SPECTROSCOPIC BINARIES AMONG LOW-MASS PRE-MAIN SEQUENCE STARS

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1. Introduction

Although the unusual nature of T Tau was noted over four decades ago, the first orbit for a low-mass pre-main sequence (PMS) spectroscopic binary was not determined until Mundt *et al.* (1983) serendipitously discovered the double-lined nature of V826 Tau. To some degree the paucity of spectroscopic binary detections may be attributed to the faintness of such stars and the consequent difficulty in obtaining high resolution spectra; the first high-precision radial-velocity survey was that of Herbig (1977). Advances in radial-velocity measurement technology now permit relatively easy velocity measurements of PMS stars. However, V826 Tau was also one of the first discovered members of the naked T Tauri (NTTS) class of PMS stars (Walter 1987) and its discovery as a spectroscopic binary foreshadowed a prevalence for binary detection among this population. In this short paper we review the present observational status of PMS spectroscopic binaries and present several initial results and thoughts for consideration.

2. The Roster of PMS Spectroscopic Binaries (August 1988)

At present, the roster of low-mass PMS spectroscopic binaries with orbit determinations stands at nine.These are listed in order of increasing period in Table 1, where the orbital periods, eccentricities, mass ratios for the double-lined cases, status of the binaries as classical T Tauri stars (CTTS) or NTTS and the relevant references are presented. We have also included in the list the star 045251+3016 as at present the data show a systematic increase in velocity of 15 km/sec over 800 days; this is clearly a long-period system for which an orbit determination will require further monitoring. Finally we include the double-lined eclipsing binary EK Cep. Arguably, EK Cep might not be considered a PMS binary as the primary is a 2.0 M_O star on the ZAMS. However, Popper (1987) argues that the 1.1 M_O secondary is still contracting to the main sequence and hence we include it here. We note that numerous other authors have suggested velocity variability for additional PMS stars (e.g., Herbig 1977, Bouvier *et al.* 1986, Hartmann *et al.* 1986, Edwards *et al.* 1988). However, as later observations have not always corroborated earlier indications of variability (e.g., Hartmann *et al.* 1986) we have taken the conservative position of assigning binary status only to those stars with clear evidence for orbital motion.

Several trends are evident in Table 1. The distribution of spectroscopic binaries among PMS populations and the orbital eccentricity distribution are discussed further below. The high frequency of both double-lined binaries and short-period systems are

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TABLE 1. Roster of PMS Spectroscopic Binaries

	P (d)	e	q	Population	Reference
155913-2233	2.4237	0.00		NTTS	MWM
V4046 Sgr	2.43	0.00	1.	CTTS	BDLR
V826 Tau	3.9063	0.00	1.	NTTS	MUN
EK Cep	4.42782	0.109	1.8	?	TPO
160905-1859	10.401	0.18		NTTS	MWM
AK Sco	13.6093	0.469	1.	CTTS	AND
P1540	33.73	0.12	1.3	NTTS	MM
162814-2427	35.95	0.49	1.1	NTTS (?)	MWM
162819-2423	89.0	0.5		NTTS (?)	MWM
160814-1857	144.5	0.24		NTTS	MWM
045251+3016	>800			NTTS	MWM

AND = Andersen *et al.* 1989; BDLR = Byrne 1986, de la Reza *et al.* 1986; MM = Marschall and Mathieu 1988; MUN = Mundt *et al.* 1983; MWM = Mathieu, Walter and Myers 1989; TPO = Tomkin 1983, Popper 1987

certainly the result of selection biases. Only the NTTS binaries, excluding P1540, are the product of a comprehensive radial-velocity survey (Mathieu, Walter and Myers 1989; MWM). Of these seven binaries, only two are double-lined, a frequency not significantly different from that found among solar-mass field stars. Similarly, most of the stars in that study have only been observed over 2-3 yr, biasing the sample to shorter periods.

3. Issues and Results

3.1 Spectroscopic Binary Frequency Among PMS Stars

If the number of binaries are conserved after reaching the PMS stage of evolution, than the frequency of binaries among all PMS stars of a given mass at any given age should be comparable to that found among the field population. This need not be true within subgroups of the PMS population. For example, the presence of a close binary companion will likely alter the distribution and evolution of circumstellar material; indeed it has been conjectured (Walter *et al.* 1988) that the action of such companions may be one process by which CTTS evolve into NTTS. Comparison of CTTS, NTTS and field short-period binary frequencies may provide insight into such processes.

