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Spectroscopic properties of stars in young binaries: fundamental data for understanding binary formation and disk evolution

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Abstract This contribution combines a relatively comprehensive review of the spectroscopic study of the individual component stars and their associated disks in young binary systems, outlines the need for more in-depth studies, and previews the results of a high-spectral and high-angular resolution survey of $\sim$ 100 young binaries located primarily in the Taurus and Ophiuchus star forming regions. Observed spectra, synthetic spectral analysis, and preliminary outcomes for 3 systems are presented, illustrating the power and potential of adaptive optics-fed, high-resolution, infrared spectroscopy for our understanding of the dynamical and physical properties of young binary stars and their circumstellar disks and environments, especially when combined with ancillary data from ALMA, K2, TESS, and other facilities. This new survey will deepen our understanding of disk evolution and planet formation in close binaries and, more broadly, will provide clues to disk dissipation processes in both singles and binaries.

1 Introduction

The early stages of planet formation are governed by stellar and circumstellar disk properties and the incident radiation field. For planets forming around stars in close binary and multiple systems, with separations of a few AU to tens of AU, tidal interactions will also impact disk stability, structure, and longevity. Crossover photoevaporation of a disk from the companion star's X-ray luminosity may also play a role for these closest systems, depending on the orbital- and disk-plane geometries. Despite these challenges to disk survival and planet formation, planets do orbit the stars in close binaries, albeit less frequently than in wide binaries and single stars [e.g., 1]. To identify the properties that enhance disk persistence and thus planet-formation potential, angularly resolved, detailed spectroscopic characterization of close, young, disk-bearing (and non-disk bearing) binaries is required. This research is important because most solar-type as well as higher-mass stars, in particular younger ones, are located in binary systems: for a full accounting of the planet formation process, we must consider the potential for planet formation in all young stellar systems. To this end, identifying the sources and triggers of circumstellar disk dissipation, a phenomenon that is poorly understood for all young star systems, single and binary, is a key task. The study of wider binaries, assuming coevality of the system components, provides a unique laboratory for exploring the disk persistence and dissipation for stars located in a common environment.

The rich results of The *Kepler*, *K2*, and *TESS* missions have ushered in an unprecedented era of comparative planetary demographics and planetary population synthesis [e.g., 2]. Yet our understanding of the specific processes driving planet formation, and the relationship through dynamical evolution to the observed outcomes, is incomplete, limiting the value of comparison between statistically significant samples of relatively old planets and models for emerging young planets. Numerous particular puzzles remain and continue to challenge both theory and observation, such as the origin of hot Jupiters [3].

The formation and evolution of planets around binary stars also present a special challenge. The circumstellar planet occurrence rate in main sequence binary systems with projected separations of < 50 AU is only a third of the rate for wider separation systems or single stars [1]; other studies have found evidence for even smaller planet formation rates in close binaries [e.g., 4]. These results are unsurprising: given factors such as tidal forces, disk radius and mass truncation, and the radiative environment set up by two stars in close proximity, the interesting question is actually how do *any* planets at all form and survive in such systems. In earlier work on young T Tauri binaries, [5] determined that circumstellar disks were similarly less frequent in pairs of stars with projected separations of < 50 AU, suggesting that circumstellar disks in young binaries effectively serve as proxies for planet formation and begging the same question: why do any disks survive in the complex and potentially dynamically and radiatively violent environment of a close young binary.

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Binary and multiple stars are critical to a full decoding of planet formation because most stars are located in non-single systems [6]. The peak of the distribution of binary separations is a function of the binary star masses, formation location in a dense cluster or loose association, and other factors, but likely ranges from $\sim$ 10–60 AU [e.g., 6, 7]. Thus the < 50 AU binary systems in which planet formation is most impacted by a companion are also the most numerous, comprising an important sample for the exploration of circumstellar disk resilience and the robustness of planet formation in a complex and potentially harsh environment.

Apart from binary separation, the factors governing circumstellar disk longevity and the implied potential for planet formation have not been well-established for multiple, or for that matter for single, systems. Disk mass correlates with stellar mass, but disk survival times do not [8, 9]. Disk lifetimes may depend on internal properties, such as inhomogeneities in the particle distribution analogous to the pressure bumps that give rise to dust traps at tens to hundreds of AU [10], or external properties such as the binary orbital elements or the stellar properties including rotation and magnetic field strength. Although ALMA has transformed our understanding of circumstellar disk structure in young systems [e.g., 11], there are limitations to what we can learn from ALMA, or even in the infrared from SPHERE, about the inner $\sim$ 1 AU and the relevant accretion status and stellar properties of the stars in young binaries. This inner region is key to understanding disk locking and the disk-star relationship.

