THE ASTRONOMICAL JOURNAL VOLUME 96, NUMBER 6 DECEMBER 1988

PARENAGO 1540: A PRE-MAIN-SEQUENCE DOUBLE-LINED SPECTROSCOPIC BINARY NEAR THE ORION TRAPEZIUM[a)]

LAURENCE A. MARSCHALL[b)]
Gettysburg College, Gettysburg, Pennsylvania 17325
and
Harvard–Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138

ROBERT D. MATHIEU
Harvard–Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138

Received 1 June 1988; revised 9 August 1988

ABSTRACT

Spectroscopic and photometric observations of the star Parenago 1540 ($V = 11.3$), located 10 arcmin west of the Trapezium in Orion, have shown the star to be a pre-main-sequence double-lined spectroscopic binary. Thirty-seven radial-velocity measurements were obtained from which the orbital elements of the binary were determined, in particular an orbital period $P = 33.73 \pm 0.03$ days and an eccentricity of $e = 0.12 \pm 0.01$. High-dispersion spectra reveal strong Li 6707 Å absorption lines in each of the components of P1540. A spectrum at lower dispersion also shows strong Ca II H and K emission lines, not resolved into individual components. P1540 also has an x-ray emission of 4×10^{30} ergs s^{-1}. *UBVRI* photometry, combined with relative luminosities at V determined from spectra, have been used to determine the locus of each component in the theoretical H–R diagram. Assuming membership in the Orion star-forming region, both stars lie substantially above the ZAMS in the pre-main-sequence domain of the diagram. All of these data support the conclusion that both components of P1540 are pre-main-sequence stars. The masses of the individual components, determined from theoretical evolutionary tracks and the requirement of satisfying the dynamical mass ratio, are approximately 2.25 $\mathscr{M}_\odot$ and 1.7 $\mathscr{M}_\odot$. Interestingly, no pair of stars satisfying both the dynamical and photometric constraints is compatible with coeval formation of the stars. If coeval formation is demanded, then the pre-main-sequence evolutionary tracks of the components of P1540 are not consistent with theoretical single-star evolutionary tracks presented by Cohen and Kuhi. Alternatively, the noncoevality of the components of P1540 might be attributed to an exchange occurring during a close stellar encounter. The space velocity of P1540 indicates that the binary is escaping from the Orion Nebula region, perhaps as the result of such a close encounter in the Trapezium cluster.

I. INTRODUCTION

Observations of double-lined spectroscopic binary stars provide a large share of the data on which we base our knowledge of stellar masses. Unfortunately, orbits have been determined for only two low-mass pre-main-sequence (PMS) double-lined spectroscopic binaries. The first of these is the star V826 Tau (Mundt *et al.* 1983). This system consists of two PMS stars of nearly equal mass ($0.6\mathscr{M}_\odot$) in a 3.9 day circular orbit. Recently, a second candidate PMS binary was independently discovered by de la Reza *et al.* (1986) and by Byrne (1986). That object, V4046 Sgr (HDE 319139), also consists of two stars of nearly equal mass ($0.7\mathscr{M}_\odot$) in a 2.42 day circular orbit.

This paper reports the discovery of a third PMS double-lined spectroscopic binary. Designated as star 1540 in the Parenago (1954) proper-motion and photometric survey of the Orion Nebula region, it is located approximately 10 arcmin to the west of the Trapezium ($\alpha = 5^h32^m12.3^s$, $\delta = -5°26'30''$ (1950); $V = 11.33$). It differs from both V826 Tau and V4046 Sgr in having a longer period (33.7^d), an eccentric orbit ($e = 0.12$), and two components of unequal mass ($\mathscr{M}_p/\mathscr{M}_s = 1.3$).

II. RADIAL-VELOCITY OBSERVATIONS

The double-lined nature of the spectrum of P1540 was first noted during a radial-velocity survey of stars in the vicinity of the Trapezium, begun by the authors in the autumn of 1985. Most of the subsequent radial-velocity measurements were obtained from spectra taken during the 1986–1987 observing season. Thirty-seven high-resolution (10 km s^{-1}) spectra, each covering a region 45 Å wide centered on 5187 Å (or, in a few cases, 5197 Å), were obtained with nearly identical echelle spectrographs and photon-counting detectors at three telescopes: the 1.5 m Tillinghast reflector at the Fred L. Whipple Observatory (FLWO), the 1.5 m Wyeth reflector at the Oak Ridge Observatory (ORO), and the Multiple Mirror Telescope (MMT). Most of the spectra had total photon counts of 40 000–60 000 (approximately 30 counts/pixel, or 180 counts/resolution element).

Details of the reduction and velocity-measurement procedures have been presented elsewhere (Latham 1985; Mathieu *et al.* 1986). The digital spectra were cross-correlated with a very high-signal-to-noise template spectrum of the dusk sky. The resulting correlation spectra showed two peaks (except at velocity crossings), the primary peak typically twice the height of the secondary peak. The individual correlation peaks showed no evidence of rotational broadening, placing an upper limit on $v \sin i$ of 15 km s^{-1}. Radial-velocity measurements were derived from the correlation spectra in three ways, depending on the velocity separation of the components. When the binary components were widely separated in velocity ($\Delta V > 30$ km s^{-1}), the two correla-

---

[a)] Some of the observations reported herein were obtained with the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona.

[b)] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, which is operated by AURA, Inc., under contract with the National Science Foundation.

0004-6256/88/061956-09$00.90

tion peaks were treated independently and the velocities were obtained by fitting Gaussian profiles to each peak. Typical single-measurement errors in these cases were 1.5–2.0 km s^{-1}. When the velocity separation of the two components was between 20 and 30 km s^{-1}, the correlation peak was a blend of the two components, with each component remaining identifiable. In these cases, the two components were determined by fitting the sum of two Gaussian profiles to the blend. The errors in velocities derived from such blended peaks may be as high as 3–4 km s^{-1} (Mathieu *et al.* 1986). Finally, when the velocity difference between the primary and secondary was less than 20 km s^{-1}, the blended peak could not be deconvolved unambiguously. For such observations, a velocity was derived by fitting a single Gaussian to the correlation peak, and the resulting velocity assigned to both primary and secondary. The velocities for each component are uncertain by ~ 10 km s^{-1} in these cases, and we have not included these measurements in the orbit calculations.

