stars. At 90% confidence, based on no detections in 12 deg^2, the projected space density of older, X-ray bright members of the Taurus population is <0.18 per square degree, while the PTT stars discussed here have a projected density of $0.22 \le N \le 0.64$ per square degree at 90% confidence. If one adds these PTT stars to the histogram of ages (Cohen and Kuhi 1979, Fig. 9) of the Taurus population, the view that star formation turned on rather abruptly about 5×10^6 yr ago then remained constant is reinforced. As also concluded by Jones and Herbig (1979), it is likely that there are no significantly older or less active members of the Taurus population.

From the X-ray observations there appear to be significantly more T Tauri stars than post–T Tauri stars in Taurus despite the expected small ratio for a molecular cloud complex in which star formation proceeds for one or more Kelvin times. This suggests that the Taurus population is not old enough to have reached this stage.

Parts of this work would not have been possible without the help of several colleagues. One of us (R. M.) is especially indebted to Drs. R. Green, D. Latham, and J. Liebert for taking additional spectra of the binary P2 during their observations. Dr. D. Latham in addition reduced a considerable fraction of the binary data, and Dr. D. Monet provided the computer program to compute the orbital elements. We also acknowledge the *UBVRI* measurements carried out for us by Dr. W. Wisniewski at the University of Arizona 61 inch (1.5 m) telescope at Mount Lemmon. In addition, we thank Dr. E. Rydgren for fruitful discussions and for communicating his results prior to publication, and Dr. D. Duncan who provided us with valuable unpublished information. R. M. is grateful for support by the Deutsch Forschungsgemeinschaft (DFG grant MU 56411). E. F. is grateful for support from grant NAS8-30752. U. F. is grateful for support by the SFB 132.

REFERENCES

Badalian, H. S. 1962, *Soobsčh. Bjurakan Obs.*, **31**, 57.
Barnes, T. G., and Evans, D. S. 1976, *M.N.R.A.S.*, **174**, 489.
Bessel, M. S. 1979, *Pub. ASP*, **91**, 589.
Bopp, B. 1980, *Highlights Astr.*, **5**, 847.
Cohen, M., and Kuhi, L. V. 1979, *Ap. J. Suppl.*, **41**, 743.
Dieter, N. 1975, *Ap. J.*, **199**, 289.
Duncan, D. 1981, *Ap. J.*, **248**, 651.
Eriksson, K., Gustafsson, B., and Bell, R. A. 1983, in preparation.
Feigelson, E. D., and Kriss, G. A. 1981, *Ap. J.* (*Letters*), **248**, L35.
Gaida, G., Krautter, J., and Zekl, H. 1979, *Astr. Ap. Suppl.*, **37**, 465.

Giampapa, M. S., Mundt, R., and Soderblom, D. 1983, in preparation.
Giampapa, M. S., Worden, S. P., and Gilliam, L. B. 1979, *Ap. J.*, **229**, 1143.
Herbig, G. H. 1973, *Ap. J.*, **182**, 129.
———. 1977, *Ap. J.*, **214**, 747.
———. 1978, in *Problems of Physics and Evolution of the Universe* (Yervan: Academy of Sciences of the Armenian SSR), p. 171.
Herbig, G. H., and Rao, N. K. 1972, *Ap. J.*, **174**, 401.
Hoffleit, D. 1935, *Harvard College Obs. Bull.*, No. 901, p. 20.
Johnson, H. 1966, *Ann. Rev. Astr. Ap.*, **4**, 193.
Jones, B. F., and Herbig, G. H. 1979, *A.J.*, **84**, 1872.
Kraft, R. P. 1967, *Ap. J.*, **150**, 551.
Kholopov, P. N. 1951, *Peremennye Zvezdy*, **8**, 83.
Kuhi, L. V. 1964, *Ap. J.*, **140**, 1409.
Latham, D. W. 1982, in *IAU Colloquium 67, Instrumentation for Large Telescopes*, ed. C. Humphries (Dordrecht: Reidel), in press.
Lucy, L. B., and Ricco, E. 1979, *A.J.*, **84**, 401.
Meys, J. J. M., Alphenaar, P., and van Leeuwen, F. 1982, *Inf. Bull. Var. Stars*, No. 2115.
Mundt, R. 1983*a*, *Ap. J.*, submitted.
———. 1983*b*, in preparation.
Mundt, R., and Bastian, U. 1981, *Pub. A.S.P.*, **93**, 601.
Mundt, R., and Giampapa, M. S. 1982, *Ap. J.*, **256**, 156.
Mundt, R., and Hartmann, L. 1983, *Ap. J.*, **268**, in press.
Robinson, E. L., and Kraft, R. R. 1974, *A.J.*, **79**, 698.
Robinson, E. L., and Wampler, E. J. 1972, *Pub. A.S.P.*, **84**, 161.
Rydgren, A. E., Schmelz, J. T., and Vrba, F. J. 1982, *Ap. J.*, **256**, 168.
Rydgren, A. E., and Vrba, F. J. 1983*a*, *Ap. J.*, **267**, 191.
———. 1983*b*, *A.J.*, submitted.
Scharlemann, E. T. 1981, *Ap. J.*, **246**, 292.
Schectman, S., and Hiltner, W. A. 1976, *Pub. A.S.P.*, **88**, 960.
Skumanich, A. 1972, *Ap. J.*, **171**, 565.
Stauffer, J. R. 1980, *A.J.*, **85**, 1341.
———. 1982, *A.J.*, submitted.
Ulrich, R. K., and Knapp, G. R. 1983, in preparation.
Vogel, S. N., and Kuhi, L. V. 1981, *Ap. J.*, **245**, 960.
Walter, F. M. 1982, *Ap. J.*, **253**, 745.
Walter, F. M., and Bowyer, S. 1981, *Ap. J.*, **245**, 671.
Walter, F. M., and Kuhi, L. V. 1981, *Ap. J.*, **250**, 254.