Component-resolved spectroscopy of the individual stars in young binaries at high-angular and high-spectral resolution provides a window on the fundamental physical and dynamical stellar properties and the presence of active accretion disks. With observations of large samples of small separation (< 50 AU), low-mass, pre-main sequence binaries, it becomes possible to correlate stellar and accretion properties, and—to the extent known—dynamical properties of the binary such as the orbital parameters and the component mass ratio, with the presence of a persistent inner disk or disks around the binary components. This contribution describes a spectroscopic survey of $\sim$ 100 young binaries with projected separations from $\sim$ 7 AU to several hundred AU, bridging the range of close to medium separations and including the peak of the binary separation distribution for most if not all binary populations [e.g., 6, 7]. Near-infrared H and K-band spectroscopy at facilities equipped with adaptive optics (AO) yield unprecedented observational detail; for some systems, multi-epoch observations capture high levels of spectral variability. Section 2 frames the context with a comprehensive review of previous surveys, almost all conducted with relatively low-spectral resolution. In Sect. 3, the motivation for and observational details of the survey in progress are outlined and some very preliminary results are presented, followed by a brief summary in Sect. 4.

2 Review

Before we could study young binaries, someone had to find them. Painstaking 1-D speckle at thermal wavelengths and infrared lunar occultation observations developed and carried out in the 1970–1980s set the stage for systematic surveys to find young binary stars. The work of [12, 13] describes speckle observations aimed at the study of early stages of star formation. Serendipitously, while looking for extended emission or a resolved circumstellar disk in the T Tauri system, [14] identified this eponymous young star as a $\sim 0.6''$ binary (later [15] identified the southern component as itself a close pair). Subsequent surveys uncovered a bounty of multiple systems in the Taurus and Ophiuchus regions in particular. As binary surveys continued into the 1990s, astrophysical studies of the nature of the individual components in wide binaries began and evolved in the twentyfirst century into more nuanced studies covering a more complete range of separations. The availability of infrared spectroscopy fed by adaptive optics (AO) systems facilitated these observational advances.

2.1 Young binary populations: identification surveys

This section is not an exhaustive review of the numerous excellent surveys cataloging young, low-mass stellar multiplicity but instead calls attention to a number of important references. The lunar occultations, speckle imaging, and direct imaging techniques used in the first generation of dedicated young binary surveys each had their associated advantages and disadvantages. Lunar occultation surveys of young stars in the Taurus and Ophiuchus regions, both located along the ecliptic, achieved angular resolutions, a function of temporal sampling, as high as $0\farcs005$ at 2.2 μm [16–19]. By comparison, the resolution of speckle imaging is defined by the diffraction limit of the telescope [e.g., 20]; the survey of [21] employing the Palomar 5-m achieved $0\farcs07$ resolution. However, while binary position angles detected by speckle imaging have only a 180 degree ambiguity, lunar occultations determine the binary component separations in 1 dimension only, along the vector of the Moon's relative motion. Pre-AO imaging surveys yielded full position angle information, but were seeing limited [22, 23].

These early studies, together with subsequent speckle imaging [e.g., 24], space-based imaging [e.g., 7, 25, 26], and AO imaging [27–29] surveys, established the predominance of multiple systems in nearby, sparse regions of star formation such as Taurus and Upper Sco [30]: only $\sim$ 30 % of systems in Taurus are single stars [27]. Orion, a region denser than Taurus, Ophiuchus, and Upper Sco, appears to host fewer wide binaries [e.g., 31, 32, 33], but a population of close pairs consistent with the companion star fraction in smaller star forming regions was observed by [28]. The net result of these surveys has been the identification of a rich sample of visual binaries and higher-order multiples spanning a separation range of a few AU to hundreds of AU.

Table 1 Summary of spectroscopic component-resolved young binary surveys

Reference	λ	SFR	Spectral resolution	Separation[a] (″)	Separation[a] (AU)	Systems in study	Systems reanalyzed
Hartigan et al. [40]	Opt	Tau, Ori	2500–4200	2.6–38	420–6300	26	1
Prato and Simon [38]	IR	Tau, Oph, CrA	22,000	1.3–2.6	224–380	4	2
Brandner and Zinnecker [42]	Opt	Cha, Lup, Oph	∼ 3000	0.6–1.7	90–250	14	11
Monin et al. [45]	Opt	Tau	∼ 600–800	2.4–5.9	350–850	5	3
Duchene et al. [46]	Opt	Tau	∼ 600–800	0.9–3.5	130–500	10	7
Prato and Monin [47]	Opt+IR	…[b]	…[b]	…[b]	…[b]	53	.
Hartigan and Kenyon [c] [51]	Opt	Tau	900 & 7,000	0.1–1.6	14–220	20	19
Prato et al. [34]	IR	Oph, Lup, CrA	760	1.2–7.6	200–1200	17	13
Daemgen et al. [d] [54]	IR	Ori	1,400	0.3–1.1	125–456	16	12
Correia et al. [55]	IR	Ori	5000	0.2–1.3	85–540	8	7
Daemgen et al. [44]	IR	Cha	1500	0.2–5	27–876	26	14

The projected binary separations in AU were calculated from the separations and distances given in the respective references except for VV CrA and S CrA [38] for which parallaxes from [39] were used
[a] Projected
[b] Spectral resolutions and binary separations from [38, 40, 42, 45, 46, 82]
[c] [50] reported on preliminary observations of the same sample
[d] The targets cited in [54] from [55] not included

2.2 Young binary astrophysics: spectral characterization surveys

In the following section the young binaries described have all been observed with angularly resolved spectroscopy and the properties determined all pertain to the individual stars in the systems; for economy and simplicity, these qualifiers will not be repeated in the discussion of every publication.