In Table I, we list the heliocentric radial-velocity measurements of P1540. The Julian date and phase (calculated from time of periastron) are listed in columns 1 and 2, and the radial velocities of the primary and secondary, along with the deviations from the fit orbit, are given in columns 3–6. Weights used in computing the orbital elements are listed in column 7, while column 8 indicates the quality of the correlation peak(s) from which the radial velocities were derived: S indicates two separate peaks and B indicates blended peaks. Observations near radial-velocity crossings (unresolved correlation peaks) were accorded zero weight in the orbit solutions, and one observation, of low signal-to-noise and obtained at very large hour angle, is given a weight of 0.5.

Orbital elements were derived from these data using an iterative program that computes elements for the primary and secondary simultaneously (kindly provided by Dr. B. Bopp). The orbital elements are presented in Table II, along with the rms difference between the calculated and observed velocities for both primary and secondary. In the table, T is the epoch of periastron. The solution is plotted as a solid line in Fig. 1, with radial-velocity observations of the primary represented as dark triangles, of the secondary as ×'s, and unresolved blended observations as light circles. The orbit of P1540 differs from that of both V826 Tau and V4046 Sgr in

TABLE I. Radial-velocity measurements of Parenago 1540.

Julian Day (240000 +)	Phase	V_p (km s^{-1})	O − C (km s^{-1})	V_s (km s^{-1})	O − C (km s^{-1})	Wt	Q	Telescope
46429.75	0.1876	− 5.9	− 1.7	51.8	− 0.7	1.0	S	FLWO
46778.86	0.5372	38.2	− 0.6	− 2.6	1.9	1.0	B	FLWO
46786.67	0.7687	41.9	1.9	− 4.3	1.8	1.0	S	ORO
46801.76	0.2160	− 1.4	− 0.3	49.2	0.6	1.0	S	FLWO
46802.71	0.2442	2.9	0.6	41.9	− 2.1	1.0	B	FLWO
46804.70	0.3031	11.4	1.1	30.9	− 2.4	1.0	B	FLWO
46805.75	0.3344	20.5	5.7	20.5	− 6.9	0.0	B	MMT
46806.77	0.3644	21.2	2.2	21.2	− 0.6	0.0	B	MMT
46807.79	0.3947	20.9	− 2.2	20.9	4.6	0.0	B	MMT
46808.67	0.4209	20.5	− 6.0	20.5	8.7	0.0	B	MMT
46814.74	0.6008	42.7	− 0.2	− 12.0	− 2.1	1.0	S	MMT
46815.68	0.6286	44.1	0.2	− 12.3	− 1.1	1.0	S	FLWO
46816.73	0.6598	44.4	0.0	16.9	− 4.9	1.0	S	FLWO
46834.66	0.1914	− 2.8	1.0	52.6	0.5	1.0	S	FLWO
46835.66	0.2210	− 0.7	− 0.1	48.6	0.8	1.0	S	FLWO
46836.63	0.2496	4.2	1.3	44.8	1.7	1.0	B	FLWO
46837.71	0.2817	10.2	2.8	35.1	− 2.2	1.0	B	FLWO
46838.73	0.3120	20.1	8.5	20.1	− 11.5	0.0	B	FLWO
46839.66	0.3396	20.2	4.7	20.2	− 6.2	0.0	B	FLWO
46840.57	0.3666	22.0	2.7	22.0	0.6	0.0	B	ORO
46842.56	0.4255	21.6	− 5.4	21.6	10.6	0.0	B	ORO
46842.64	0.4280	20.2	− 7.3	20.2	9.6	0.0	B	FLWO
46844.60	0.4861	33.0	− 1.0	4.4	2.6	1.0	B	FLWO
46845.61	0.5160	37.5	0.6	− 0.8	1.3	1.0	B	FLWO
46847.60	0.5747	41.3	− 0.2	− 7.7	0.4	1.0	S	ORO
46849.52	0.6317	43.2	− 0.7	− 12.7	− 1.3	1.0	S	ORO
46862.61	0.0200	− 2.8	− 0.5	45.3	− 4.8	0.5	S	ORO
46862.67	0.0218	− 4.6	− 2.0	49.7	− 0.7	1.0	S	FLWO
46866.63	0.1391	− 7.3	0.3	56.9	− 0.3	1.0	S	FLWO
46867.71	0.1710	− 5.1	0.5	45.3	1.3	1.0	S	FLWO
46889.64	0.8213	34.0	0.2	5.7	3.5	1.0	B	FLWO
46891.65	0.8807	21.4	− 2.3	21.4	5.9	0.0	B	FLWO
46892.64	0.9103	22.1	4.2	22.1	− 1.2	0.0	B	FLWO
46894.64	0.9695	9.3	3.3	38.2	− 0.8	1.0	B	FLWO
46895.63	0.9989	1.3	0.5	45.4	− 0.5	1.0	B	FLWO
46896.54	0.0256	− 5.8	− 2.7	51.4	0.3	1.0	B	ORO
46900.62	0.1466	− 7.4	− 0.1	56.5	− 0.1	1.0	S	FLWO

TABLE II. Orbital elements of Parenago 1540.

Element		Value	+/−
P days		33.73	0.030
T (J.D. + 2400000)		44972.95	1.75
ω (°)		131.3	6.7
e		0.12	0.01
γ (km s^{-1})		20.2	0.3
K (km s^{-1})	Primary	26.4	0.5
	Secondary	34.9	1.0
$\mathscr{M}_1/\mathscr{M}_2$		1.32	0.03
$a \sin i$ ($\times 10^6$ km)	Primary	12.14	0.22
	Secondary	16.01	0.46
$m \sin^3 i$ ($\mathscr{M}_\odot$)	Primary	0.45	0.02
	Secondary	0.34	0.01
rms error (km s^{-1})	Primary	1.3	
	Secondary	1.8	

every essential respect, having longer period (33.73 days), nonzero eccentricity ($e = 0.12$), and components of differing mass ($\mathscr{M}_1/\mathscr{M}_2 = 1.3$). However, its orbital characteristics are not remarkable when compared to the field population of binaries.

III. PHOTOMETRY OF P1540

In January and December 1987, *B*, *V*, *R*, and *I* CCD frames of the field of P1540 were obtained with the 0.61 m telescope at FLWO by Dr. R. Schild. Instrumental magnitudes were reduced to the Kron–Cousins system using a single observation in each filter of a standard photometric field in M67 (Schild 1985). The derived *BVRI* magnitudes for P1540 are presented in Table III. As we note later, this photometry has been confirmed with independent photoelectric observations; we estimate the 90% confidence limit to be 0.02 mag. In addition, single *JHKL* observations were obtained by Vrba (private communication) at the KPNO 1.3 m telescope using the Otto detector. These data are also presented in Table III. Errors in *JHK* magnitudes are 0.02 mag. The error in the *L* magnitude is 0.15 mag.