ERIC D. FEIGELSON: Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139

ULRICH FINKENZELLER: Landessternwarte, Königstuhl, D-6900 Heidelberg 1, West Germany

GEORGE H. HERBIG: Lick Observatory, University of California, Santa Cruz, CA 95064

REINHARD MUNDT: Max-Planck-Institut für Astronomie, Königstuhl, D-6900 Heidelberg, West Germany

ANDREW P. ODELL: Department of Physics and Astronomy, Northern Arizona University, Flagstaff, AZ 86001

FREDERICK M. WALTER: Joint Institute for Laboratory Astrophysics, University of Colorado, Mail Code 440, Boulder, CO 80309

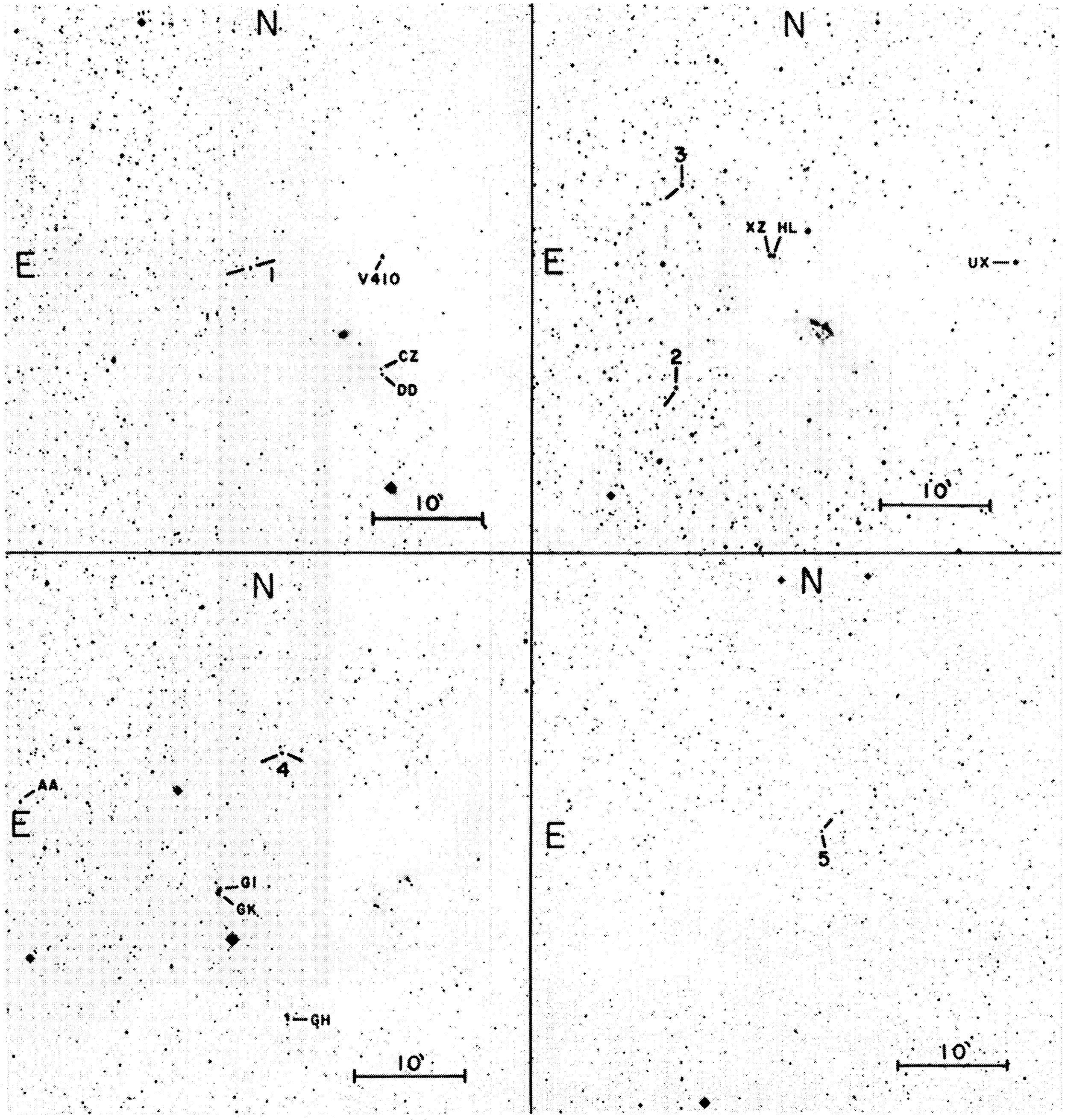

FIG. 1.—Finding charts for the five suspected post-T Tauri stars. We have indicated prominent nearby T Tauri stars. Note the proximity of the post-T Tauri stars to the dark clouds. These figures are enlargements of the POSS red plates.

MUNDT *et al.* (*see* page 230)