In the review of young binary spectroscopy literature that follows, the circumstellar disk characteristics for each component star is stressed because of the importance of the role of disk lifetimes and evolution for planet formation and the characterization of binary formation models. The data in the publications listed are reassessed for evidence of actively accreting circumstellar disks, as well as the relative statistics of their occurrence rates, on the basis of spectroscopic diagnostics only. Higher-level hydrogen emission lines, such as the near-infrared Brackett series, are relatively weak in comparison to Balmer lines for example. Thus [34] noted that *any* detectable Brγ line emission signals accretion from an inner disk; K-band spectral veiling >0.3 provides a complementary diagnostic. In the literature, values for Brγ emission equivalent widths are often provided without correction for veiling, rendering underestimates in the line strengths. For optical spectroscopic studies, veiling and emission lines are used as disk diagnostics; in the following analysis, corrections for chromospheric activity [35] were applied if they were not already taken into account by the authors. Continuum excess emission from dust in disks [e.g., 36, 37], while a highly valuable diagnostic, does not necessarily trace active accretion processes and is not included in this review.

The papers analyzed here are summarized in Table 1. Because there are relatively few papers in this area, this section provides a fairly comprehensive overview.The references are listed with the instrumental resolutions, relevant wavelength region of the observations, binary separations (projected) in arcseconds and AU (using distances given in the references except in the case of [38] for VV CrA and S CrA as GAIA parallaxes indicate a significantly larger distance, 156 pc and 160 pc, respectively [39]), the number of systems reported in the reference as *spectroscopically* observed, and the number used in the meta-analysis reported in the discussion below.

2.2.1 Early (mostly optical) surveys: 1990s

As the early large samples of young binaries were still being identified, spectroscopic surveys of their fundamental properties were already underway. In a pioneering optical study ($R = 2500$–4200), [40] obtained spectra of 28[1] wide, young Taurus and Orion systems with separations of ~ 2–$40''$. For 26 pairs, they identified stellar $T_{\rm eff}$, luminosity, and characterized the circumstellar accretion by measuring the Hα emission lines. By placing systems on HR diagrams and comparing with models of young star evolution, they inferred ages and masses to test coevality and models of binary formation. Two-thirds of the systems appeared to be

[1] Although 39 systems were observed in total, only for 28 were resolved spectra obtained.

coeval and systems identified as non-coeval showed no trends with the presence of circumstellar disks, age, component mass ratio, or projected binary separation. Data collected since the publication of this early survey suggest that several factors likely impacted the results: (1) not all of the targets included were bona fide Taurus members [41], (2) given the large component separations and in particular the high stellar density in Orion, many of the wider pairs are likely chance superpositions, and (3) a high fraction of the binary components studied by [40] are themselves tighter binaries, distorting the determination of luminosity and spectral type. Figure 6 of [42] clearly demonstrates this impact. The high incidence of coevality in the sample of [40] is probably indicative of the general consistency in the ages of neighboring stars in the Taurus and Orion regions. Although limited in impact by the sample, this work laid out the groundwork and methodology for subsequent studies of tighter, bound binaries at higher angular resolution.

Brandner and Zinnecker [42] explored optical spectroscopy (spectral resolution of a few thousand assumed from the instrument used; this value was not provided in the manuscript) of the properties of stars in 14 close (0.″6–1.″7) young pairs in southern star forming regions. These authors were presciently motivated in part by the likelihood of circumstellar disk-mediated binary interdependence, recently delineated in dramatic images from SPHERE [43]. This was the first study to push down into the subarcsecond regime, critical for the representation of most young pairs and to the exploration of star-disk interactions in young binaries. After eliminating one system, ESO-HA 281, as a chance superposition, [42] were able to compare eight of their target systems with pre-main sequence evolutionary models on an HR diagram and found every pair to be coeval, implying simultaneous formation.

The Hα equivalent widths, modulo the spectral type criteria of [35] to avoid confusion with chromospheric activity, for the 13 systems in [42] reveal the presence of actively accreting circumstellar disks around both stars for most of the binaries in the sample across the full range of separations studied. Using AO imaging, [44] identified two of the [42] targets as triples; after removing these from the sample, two of the binaries in [42] show no evidence for any disks and 3/11 are mixed disk systems, one with a primary disk only and two with secondary disks only.

Although other early efforts to characterize young binaries spectroscopically applied optical observations, [38] explored high-resolution K-band observations to take advantage of the better seeing afforded in the IR and to avoid the higher extinction commonly found in optical observations of sometimes embedded targets in dusty star forming regions. K-band spectra of four young, close binaries (1.″3–2.″6) at R=22,000 [38] pointed to the presence of disks around both stars in these systems; combined with non-spectroscopic data, this work suggested correlated dissipation of inner disks, possibly regulated by a circumbinary reservoir. Two of the four systems observed spectroscopically were later shown to be triples, yet subsequently the study of correlated disk evolution using larger and more statistically significant samples was taken up by several teams.

For their investigation of binary and circumstellar disk formation, [45] and [46] obtained optical spectra at low resolution ($<\sim$ 1000) of 16 young systems and concluded that the disk status of Taurus binary components was highly correlated. Ten of their targets are confirmed Taurus members and simple binaries; only 1/10 is a mixed system. Hα emission luminosities demonstrated that primary stars typically showed stronger lines by up to a factor of ten. They speculated that the coeval disk evolution may result from proportionality between the disk and stellar mass that yields a similar timescale for disk dissipation in an individual system.