TABLE III. Photometric measurements of Parenago 1540.

V	$B-V$	$V-R$	$R-I$	$J-H$	$H-K$	K	$K-L$
11.33	1.28	0.73	0.76	0.72	0.17	8.02	0.13

IV. THE YOUTH OF P1540

Young low-mass stars are normally distinguished by a combination of observational characteristics: higher luminosity than main-sequence stars of the same effective temperature, light variability, excess ultraviolet and infrared emission, x-ray emission, chromospheric emission (notably Ca II H and K and Hα), and strong Li absorption lines. Although these properties are most evident in T Tauri stars, which are surrounded by circumstellar material, many are also present in the naked T Tauri stars (NTTS; Walter 1987). Unlike T Tauri stars, the NTTS do not typically have ultraviolet and infrared excesses or very strong Hα emission, but they are distinguishable as x-ray sources with chromospheric emission and Li absorption, and they share the photometric characteristics and the association with star-forming regions of the classical T Tauri stars.

The components of P1540 have properties typical of NTTS. While the inclusion of P1540 in our observing program was not based on x-ray emission, P1540 was in fact detected at the 4.6σ level by the *Einstein Observatory* High-Resolution Imager. The x-ray flux (corrected for absorption assuming a 1 keV thermal spectrum) was 1.4×10^{-13} ergs cm^{-2} s^{-1}; at the distance of the Trapezium (470 pc; Jones and Walker 1988), this represents a flux of 4×10^{30} ergs^{-1}. This luminosity is typical of NTTS (Feigelson and Kriss 1981; Walter and Kuhi 1981; Walter 1987).

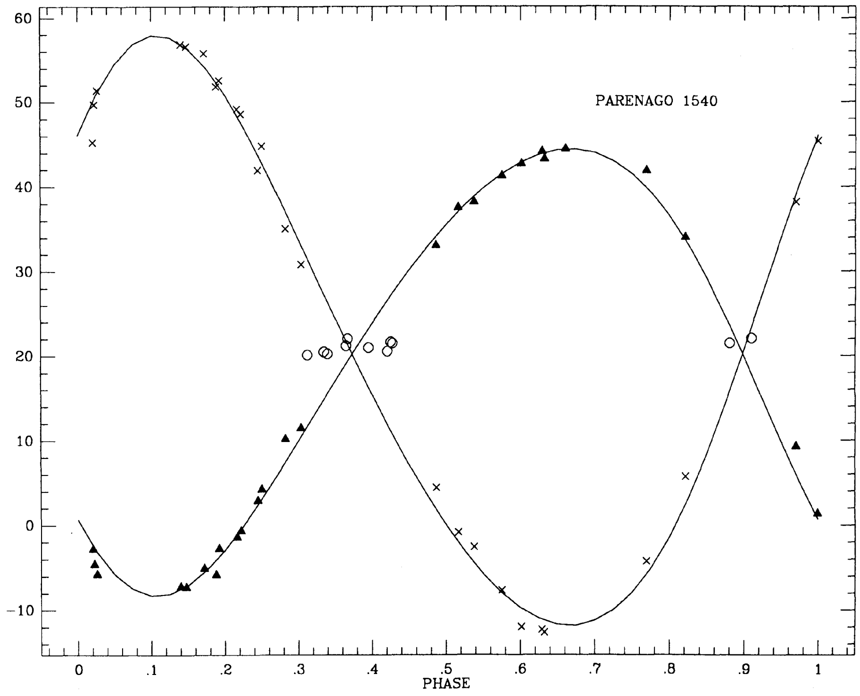

FIG. 1. Measured heliocentric radial velocities of both components of P1540 and radial-velocity curves derived from the best-fit orbit solution, both plotted against orbital phase. Dark triangles represent observations of the primary and ×'s are observations of the secondary. The light circles are observations made near radial-velocity crossings (unresolved correlation peaks). These blended observations were given zero weight in the orbital solutions.

Dr. F. Walter* has kindly provided a blue spectrum taken at 1.7 Å resolution with the IIDS at the KPNO 2.1 m telescope. His analysis shows the composite blue spectrum of P1540 to be that of a chromospherically active K2 star, with an uncertainty of ± 1 spectral subclass. Ca II H and K are seen prominently in emission. The spectral resolution is insufficient to separate the emission from each binary component; the composite H and K lines each have surface fluxes (corrected for absorption) of 6×10^6 ergs $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, comparable to typical NTTS (Walter 1987; Walter *et al.* 1988). Other than the H and K emission, the blue spectrum shows no features of T Tauri stars. Higher-resolution spectra around the Hα line were obtained with the echellette configuration of the MMT spectrograph. After subtraction of the nebular emission, no additional Hα emission was detected from the star.

The most direct spectroscopic evidence for the young age of P1540 is the strength of the Li 6707 Å absorption line of both components. Three echelle spectra centered at 6700 Å have been obtained, two at ORO and one at FLWO, all showing strong Li absorption. One of these spectra, taken near the maximum radial-velocity separation of the components, is shown in Fig. 2. Li 6707 Å absorption lines are clearly evident in both the primary (the blueward line) and the secondary; the velocity separation measured from the spectrum agrees with the orbit solution to 0.5 km s^{-1}. The apparent equivalent widths are 240 and 160 mÅ for the primary and secondary. These apparent equivalent widths are measured with respect to a continuum that arises from both stars. If we correct for this, using a ratio of primary to secondary continuum intensity of 1.6 ± 0.4 (a value we derive later in this paper), the actual equivalent widths of the primary and secondary are 390 ± 40 and 420 ± 70 mÅ, respectively. Such large Li 6707 equivalent widths are typical for both T Tauri and NTTS (Cohen and Kuhi 1978; Walter *et al.* 1988). Because Li is readily processed in low-temperature nuclear reactions, the presence of strong Li 6707 absorption is evidence for an age less than a few times 10^7 yr (Duncan 1981). The equivalent widths of main-sequence stars of similar effective temperature are smaller. For example, Hobbs and Pilachowski (private communication) find maximum Li 6707 equivalent widths among late G–early K Pleiades stars (age 7×10^7 yr) of 200 mÅ, and Boesgaard and Tripicco (1986) find smaller equivalent widths in late-type main-sequence stars in older clusters. Thus the presence of two strong Li 6707 Å absorption lines argues that both stars of P1540 have ages of order less than 10^7 yr.