The evidence to date indicates that the spectroscopic binary frequency among the NTTS is indistinguishable from that in the field. In total, eight spectroscopic binaries have been found among the NTTS. Considering only the shortest period ($P < 100$ days) binaries in the Taurus-Auriga and Ophiuchus star-forming regions, MWM find a frequency of 10 ± 4% (5 out of 49), to be compared to 13% among the field solar-mass stars (Abt and Levy (1976), modified as Morbey and Griffin (1987) and Abt (1987)).

Interestingly, among the CTTS there are only two confirmed spectroscopic binaries, V4046 Sgr and AK Sco. (The classification of AK Sco as CTTS is based only on its infrared excess and light variability; CTTS emission lines are not present (Andersen *et al.* 1989, Brown and Walter, priv. comm.)). Several high-precision radial-velocity

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surveys of CTTS, with total numbers of stars comparable to those for the NTTS, have been completed and other spectroscopic binary candidates have been suggested (references in Sec. II). Unfortunately sufficient numbers of velocity measurements to confirm orbital motion have not yet been obtained for any of these candidates and conclusions regarding binary frequencies must be drawn from less secure analyses of velocity measurement distributions. A high-precision radial-velocity survey of CTTS in the Taurus-Auriga, NGC 2264 and λ Orionis star-forming regions is ongoing at the Harvard-Smithsonian Center for Astrophysics (in collaboration with Hartmann, Latham and Stahler). Approximately two thirds of the nearly 100 program stars have spectra at 5200A permitting high quality velocity measurements; the remainder provide lower quality or no measurements due to emission, veiling or rotation. All stars have been observed in at least two observing seasons and typically in three or more. Among those stars providing high-quality velocity measurements, the largest peak-to-peak velocity variations have been at only the 10 km/sec level. The lack of higher amplitude velocity variability, as well as double-lined systems, is in notable contrast to an essentially identical study of NTTS (MWM) and may indicate a lower frequency of the shortest period binaries among the CTTS. However, the observations per star, as with previous studies, are still too few to permit a definitive conclusion. Nonetheless, these preliminary results and the paucity of known short-period binaries among the CTTS are intriguing; the implications regarding the evolution of circumstellar material and accretion disks in binary systems are sufficiently important that a substantial continued observational effort is warranted.

While the CTTS spectroscopic binary frequency remains uncertain, two important conclusions can still be drawn. First, V4046 Sgr and AK Sco are clear evidence that the presence of close stellar companions does not necessarily preclude T Tauri characteristics. Second, given a short-period binary frequency among the NTTS of only 10%, the action of stellar companions at separations of less than 1 A.U. on circumstellar material is not the dominant mechanism converting CTTS into NTTS. Whether companions at wider separations might also be effective needs to be investigated, but at first glance it seems unlikely given the substantial frequency of wide binaries among the CTTS (Simon (this volume), Cohen and Kuhi 1979).

3.2 Masses of PMS Stars

To date the only dynamical mass determination of a low-mass PMS star is that of 1.12 M_O for the secondary of EK Cep. A preliminary analysis by Popper (1987) finds the position of the secondary in the theoretical H-R diagram to be between the 1.0 M_O and 1.25 M_O evolutionary tracks of Iben at an age of 2 x 10^7 yr. Increasing the number of fundamental mass determinations, particularly for binary components with ages of 10^6 yr or less, must be a primary goal of future spectroscopic binary work.

3.3 The Epoch and Coevality of Formation of Stars in Binary Systems

Young stars are typically dated through reference to PMS stellar evolutionary models for single stars. As yet, the relevance of these models for the components of short-period binaries has not been investigated. With this caveat, the ages of the NTTS binaries range from somewhat less than 10^6 yr to 10^7 yr (references in Table 1). Thus by ages of 10^6 yr close binary systems exist and indeed are indistinguishable from those in the field except for the PMS nature of the components and their eccentricity distribution (discussed below). Although the numbers are small, the age distribution of the NTTS binaries does not differ from that of the entire NTTS population (MWM; Walter *et al.* 1988). V4046 Sgr and AK Sco both have ages of 5-10 x 10^6 yr, older than typical CTTS.