In an overview of unpublished and, primarily, previously published results from the 1990s, [47] focussed on the presence of circumstellar disks and found a fraction of mixed systems of $\sim$20%. In almost all cases, the lone disk was circumprimary. However, many of the hydrogen Brγ emission lines used as disk diagnostics in the infrared spectra used in this study were not corrected for the K-band continuum excesses common in these systems, leading to underestimates of the equivalent widths and line fluxes and potentially distorting the results for the fraction of mixed systems. These authors illustrated the potential for misclassification of actively accreting disks with their comparison of Hα equivalent widths and Hα emission line fluxes, depending on where the cutoff for active accretion is determined. [48] make the argument for the use of 10% full widths of the Hα emission line peak as a potentially more accurate discriminant for accretion by an active disk, although low S/N and line variability may impact results [49].

2.2.2 Infrared and space-based surveys: 2000s

To avoid reliance on the vagaries of a sole disk indicator, such as confusion with chromospheric activity in late type stars [35] and emission line variability [49], [50] and [51] applied a Venn diagram-type analysis to the determination of circumstellar disk presence for a high level of reliability. Their results for HST spectra of the stars in 20 close pairs (separations 0.″10–1.″56) in the Taurus region at spectral resolutions of $R = 900$ and $R = 7000$ yielded stellar luminosities, reddening, ages, masses, mass accretion rates, infrared excesses, and emission-line luminosities for each star in the target systems. Most of the systems appeared to be coeval and primary and secondary star accretion rates correlated well. Hα emission, veiling, and [OI] emission were analyzed to determine disk status. Eliminating one target, V807 Tau, later identified as a triple [52], and modifying the characterization of DF Tau B to diskless, as per [53], 4/19 of the systems in [51] appear to be mixed, consistent with the correlated disk hypothesis described by [46]. No obvious dependence on binary separation in the mixed systems was evident. As noted in previous investigations, in many of the pairs with two disks, the primary star accretion rates tend to dominate.

[34] observed 17 young binaries in Corona Australis, Lupus, and Ophiuchus with $R = 760$ IR spectroscopy. The sample separations covered 1.″2–7.″6. For most of these systems it was possible to determine both stars' spectral types, extinctions, K-band excesses, and luminosity and to place them on an HR diagram with model tracks and isochrones to estimate masses and ages. The majority of the systems appeared to be coeval. To assess the disk homogeneity, two wide, non-coeval binaries SR 21 and YLW

15A, possible chance superpositions, and AS 205 and AS 353, both triples, were eliminated. One or both of the spectroscopic disk diagnostics, hydrogen Brγ emission line equivalent widths and/or K-band veiling > 0.3, for the components in the remaining binaries indicates that 3/13 are mixed disk systems.

A relatively high fraction of mixed systems was identified by [54] and [55] in their investigations of binaries in Orion. [54] obtained AO-fed IR $R = 1400$ spectroscopy for 16 close systems at the VLT; [55] observed 8 pairs with AO-fed IR spectroscopy at Gemini North. The separation range for these 24 systems was $0\farcs22$–$1\farcs3$. The presence of Brγ emission was used as the main disk diagnostic in these studies. Eliminating one relatively massive (G0/F7) pair, and three systems with low signal to noise spectra from [54], and reassessing disk status on the basis of Brγ line emission and/or K-band veiling >0.3, yields 5/12 mixed systems. One of the eight multiples, JW 248, reported in [55] was identified as a triple; after removing this multiple and reevaluating the spectroscopic diagnostics for the remaining seven pairs, only 1/7 appears to have a mixed disk status. This reanalysis leads to a significantly lower number of mixed disk binaries than identified by the authors of these two studies, yet results in not dissimilar conclusions, i.e., that disk lifetimes at least in closer binaries are correlated.

Subsequently, [44] obtained spectra of 19 young multiples in Chamaeleon with a similar observational approach as [54]: $R = 1500$ AO-fed near-IR spectroscopy of systems with separations of $0\farcs1$–$5\farcs5$. The authors used Brγ emission as a diagnostic and identified significantly fewer actively accreting disks among the closest systems in the sample compared to wider pairs. On the basis of this analysis, [44] found that in this Chamaeleon sample, disks were only present in mixed systems with mass ratios < 0.8, and almost exclusively around the primary stars of mass > 0.3 $M_\odot$, consistent with dynamical truncation of the secondary star's disk.

Removing targets with low signal to noise spectra and unresolved triples, and considering only the inner pair of the triple system, T 39, yields 14 binaries in the [44] sample. Reexamination of their published spectra for evidence of Brγ emission together with the veiling measurements provided indicates a relatively high fraction, 6/14, of mixed systems, all with disks around the primary star. Two binaries, Hn 4 and CHXR 47, appear to have disks around both components, in contrast to the interpretation of [44].