Optical variability of up to 2 mag is often observed in T Tauri stars (Herbst 1986), while NTTS typically show lower amplitude variability of order 0.1 mag. No systematic photometric monitoring of P1540 has yet been done, but an inspection of 50 plates taken with the Metcalf telescope between 1911 and 1987 showed no variation of more than 0.5 mag in the *V* brightness of P1540. In addition, photometry was obtained by R. Schild from CCD frames taken at the 0.61 m telescope at FLWO in January and December 1987, and photoelectric magnitudes of P1540 were obtained at Kitt Peak on two nights a month apart in November and December 1987 by T. Liu (Boston University) and by one of the authors (L.A.M.). None of these measurements indicated any change in the *V* magnitude of P1540 greater than 0.05 mag. Finally, Jones and Walker (1988) have searched for variable stars in a photographic survey of the Orion Nebula region. P1540 is among the stars they examined; they noted no variability for it.

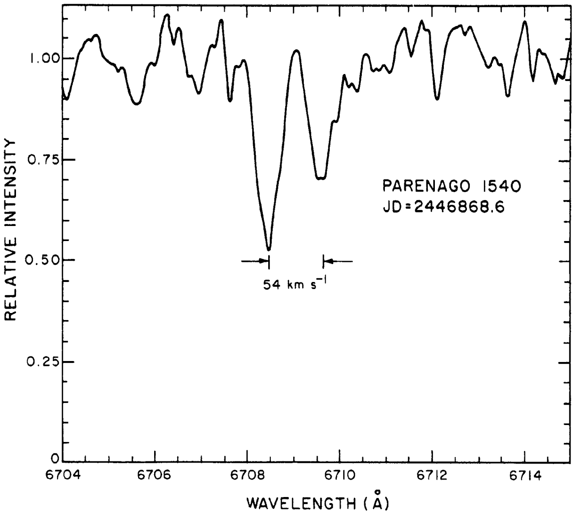

FIG. 2. Li 6707 Å spectrum of P1540 taken with the echelle spectrograph on the 1.5 m Tillinghast reflector at the Fred L. Whipple Observatory. The continuum level corresponds to about 300 counts/pixel. The spectrum was obtained near maximum velocity separation. Strong lithium absorption is evident in both components of the binary. The equivalent width of the blueward component is 240 mÅ and of the redward component 160 mÅ.

Infrared excesses are also typical of T Tauri stars, but not NTTS. There are no point sources listed in the *IRAS Point Source Catalog* (Beichman *et al.* 1986) within 10′ of P1540, although confusion from dust emission in the nebula may exist. The *JHKL* observations in Table III show that the near-infrared colors of P1540 are consistent with the expected composite colors of both P1540 components, as derived below. Thus we find no evidence for a significant infrared excess in P1540.

In summary then, the spectroscopic and photometric evidence, in particular the strong Li absorption seen in both components, the Ca II H and K emission and the x-ray flux, argue that P1540 is composed of two young stars.† The lack of an evident infrared excess or spectral features typical of T Tauri stars suggests that both stars are naked T Tauri stars. Finally, being projected upon the Orion Nebula, a region of rich star formation, suggests that P1540 formed in the Orion Cloud. As we show below, at the distance of the Orion Cloud, P1540 is photometrically a pre-main-sequence star.

Unfortunately, the kinematic evidence makes the association with the Orion star-forming region problematic. The

---

*Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, which is operated by AURA, Inc., under contract with the National Science Foundation.

† It was pointed out by the referee that much of the evidence for the youth of P1540 might also hold for a post-main-sequence system, in particular a member of the RS CVn class. However, the observed Li 6707 Å equivalent widths of 400 mÅ permit a definitive argument that P1540 is not a post-main-sequence system. Among post-main-sequence stars, such strong Li absorption lines are only seen in stars of several solar masses. Given the observed visual extinction of 1 mag, the luminosities of such stars would require that P1540 be located behind the Orion Cloud, which is inconsistent with an extinction of only 1 mag. Considering the RS CVn stars in particular, Walter (private communication) has not detected Li absorption in any RS CVn system at greater than the 50–100 mÅ level.

center-of-mass radial velocity of P1540, 20.2 km s^{-1}, is consistent with membership in the Orion Id association. The mean radial velocity of late-type stars in the Orion Id association is 26 km s^{-1} (Marschall and Mathieu, in preparation), and the one-dimensional velocity dispersion in the region is 2.5 km s^{-1} (McNamara 1976; Jones and Walker 1988; Marschall and Mathieu, in preparation). However, a precise proper motion for P1540 has been measured by Jones and Walker (1988), who find a two-dimensional proper motion of 0.65 ″/century. They also measure a two-dimensional proper-motion dispersion for members of the Trapezium cluster of 0.16 ″/century. The errors on both measurements are small compared to the motions themselves. Thus the proper motion of P1540 is a 4σ deviation from the mean motion of stars associated with the star-forming region, and Jones and Walker assign it a membership probability of 0. A similar conclusion is drawn by van Altena *et al.* (1988). Including the radial-velocity data, the space velocity of P1540 is 3.5σ from the mean of the three-dimensional velocity distribution. Thus the kinematic data do not support the membership of P1540 in the Orion star-forming complex.

Nevertheless, there are strong reasons for concluding that, despite the kinematic evidence, P1540 is indeed a member of the Orion complex. First, the spectroscopic and photometric evidence supports the conclusion that P1540 is a young star. The vast majority of such stars are associated with sites of recent star formation, such as the Orion Nebula region, and there are no other known star-formation sites between the Earth and the Orion Cloud. There are a few instances of young stars isolated from any known molecular clouds (Herbig 1978; Rucinsky and Krautter 1983; Walter *et al.* 1988), but given their apparent rarity it seems unlikely (though not impossible) that one should happen to be located along the line of sight to the Orion Nebula.

Stronger support for the association of P1540 with the Orion star-forming complex comes from a study of the extinction and polarization toward the star. As we will show below, the reddening to P1540 is about E $(B-V)=0.35$. Breger, Gehrz, and Hackwell (1981) find the reddening between the Earth and the Orion Nebula region to be $E(B-V)=0.05$. Values of $E(B-V)=0.3$ within the Orion Nebula are common (Walker 1969; Breger, Gehrz, and Hackwell 1981); from polarization data of Breger, Gehrz, and Hackwell one finds that two stars projected near P1540, P1623, and P1685 both have reddenings of $E(B-V)=0.3$. Furthermore, Breger (1976) has measured the polarization of many stars projected within the Orion Nebula. Of the 27 stars with both polarization measurements and measured proper motions by Jones and Walker, Breger finds 12 to show strong polarization $(p>0.9\%)$, one of which is P1540. Except for P1540, all have membership probabilities greater than 75%.