While the coevality of formation of binary components is often taken as a given, it

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is subject to observational test. For short-period binaries, double-lined PMS binaries represent a valuable tool in this regard. At the simplest level, two coevally formed stars of the same mass should have the same photospheric luminosity and spectra. Interestingly, the three binaries listed in Table 1 with q~1, V4046 Sgr, V826 Tau and AK Sco, have apparent brightness ratios (in limited spectral ranges) of 2, 1-1.15 and 2.0-0.5, respectively (references in Table 1). Only V826 Tau can be straightforwardly interpreted as having coevally formed components. However, the remarkable variation in the brightness ratio of AK Sco is interpreted by Andersen *et al.* (1989) as evidence for substantial extinction gradients on size scales comparable to the binary orbit and the system acts as a warning, once again, against interpreting apparent brightness differences as intrinsic luminosity differences, at least among CTTS binaries.

A somewhat more sophisticated analysis has been applied to the NTTS double-lined binary Parenago 1540 by Marschall and Mathieu (1988), who deconvolved the composite light and obtained age estimates for each component. Interestingly, using the PMS evolutionary tracks compiled in Cohen and Kuhi (1979) they find the primary and secondary ages to differ by a factor two.The most straightforward interpretation of this result is that the two stars in fact formed noncoevally in a bound system. An alternative interpretation derives from the fact that the center-of-mass space velocity of P1540 deviates from the Trapezium cluster velocity by four times the cluster velocity dispersion; apparently the binary is presently escaping from the cluster. This suggests that P1540 may have been recently involved in a close stellar encounter, during which exchange of an original binary component with an encountered star may have occurred. Given that star-formation regions have formation timespans of up to 10^7 yr, this would easily explain the noncoevality. A more conservative, but perhaps wiser, conclusion is that such analyses are beginning to seriously test the accuracy of PMS isochrones. Similar analyses of a sample of double-lined PMS binaries will provide a benchmark for testing the PMS evolutionary tracks and the coevality of formation.

3.4 Evolution of Binary Orbits

This important issue can best be introduced by noting that two solar-mass stars in an orbit of 2.5 day period are separated by 10 R_O. This separation is comparable to the radii of solar-mass stars at the stellar birthline. It is difficult to avoid the conclusion that either the single-star PMS evolutionary tracks are not valid for close binary components or the orbital separations of at least short period systems decrease with time. Furthermore this argument shows that the issue of orbital evolution and interaction between binary components is not restricted to the earliest stages of the star-formation process; it remains relevant into the PMS phase. The relative timescales of the decrease in stellar radii and orbital semi-major axis will dictate the nature of any interaction between two binary components during the PMS phase. Observation of the youngest and shortest-period systems should provide the best insight into the nature of early binary evolution. At present we have yet to find a binary substantially younger than 10^6 yr, by which age the stellar radii are such that solar-mass stars lie well within their Roche radii even for orbital periods of only a few days. Hence it is not surprising that at present the binary 155913-2233 with a period of 2.4 days shows no evidence of interaction between the stars. On the other hand, V4046 Sgr - also having a period of 2.4 days - has both strong emission activity and large infrared excesses. V4046 Sgr is one of the rare cases of a CTTS isolated from any dark cloud or molecular material; Herbig (1978) has suggested interaction between the two stars as one explanation for the continued emission activity. Better observational insight into the evolution of binary separation during the PMS phase will improve with the discovery of binaries of younger age than those presently known.

That orbital evolution does occur however is indicated by the orbital eccentricity

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distribution shown in Table 1. The binaries with periods of less than 4 days have circular orbits while those with longer periods have eccentric orbits. Indeed this eccentricity distribution represents one of the most solid observational facts that any theory of binary formation must explain: among all young stellar systems (Hyades, Pleiades, α Per and the PMS population), with only rare exception, every low-mass binary with a period greater than 4-6 days has an eccentric orbit while every binary with shorter period has a circular orbit. This is a remarkably robust result in the face of a presumed variety of formation conditions for each binary. Perhaps the most straightforward explanation would be to attribute the circular orbits to circularization processes occurring relatively late in the star-formation process when the differences in the initial conditions have been erased. In this picture, the cutoff period of 4 days between the circular and eccentric orbits becomes a critical benchmark for the evolution of internal stellar structure, stellar radius and orbital separation prior to 10^6 yr. However complex that evolution may be, the process must ultimately be capable of producing a 4 day period binary with a circular orbit. It is worth noting that in 10^7 yr two solar-mass stars with ZAMS internal structure can only circularize orbits with periods of less than two days (Mathieu and Mazeh 1988). That tidal circularization is more effective during the PMS stage is likely due to larger stellar radii and deeper convective zones.

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