2.2.3 Discussion

Over a period of $\sim$ 20 years, considerable effort was invested in these spectroscopic studies, often at the cutting edge of technological advances of the time to facilitate the acquisition of angularly resolved spectra. The results yielded a number of important insights into young binary systems, e.g., that typically both stars are coeval and both either have disks or both do not have disks, implying correlated disk evolution, at least among the closest pairs, and narrowing the binary formation possibilities. However, most conclusions were based on highly inhomogeneous samples which included unresolved triple systems, in some cases low-signal to noise spectra, small numbers of targets (almost always fewer than $\sim$20), often drawn from a variety of regions (e.g., [34]), and analyses based not only on spectroscopic data but also near- and mid-IR colors, excellent tracers of warm dust in disks but not always correlated with active accretion.

The analyses presented in the papers reviewed above hint at intriguing results: differences in mixed pair frequency as a function of separation, mass ratio, or star forming region; tighter coevality between binary components than among single stars in the same regions; evidence for higher mass ratios among closer binaries; hints that distinct binary formation mechanisms may be functioning in different binary separation ranges, although no telltale break has been observed in the binary separation distribution [30]. Although the target binaries in particular regions appear to be largely coeval, the regions studied also span a range of ages and are located in diverse environments (e.g., the stellar density and ionizing flux in Orion is considerably higher than that of e.g., Taurus), thus comparing frequencies of mixed disk systems between regions may be misleading. Spectral resolution also plays an important role in the determination of spectral types and veiling: the filling in of absorption lines, especially for highly veiled stars, can result in inaccurate spectral types as well as the obscuration of small emission line features. The more subtle results of the works reviewed are impossible to validate, given the small sample sizes of each individual study. Without a large sample of homogeneously observed young binaries, it is difficult to know if the sometimes contradictory results between the studies described are representative or particular to the specific stars selected.

In order to consider a statistically more significant sample, and combine the rich results from the entirety of the cited works, each of the studies described above with spectroscopic disk indicators was reexamined and reassessed for evidence of disks. Based on the most up to date information, triples and low signal to noise spectra were eliminated from the samples. For optical studies, veiling and Hα equivalent widths, modulo the spectral type criteria for the accretion thresholds outlined by [35], were used to identify disks. IR K-band spectra were visually analyzed for any evidence of Brγ emission, supplemented with veiling results reported in the papers. Objects common to more than one paper were only included once. The resulting meta-sample of 84 young systems is shown in Fig. 1 in a histogram of binary separation presented in four separate panels for the possible range of disk status (CC, CW, WC, WW). No clear trends are obvious, although a KS test yields a statistic of 0.13 with a 95% probability that the CC and WW distributions were drawn from the same parent sample. Similar limitations and biases apply to the combined sample as to each individual one. The last column in Table 1 lists the number of objects from each publication used in this meta-analysis before the redundant targets were culled.

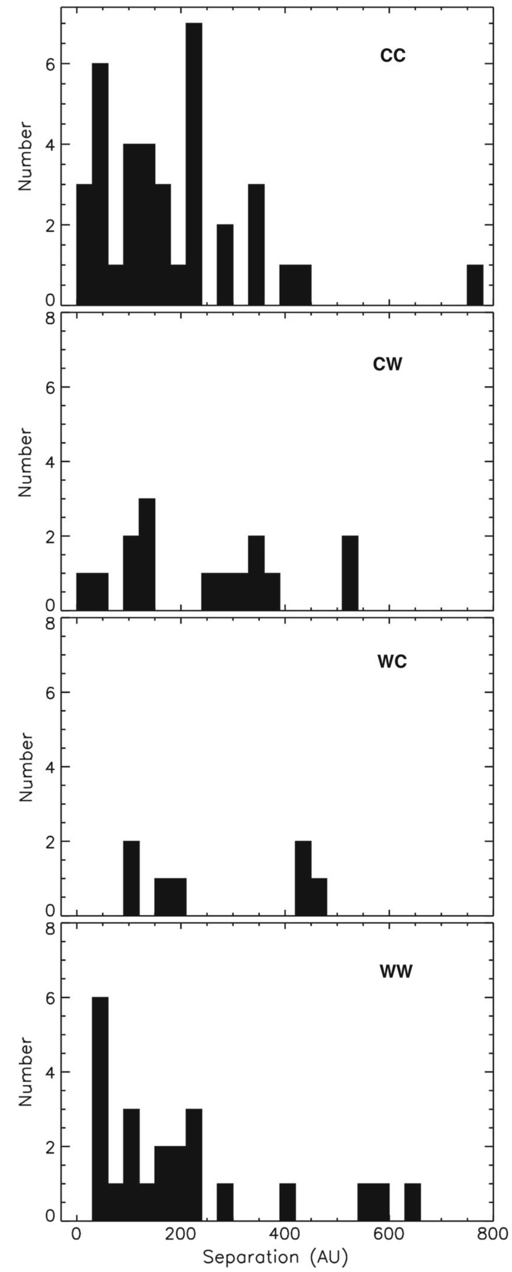


Fig. 1 The distribution of young binary separations shown for the studies listed in Table 1. From top to bottom the panels show the distributions for systems with two disks (CC), one primary disk (CW), one secondary disk (WC), and no disks (WW)

3 A high-spectral and angular resolution IR spectroscopic survey of young binaries

3.1 Motivation and new survey

The investigations described above represent a significant effort to spectroscopically characterize the stellar properties such as effective temperatures (T_{eff}) and disk presence plus active or passive accretion status for both stellar components in young binaries. In some cases, results included additional properties such as extinction. However, these works were based on samples of no more than a couple of dozen systems, typically fewer than ten, often were contaminated by unresolved triples, and applied spectral resolutions of a few thousand or less, limiting the statistical significance of the results and the scope of the accessible physical and dynamical properties. A few in-depth studies of one or two binaries employed high-resolution spectroscopy to determine the projected rotational velocity ($v \sin i$) and radial velocities (RVs) for each component [e.g., 53, 56, 57, 58], but the application to a broader analysis is limited given the specific focus.