Finally, our *UBVRIJHKL* photometric data are sufficient to allow the total-to-selective extinction R to be estimated toward P1540. Following Cardelli, Clayton, and Mathis (1988), we derive R by fitting the P1540 colors to the average near-infrared curve of Rieke and Lebovsky (1985). Adopting the intrinsic colors of a K2 V star, we find that the data are well fit with $R=3.6$. This is a conservative estimate since (1) P1540 has a cooler companion and (2) if P1540 is a pre-main-sequence star, its surface gravity will be smaller than luminosity class V; we find that using the intrinsic colors of either a later-spectral-type star or of a giant increases the best-fit value of R. A value for R of 3.6 or greater is significantly larger than that found in the general interstellar environment, where a typical value would be $R=3.1$. However, the Orion Nebula region has long been known to have anomalously high values of R. More generally, Breger, Gehrz, and Hackwell (1981) argue that regions of high R $(R=4–5)$ are correlated with the presence of extended H II regions. P1540 is, in fact, projected within the Orion nebulosity. Thus this analysis of the nature of the reddening toward P1540 also suggests that P1540 is physically associated with the Orion Nebula.

From these data then, two alternative conclusions may be drawn: (1) P1540 is an isolated young NTTS that happens to be located between the Earth and the Orion Nebula, is substantially reddened compared to other stars located in front of the Orion Cloud, and shows an anomalous extinction curve similar to stars associated with the Orion Nebula, but is, in fact, not associated with the Orion star-forming region; or (2) that P1540 is an NTTS recently formed in the Orion Cloud that has a velocity 3–4 times larger than typical for other stars formed in the same region. We cannot definitively argue for either alternative, but we consider it far more likely that P1540 is a young star associated with the Orion star-forming region.

Given that P1540 is a hard binary with respect to the internal motions of the Trapezium cluster, a reasonable explanation for its high velocity is ejection from the very compact core of the cluster via a close stellar encounter. The proper-motion vector of P1540 does indeed point away from the cluster. Furthermore, taking the present projected separation from the cluster (9′ from Θ Ori C) and the proper motion given by Jones and Walker (0.65 ″/century), the encounter time would have been 8×10^4 yr ago, easily within the age of P1540 itself.

V. EVOLUTIONARY STATUS OF P1540

Finally, we consider the positions of each component of P1540 in the theoretical Hertzsprung–Russell diagram. We have used synthetic double-lined spectra to calibrate the ratio of relative correlation peak heights with (1) relative luminosities and (2) spectral type. Composite spectra were constructed by combining echelle spectra of Hyads (kindly provided by Dr. R. Stefanik) scaling the relative continuum levels to represent different relative luminosities. While the use of Hyads to represent pre-main-sequence spectra is an approximation, NTTS spectra, in fact, do not differ substantially from main-sequence stars in the wavelength region considered here (Walter *et al.* 1988).

We have assumed that the primary dominates the composite light, so that the primary spectrum was chosen to be K2 V. Secondary spectral types were chosen from G2 V to M0 V, permitting analysis of the dependence of the relative correlation peak heights on secondary spectral type as well as luminosity. The velocity difference between primary and secondary was set at 60 km s^{-1}. The composite spectra were then correlated against high-signal-to-noise spectra of both the dusk sky and an M2 III star (HD 115521), hereafter referred to as the "M template." As expected, the ratio of the primary-to-secondary correlation peak height increased with lower secondary luminosity. Interestingly, however, we found that the relative peak heights were rather insensitive to secondary spectral type when using the M template but varied with secondary spectral type when using the sky template. Thus the use of both the sky and M templates permit-

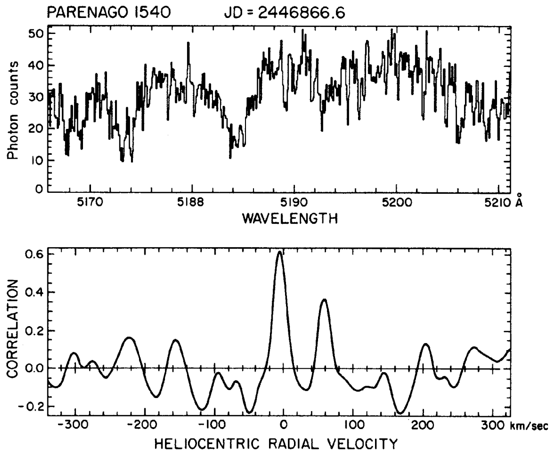

FIG. 3. Typical high-resolution spectrum of P1540 used for radial-velocity measurements (top) and its cross-correlation against a template spectrum of the twilight sky (bottom). The relative heights of the primary and secondary correlation peaks have been used to constrain the relative continuum fluxes (at 5200 Å) and the relative spectral types of the two stars.

ted estimates of both the luminosity ratio and the secondary spectral type. Using only those 11 spectra in which the velocity difference between primary and secondary was between 50 and 60 km s^{-1} (see Fig. 3 for an example), this analysis yielded a primary-to-secondary continuum ratio in the region around 5200 Å of 1.6 with a maximum range between 1.2 and 2.0, and a secondary spectral type between G9 and K5. With the addition of photometric data, we can more precisely constrain the secondary spectral type, as we discuss next.

Walter *et al.* (1988) find that the observed colors of NTTS agree well with the spectral types inferred from IIDS data similar to those used here and that the application of main-sequence bolometric corrections gives luminosities in good agreement with integration of broadband photometry from *U* through *L*. (Mundt *et al.* (1983), however, present arguments for a different conclusion.) Thus, as a first approximation we will adopt effective temperatures and bolometric luminosities using standard data appropriate for main-sequence stars, in particular effective temperatures from Böhm-Vitense (1981) and main-sequence bolometric corrections from Schmidt-Kaler (1982). Finally, from our analysis above we adopt a range of primary-to-secondary continuum ratios at 5200 Å of 1.2 to 2.0 and a ratio of selective-to-total extinction of $R = 3.6$.

These data and conversions permit us to define a locus in the H-R diagram where the primary and secondary spectral types and the extinction are consistent with the observed colors of P1540. Such consistent solutions were found only for secondary spectral types later than primary spectral types. Thus, given primary spectral types in the range from K1 V to K3 V, secondary spectral types were constrained to K2 V to K5 V (the early limit for the secondary is taken to be one spectral type later than that of the primary). Then, adopting a distance to P1540 of 470 pc, we determine log L and log T of primary and secondary for each combination of primary and secondary spectral type. Typical values of the color excess are $E(B-V) = 0.35$ and of visual extinction $A_V = 1.3$.