This underscores the need for an angularly resolved spectroscopic survey of a large sample of young binaries at high spectral resolution, encompassing systems with small separations with the potential for star-disk interactions, known to impact the formation and/or evolution of circumstellar, planet-forming disks. Such observations permit the accurate and precise determination of component-resolved $T_{\rm eff}$, $v \sin i$, RV, veiling (defined as the excess continuum flux divided by the stellar photospheric flux), surface gravity (log[g]), accretion luminosity, and surface-averaged magnetic field strength (B); most of these properties are inaccessible to spectroscopy of only a few thousand resolution. Furthermore, although remarkable results are attainable from angularly unresolved multiple systems [e.g., 59], observations at high spatial resolution are critical for identifying the precise properties of individual stars and their circumstellar disks and accretion status.

Monin et al. [60] compiled the circumstellar disk diagnostic data available at that time from the literature, photometric as well as spectroscopic, for young binary components. On the basis of spectral types, they estimated the mass ratios and examined their distribution as a function of separation for 46 fully accreting and mixed disk systems, shown in their Fig. 4. As with the results shown here in Fig. 1, their analysis is based on a highly inhomogeneous data set that traces not only active accretion but also warm dust in evolving disks. Although they identify similar trends as other groups, i.e., the tendency for small separation binaries to have high mass ratios, it is not possible to disentangle these from selection effects such as a bias against the detection of small separation systems with relatively low mass and hence faint companions. They comment that “Further analysis... is rendered difficult by the small total number of objects, so any trends that might appear to be qualitatively significant do not correspond to an impressively significant KS statistic.” and conclude that “The most formidable obstacle to furthering our understanding of disk evolution in young binaries is the relatively small size of our database.” Little has changed in this regard over the last 15 years beyond a trio of papers in 2013 and 2014 [44, 54, 55].

The following sections provide a preliminary overview of a long-term effort, driven in part by these conclusions of [60], to amass a statistically significant ($\sim$ 100 systems) sample of $R \geq 30{,}000$ IR spectra of each individual star in young binary and multiple systems. The AO-fed observations were primarily undertaken at the Keck II 10 m telescope on Mauna Kea, Hawaii; some additional data were collected with the VLT on Cerro Paranal, Chile. A condensed description of the observational approach, data analysis, ancillary data, and spectra for several representative systems are presented in the following sections. A detailed report on the project and meta-analysis of the spectra and complete results for the full sample are forthcoming (Prato et al. in prep 2023).

IR observations are optimal for small-separation, low-mass young binaries for several reasons: (1) AO fed high-resolution spectroscopy on 8–10 m class telescopes has been available and has been continuously improving for over two decades, (2) seeing is superior in the IR, which aids in the feasibility of resolving systems both with and without the benefit of AO (under conditions of good seeing, AO system performance improves), (3) dusty star forming molecular clouds are less opaque in the IR, (4) given the low $T_{\rm eff}$ values of low-mass stars, they emit most of their flux in the IR, and (5) B-fields are more readily measurable in the IR because Zeeman splitting is proportional to wavelength [61]. The Keck spectroscopy described here is focussed on one order ($\lambda = 1.545 - 1.567\,\mu$m) in a region of the H-band rich in atomic and molecular lines sensitive to $T_{\rm eff}$, log(g), and B. The VLT data cover several standard diagnostic regions of the K-band sensitive to $T_{\rm eff}$, log(g), and active accretion (Br γ, CO, and CaI).

3.2 Sample

Orbital parameters yield the vital information required to turn observed trends into a predictive description of planet formation in the binary environment. Young binary systems with individually observable components and at least partially characterized orbits represent the gold standard [e.g., 62]. Clearly this ideal is challenged by the trade off between the determination of orbital periods in a practical time frame (i.e., sufficiently short periods and hence small separation binaries) and the diffraction limit of the largest telescopes which permit AO-assisted high-resolution spectroscopy of individual stars in systems with resolvable separations (and correspondingly larger separation binaries with longer orbital periods). The nearest star forming regions rich in young binaries hosting primordial disks are located at $\sim$ 120–160 pc [63], intensifying the challenge of resolving the closest pairs while mapping a significant fraction of the binary orbit.