The results of this analysis are shown in Fig. 4, where we show the locus of possible positions for both primary and secondary components. The sense of primary–secondary combination is that hotter, more luminous primaries correspond to cooler, less luminous secondaries. Also shown are pre-main-sequence evolutionary tracks and isochrones, taken from Cohen and Kuhi (1979). Both components of P1540 fall in the region occupied by pre-main-sequence stars. However, the large uncertainty in the relative luminosity and spectral type of the secondary contributes a substan-

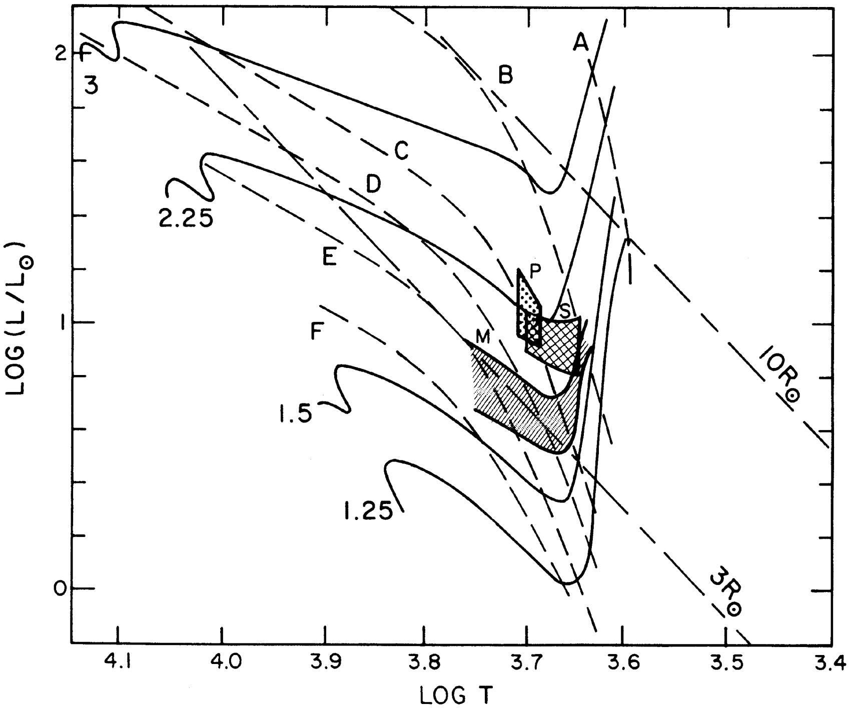

FIG. 4. Loci of the primary (shaded region P) and secondary components (shaded region S) of P1540 in the theoretical HR diagram, as determined from spectral types and photometry. Also shown is the region permitted for the secondary component by the dynamical mass ratio (shaded region M). The diagram is adapted from Cohen and Kuhi (1978). The solid lines are pre-main-sequence evolutionary tracks for stars of different masses. The dotted lines are isochrones corresponding to ages of: (A) 3×10^4 yr, (B) 3×10^5 yr, (C) 1×10^6 yr, (D) 1.75×10^6 yr, (E) 3×10^6 yr, (F) 6×10^6 yr.

tial uncertainty to the determination of a precise age and mass for each star.

The dynamical-mass ratio ($\mathscr{M}_1/\mathscr{M}_2 = 1.3$) determined from the radial-velocity orbit solution provides a further constraint on the nature of primary and secondary. From the evolutionary tracks on Fig. 4, the photometric analysis sets limits on the primary mass of between 2.4 and 2.1 $\mathscr{M}_\odot$; thus the secondary mass must lie between 1.8 and 1.6 $\mathscr{M}_\odot$. This domain is shaded (region M) on the theoretical H–R diagram in Fig. 4. A very limited combination of primary and secondary effective temperatures, in particular near a K3 V primary and a K5 V secondary, satisfies this constraint. This solution requires the ratio of primary-to-secondary continuum light at 5200 Å to be about 2.0. Both the continuum ratio and spectral types lie at the extremes of our range of reasonable values for spectral type and light ratio.

It is notable that this solution indicates different ages for the primary and secondary stars, in particular 1×10^6 yr for the primary and 5×10^5 yr for the secondary. Thus, given the assumptions of this analysis and the evolutionary tracks given by Cohen and Kuhi (1979), the components of P1540 differ in their ages by 5×10^5 yr, or roughly a factor of 2. Alternatively, any secondary that matches the dynamical mass ratio and lies on the same isochrone as the primary would lie well outside the constraints of our photometry. Indeed, secondary stars that satisfy both the mass-ratio constraint and are coeval with the primary would be difficult to detect as a second velocity component in our spectra.

Noncoeval formation of the components of a close binary is a surprising and intriguing result which requires careful consideration of the assumptions involved in its derivation. Taking the observational data as accurate, the essential assumptions in the analysis are (1) our techniques for deriving primary and secondary relative luminosities and spectral types, (2) the use of main-sequence effective-temperature conversions and bolometric corrections, (3) the location of P1540 at the distance of the Orion Cloud, (4) similar extinctions to both components, (5) the validity of the PMS evolutionary tracks, and (6) that the two stars in P1540 formed as a binary system. We briefly consider each in turn.

Our techniques for determining the nature of the secondary from the correlation spectra are newly derived here and are otherwise untested. However, if we presume that the composite light is dominated by the primary contribution, we can alternatively ask what secondary is required to maintain coevality at an age of 10^6 yr and satisfy the mass-ratio requirement. We find that a K2 primary (2.2 $\mathscr{M}_\odot$) and a K5 secondary (1.6 $\mathscr{M}_\odot$) pair satisfies these requirements. In this case, the primary bolometric luminosity would exceed the secondary bolometric luminosity by a factor of 3.2. Adopting main-sequence bolometric corrections, the luminosities would differ by a factor of 4.2 at V. When correlated against a sky spectrum, such a secondary would not produce as strong a correlation peak relative to the primary as shown in Fig. 3. Varying the primary within reasonable errors in spectral type, we find that a K1 primary (2.25 $\mathscr{M}_\odot$) and a K4 secondary (1.7 $\mathscr{M}_\odot$) would also be acceptable and produces the smallest ratio of primary-to-secondary luminosity at V, a ratio of 2.7. Even this luminosity ratio, however, seems unlikely to produce a primary-to-secondary correlation-peak ratio of less than a factor of 2 as observed. Thus, our conclusion of noncoevality is not sensitive to our techniques for deconvolving the primary and secondary light.