Figure 2 shows the projected separation distribution of $\sim$ 80% of the 100 systems in the survey sample, from $0''.04$, the diffraction limit of the Keck II telescope 10 m aperture, to $4''.0$, a highly conservative cutoff for bound binary pairs given the stellar density of the Taurus and Ophiuchus regions [e.g., 38]. Circumstellar disk bearing systems are not distinguished in terms of whether disks are circumprimary, circumsecondary, or both. Spectral types range almost entirely from early K to late M: it is the stars in this pre-main sequence range that will mature to solar analogues on the main sequence. Although the targets do not comprise a complete sample of every binary in the Taurus and Ophiuchus star forming regions, they do represent almost all of the pairs accessible to component-resolved spectroscopy, modulo an effort to roughly balance the number of systems with and without circumstellar disks across the range of projected separations. Roughly 55% of the targets are from Taurus, 35% from Ophiuchus, and an additional 10% from other regions such as TW Hya. Triples are included only if the closest components have been angularly resolved with the spectroscopy.

A detailed cross match of this sample with GAIA will be performed; however, presently this is of limited usefulness because many if not most of the binaries in the sample do not have reliable DR3 parallaxes precisely because they are binary. For example,

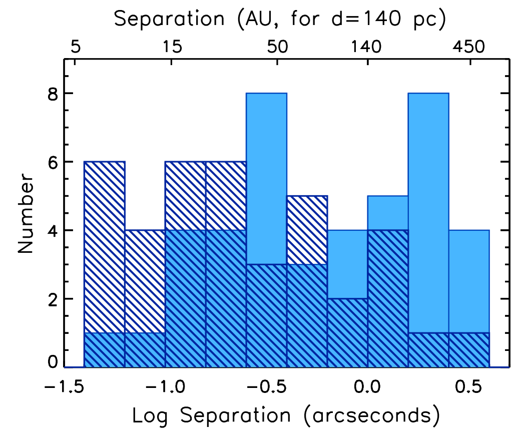


Fig. 2 The separation distribution of binaries for 80% of the full sample. The disk-bearing systems are indicated with the filled region and the diskless binaries are overplotted in cross-hatch. The paucity of disk-bearing, small separation systems is clear

the Renormalized Unit Weight Error (RUWE) value for DF Tau is 21.92; a value of <1.4 is the nominal cutoff for reliable GAIA astrometry. A cross match with the DR4 release will provide a more meaningful result. Alternate studies of Taurus and Ophiuchus, [e.g., 41, 64] will be used in the meantime to assess membership.

3.3 Observations, data reduction, analysis, examples of preliminary results

Angularly resolved spectra of young binary components were observed at the Keck II 10 m telescope with the facility near-IR spectrograph NIRSPEC [65, 66] behind the AO system (NIRSPAO) since 2002 but primarily in the last 10 years. The AO reimaged plate scale of NIRSPAO yields a 2-pixel slit-width of 0.″027 with $R \sim 30{,}000$; the NIRSPAO slit length is 2.″26. The echelle and cross-disperser gratings setting were set to target a central wavelength of 1.56 μm in the middle H-band order (Sect. 3.1). This spectral region includes features sensitive to $T_{\rm eff}$, log(g), and B. At the ∼4.2 km altitude, relatively constant ∼ 0 °C ambient temperature, and typically low precipitable water vapor of Mauna Kea, this wavelength range is almost devoid of telluric absorption lines. To correct for dark current and non-uniform pixel-to-pixel detector response, dark and flat-field frames were obtained; Ne, Ar, Xe, and Kr comparison-lamp frames provided wavelength and zero-point calibrations. Typical integration times were 300 s, taken with an AB or ABBA nodding pattern at two slit locations.

For wider binaries, NIRSPEC was employed without AO. In this case the 2-pixel slit-width was 0.″288 × 24.″. The OH night-sky emission lines prominent in the H-band were used for wavelength and zero-point calibration [67].

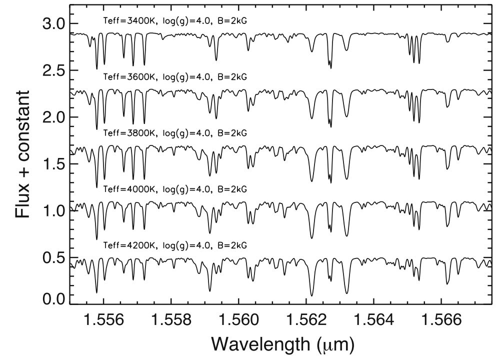
Data reduction was accomplished with the REDSPEC package [68]. Details are provided in [53]. For the closest stellar pairs, the point spread functions (PSFs) in the spatial dimension overlap in the two-dimensional spectra. After spatial and spectral rectification of the spectral orders on the array, a byproduct of the REDSPEC reduction is a FITS file of the order of interest with the two-dimensional spectrum of that isolated region. Individual spectra were extracted via a column by column Gaussian fit to the blended PSFs.

For about two dozen targets in the Ophiuchus star forming region, high-spectral resolution K-band spectra were obtained with the CRIRES IR spectrograph in collaboration with J.-L. Monin; these observations and results will be discussed in a joint publication (Prato, Monin, 2023, in prep).