The component stars fall within the subgiant domain of the theoretical H–R diagram. The use of main-sequence effective-temperature conversions and bolometric corrections is an approximation based on the assumption that the components are NTTS and follow Walter *et al.* (1988), who find that the total luminosity derived from *UBVRIJHKL* photometry agrees well with that derived from main-sequence bolometric corrections. As a check, we have also repeated the analysis using effective-temperature conversions and bolometric corrections for giants, certainly an extreme assumption. In this case, the permitted domain of the secondary demands a larger age difference between primary and secondary than the age difference found when using main-sequence corrections.

The location of P1540 has already been discussed at length in Sec. III; we feel confident that P1540 is a member of the Orion star-forming complex. However, we note that simply changing the distance modulus to the system cannot produce a coeval solution for the two binary components.

Perhaps the least definitively justifiable assumption in the analysis is that the extinctions to both components of the binary are the same. Since the primary dominates the light at 5200 Å, the reddening determination of $E(B-V) = 0.35$ is likely to be correct for the primary. If the secondary is substantially less reddened ($E(B-V) < 0.1$), then coevality of the primary and secondary could be retained. Such a low reddening for the secondary would require that the source of the extinction to the primary be local to that star alone (within roughly 0.1 AU given a binary semimajor axis of 0.26 AU for solar-mass stars) and does not give rise to any T Tauri phenomena. In addition, the low extinction to the secondary would again demand that P1540 be placed in front of the Orion Nebula, for which the same arguments given in Sec. III would apply. The requisite combination of *ad hoc* assumptions argues against such a large reddening difference between the components.

Hence the essential assumptions involved in placing the components of P1540 on the theoretical H–R diagram are reasonable. We next turn to the validity of the PMS evolutionary tracks themselves. Retaining coevality of the components of P1540 would require substantial revision of the pre-main-sequence evolutionary tracks given in Cohen and Kuhi (1979). The stellar models from which the Cohen and Kuhi evolutionary tracks are derived are now over a decade old, during which time substantial improvements have been made in our understanding of stellar physics, particularly regarding opacities. VandenBerg has computed updated pre-main-sequence evolutionary tracks, a few of which are presented in Andersen *et al.* (1988). The VandenBerg tracks differ substantially from those tracks presented in Cohen and Kuhi, so that certainly a reanalysis of the P1540 system with these updated pre-main-sequence tracks is merited when they become available. Indeed, assuming coevality of the binary components, the P1540 system might be used as a critical test of pre-main-sequence evolutionary models. However, that binary components do in fact form coevally is not firmly established, and certainly neither the evolutionary tracks or the assumption of coevality will be discarded on the basis of a complex analysis of one binary. Our results for P1540 are intriguing and should motivate both similar analyses of other PMS double-lined systems and further development of pre-main-sequence dating procedures.

An alternative means of avoiding the conclusion of noncoeval formation of close binaries is the interesting possibility that the stars in P1540 did not form together in a close binary. This idea is motivated by the high space velocity found for the P1540 system relative to the motions of other stars in the Orion Nebula region. If, as we suggested above, this high velocity is the result of a stellar encounter in the Trapezium cluster, then there is a possibility that the two stars presently in the P1540 binary did not form together. An encounter between a binary and a single star often results in an exchange of the single star with one binary component, particularly if the single star is more massive than one of the original stars in the binary (e.g., Heggie 1975). It is also possible, given the density of the Trapezium cluster, that a binary may form through a simultaneous encounter of three single stars. As there is substantial evidence that stars in star-forming regions form over timespans of as much as 10^7 yr, an essentially random pairing of two stars resulting from an encounter event would very likely produce a binary with noncoeval components.

VI. DISCUSSION

The study of PMS binaries will ultimately address many issues regarding binary formation and, more generally, star formation. Although the roster of low-mass PMS spectroscopic binaries stands presently at only three, some preliminary comments can be made. First, as shown here, PMS double-lined spectroscopic binaries permit a test of the coevality of star formation in close binaries. A secondary with luminosity as much as a factor of 3 fainter than the primary luminosity can be detected spectroscopically. For comparable-mass stars with similar extinction, a relative luminosity of 3 can represent a difference of as much as a factor of 6 in age (Fig. 4). Mundt *et al.* (1983) note a 15% difference in primary and secondary line strengths in most of their spectra of V826 Tau, despite the two components having very similar masses, but variation in the relative line strengths led them to attribute the difference to surface activity on one of the stars rather than a luminosity difference. De la Reza *et al.* (1986) find that the two CORAVEL correlation dips of V4046 Sgr differ by a factor of 2 and thus argue that the secondary is a factor of 2 fainter, despite the two components being almost equal in mass. The issue of the coevality of these two stars has not yet been addressed. In this paper, we find that the components of P1540 do not fall on the same isochrone, differing by a factor of 2 in age. This result is, of course, dependent on the validity of pre-main-sequence evolutionary tracks. The study of other double-lined PMS binaries will further provide tests of the pre-main-sequence evolutionary tracks and the coevality of formation.

Second, PMS binaries permit study of the orbital evolution of binary systems. There is much evidence to indicate that tidal-circularization processes modify the orbits of short-period binaries (e.g., Mathieu and Mazeh 1988). It is of interest to know at what period, if any, binaries form with circular orbits. It is notable that V826 Tau, with a period of 3.9 days, has a circular orbit at an age of only 3×10^6 yr. Binaries with two 0.6 $\mathscr{M}_\odot$ main-sequence stars would in 3×10^6 yr have tidally circularized orbits only for periods of less than 2.0 days (Mathieu and Mazeh 1988). However, tidal circularization is very sensitive to the size of the stellar radii relative to the semimajor axis of the orbit, and to the depth of the convective zones, so the circular orbit of V826 Tau may yet be attributable to circularization of a binary with an initially eccentric orbit and components having larger stellar radii as well as deep convective zones during the PMS phase. In addition, the circularization theory itself is at an early stage of development. With more detailed theoretical work, the orbital data for PMS binaries should ultimately reflect on the formation and evolution of both the binary orbits and the structure of the PMS stars themselves. In this regard, we note that solar-mass binaries have been found in the Hyades and Praesepe clusters with substantially eccentric orbits and periods as short as 5.7 days (e.g., Mayor and Mermilliod 1984). The separations of these binary components (tenths of AU) are far smaller than the size scales of observed protostellar disks (100 AU; e.g., Grasdalen *et al.* 1984). The source of the eccentricity of these orbits is an intriguing problem which any theory of binary formation must address.

Finally, P1540 may represent an important case study for the theory of stellar encounters. Many dynamical studies have shown that in stellar systems encounters of binary stars with other single or binary stars often result in the binary being ejected from the stellar system (e.g., Spitzer and Mathieu 1980). Such ejections can occur very early in the lifetime of a stellar system, and hence binary escapers might be found near young clusters (e.g., Leonard and Duncan 1988). The center-of-mass velocity of P1540 indicates that the binary is in fact presently escaping from the Orion Nebula region, and we suggest that the escape velocity derived from a close stellar encounter in the Trapezium cluster. Furthermore, should analyses of other short-period binaries find that typically the two binary components are coeval, then the noncoevality of the components of P1540 may be indicative of an exchange reaction having occurred where the single star replaces one of the original binary stars. Such exchanges have been predicted from theoretical studies (e.g., Heggie 1975), particularly when the single-star mass is greater than one of the original binary stars.

We would like to thank Fred Walter for providing observational data and helpful discussions throughout the course of this investigation, and Rudy Schild and Fred Vrba for their help in obtaining precise photometry of P1540. Jason Cardelli provided the extinction-curve analysis and much useful counsel. Thanks also to Mark Slovak, Johannes Andersen, Tsevi Mazeh, and Bernie Bopp for informative discussions, and to the staffs at Fred L. Whipple Observatory and Oak Ridge Observatory, especially Ed Horine, Jim Peters, Richard McCrosky, Skip Schwartz, and Robert Stefanik. James Nielson assisted with observations in the early stages of this project. L.A.M. would like to thank Dave Latham for support and encouragement throughout a very enjoyable visit at the Center for Astrophysics, and also Al Marscher and the Astronomy Department at Boston University. L.A.M. also acknowledges the support of the Fund for Research in Astrophysics and the National Science Foundation under grant no. AST 8503236.

Note added in proof: Dr. D. Heggie has reminded us that an orbital eccentricity of 0.12 is rather low for the product of an exchange encounter; eccentricities nearer to 0.7 are expected from theoretical work.

REFERENCES

Andersen, J., Clausen, J. V., Gustafsson, B., Nordstrom, B., and VandenBerg, D. A. (1988). Astron. Astrophys. **196**, 128.

Beichman, C. A., Neugebauer, G., Habing, H. J., Clegg, P. E., and Chester, T. J., editors (1985). *Explanatory Supplement to the IRAS Catalogs and Atlases* (U.S. GPO, Washington, DC).

Boesgaard, A. M., and Tripicco, M. J. (1986). Astrophys. J. Lett. **302**, L49.

Böhm-Vitense, E. (1981). Annu. Rev. Astron. Astrophys. **19**, 295.

Breger, M. (1976). Astrophys. J. **204**, 789.

Breger, M., Gehrz, R. D., and Hackwell, J. A. (1981). Astrophys. J. **248**, 963.

Byrne, P. B. (1986). Ir. Astron. J. **17**, 290.

Cardelli, J. A., Clayton, G., and Mathis, J. S. (1988). Astrophys. J. Lett. **329**, L33.

Cohen, M., and Kuhi, L. V. (1979). Astrophys. J. Suppl. **41**, 743.

de la Reza, R., Quast, G., Torres, C. A. D., Mayor, M., Meylan, G., and Llorente de Andres, F. (1986). In *New Insights in Astrophysics*, ESA SP-263 (ESA, Noordwijk), p. 107.

Duncan, D. K. (1981). Astrophys. J. **248**, 651.

Feigelson, E. D., and Kriss, G. A. (1981). Astrophys. J. Lett. **248**, L35.

Grasdalen, G. L., Strom, S. E., Strom, K. M., Capps, R. W., Thompson, D., and Castelaz, M. (1984). Astrophys. J. Lett. **283**, L57.

Hartmann, L., Hewett, R., Stahler, S., and Mathieu, R. D. (1986). Astrophys. J. **309**, 275.

Heggie, D. C. (1975). Mon. Not. R. Astron. Soc. **177**, 729.

Herbig, G. H. (1978). In *Problems of Physics and Evolution of the Universe*, edited by L. V. Mirzoyan (Armenian Academy of Science, Yerevan, USSR), p. 171.

Herbig, G. H., and Terndrup, D. M. (1986). Astrophys. J. **307**, 609.

Herbst, W. (1986). Publ. Astron. Soc. Pac. **98**, 1088.

Jones, B. F., and Walker, M. F. (1988). Astron. J. **95**, 1755.

Latham, D. W. (1985). In *Stellar Radial Velocities*, IAU Colloquium No. 88, edited by A. G. D. Philip and D. W. Latham (Davis, Schenectady), p. 21.

Leonard, P. J. T., and Duncan, M. J. (1988). Astron. J. **96**, 222.

Mathieu, R. D., Latham, D. W., Griffin, R. F., and Gunn, J. E. (1986). Astron. J. **92**, 1100.

Mathieu, R. D., and Mazeh, T. (1988). Astrophys. J. **326**, 256.

Mayor, M., and Mermilliod, J.-C. (1984). In *Observational Tests of Stellar Evolution Theory*, IAU Symposium No. 105, edited by A. Maeder and A. Renzini (Reidel, Dordrecht), p. 411.

Mundt, R., Walter, F. M., Feigelson, E. D., Finkenzeller, U., Herbig, G., and Odell, A. P. (1983). Astrophys. J. **269**, 229.

Parenago, P. (1954). Trud. Astron. Inst. Sternberg. **25**.

Rieke, G. H., and Lebofsky, M. J. (1985). Astrophys. J. **288**, 618.

Rucinsky, S. M., and Krautter, J. (1983). Astron. Astrophys. **121**, 217.

Schild, R. (1985). Publ. Astron. Soc. Pac. **97**, 824.

Schmidt-Kaler, T. (1982). In *Landolt-Bornstein, Numerical Data and Functional Relationships In Science and Technology*, Group VI, Vol. 2 (Springer, Berlin), p. 456.

Spitzer, L., Jr., and Mathieu, R. D. (1980). Astrophys. J. **241**, 618.

Van Altena, W. F., Lee, J. T., Lee, J.-F., Lu, P. K., and Upgren, A. R. (1988). Astron. J. **95**, 1744.

Walker, M. F. (1969). Astrophys. J. **155**, 447.

Walter, F. M. (1987). Publ. Astron. Soc. Pac. **99**, 31.

Walter, F. M., Brown, A., Mathieu, R. D., Myers, P. C., and Vrba, F. J. (1988). Astron. J. **96**, 297.

Walter, F. M., and Kuhi, L. V. (1981). Astrophys. J. **250**, 254.

Warren, W. H., and Hesser, J. E. (1977). Astrophys. J. Suppl. **34**, 115.