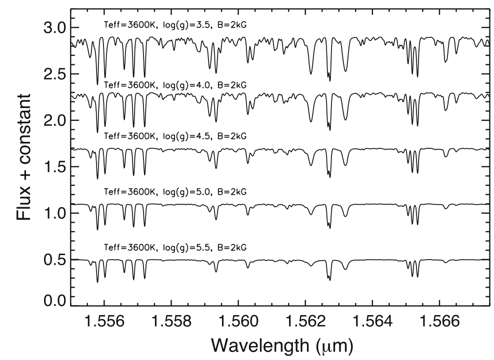
3.4 Analysis overview

The Spectroscopy Made Easy spectral synthesis code of [69] applied to the NextGen atmospheric models [70] yielded a grid of H-band (1.5440–1.5675 μm) model spectra covering parameter ranges that encompass all of the survey targets: $T_{\rm eff}$ 3000–6000 K, log(g) 3.0–5.5, B 0–6 kG. Figure 3 demonstrates the sense in which the spectra vary as a function of these parameters. The model spectra were synthesized using laboratory atomic transition data from the Vienna Atomic Line Database [71] following the procedure of [61, 72], and calibrated against the Solar spectrum [73] and the spectrum of 61 Cyg B. Key to this methodology were steps in which (1) spectral lines which appear in the VALD list but not in the solar and 61 Cyg B calibration spectra, and vice versa, were excluded from the synthesis, and (2) line oscillator strengths and van der Waals broadening constants were adjusted in the model spectra to best match the observed calibrator lines in the Sun and 61 Cyg B. Although time intensive, this procedure resulted in more precise fits and more accurate results. Starting with initial values estimated from the observed spectra by comparison to standard star data, each target star spectrum is run through the grid using a Marquardt fitting routine to identify the optimum parameter values. A fully detailed discussion of the model grid construction and fitting process will appear in Prato et al. (2023, in prep).

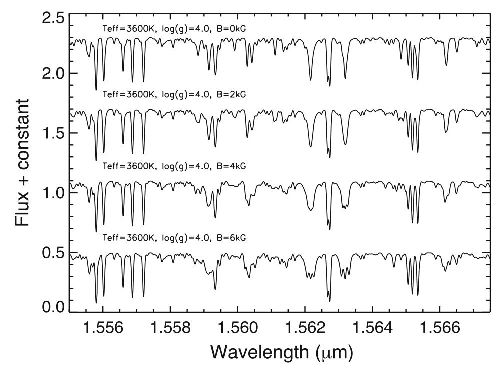
Fig. 3 Examples of synthetic spectra (with λ in air) from the grid described in Sect. 3.4 for ranges in **a** T_{eff}, **b** $\log(g)$, and **c** B, demonstrating the sensitivity of the various features, mostly atomic lines of Fe, Si, S, Ni, Ti, although the feature at 1.5627 μm is an unresolved OH doublet, to the stars' physical properties



(a) Range of T_{eff} values, log(g) and B constant.



(b) Range of log(g) values, T_{eff} and B constant.



(c) Range of B values, T_{eff} and log(g) constant.

3.5 Added value: ancillary data

3.5.1 ALMA

The unprecedented power of the ALMA array to resolve several AU scale dust and gas structures in young star disks is transformational. The angular resolution of ALMA in its most extended configuration is 20 mas at 230 GHz. The author is part of a team that obtained Cycle 7 data (PI Tofflemire) to determine the size, mutual disk inclinations, and disk morphology in a sample of 8 close binary systems ($a < 20$ AU) for which long-term AO monitoring has provided detailed orbital solutions [e.g., 62]. These data achieve spatial resolutions down to ∼1.5 AU, and reach sub-mm continuum sensitivities analogous to the DSHARP survey [11]; the results are currently undergoing analysis. Critically, these are the first sub-mm observations of any binary systems where the orbital solution is known, allowing us to link the location of disk material (circum-primary/secondary), disk mass, and projected disk inclination to the binary orbital parameters. This small but powerful sample will provide insights into how binarity shapes the planet-forming environment in the regime where it is inferred to have the largest effect. Most of the wider young pairs in the sample have already been observed with ALMA [e.g., 74, 75, 76]; these published and archival data sets will complement the component-resolved spectroscopy and will illustrate diffuse versus compact disk configurations, orientations, and internal disk structures.

3.5.2 AO imaging

Component-resolved imaging of the target systems not only provides orbital data, but also precise flux ratios, component colors, absolute photometry, and variability measurements. For wider pairs, the orbital precision is limited but for the closer binaries in the sample distribution (Fig. 2) many have approximate orbital solutions and about ten very small separation disk-bearing systems (the Cycle 7 ALMA targets) have relatively well-defined orbits [62]. Virtually all binaries in the sample have at least one epoch of angularly resolved H and K band imaging; for close to half there exists imaging across the near-IR JHKL bands.

3.5.3 Time domain monitoring

K2, *TESS*, ground-based facility data are available for almost every target in the spectroscopic sample. For photometric binaries [77], stellar rotation periods, episodic accretion, and even, potentially, planet-disk-star interactions [78] are attainable with the dense sampling of the *K2* and *TESS* missions. Furthermore, by combining stellar rotation periods determined from time domain monitoring with spectroscopically measured $v \sin i$ and model stellar radii, stellar inclinations may be determined for direct comparison with disk inclinations from ALMA.

3.6 Observed spectra, model fits, and derived parameters

Figure 4 shows initial results, observed and best fit spectra, for three binaries in the Taurus region. The signal to noise ratio (S/N) for these systems was 100–140 for the components of DF Tau and XZ Tau and ∼300 for both stars in LkCa 7. For high *S*/*N* spectra, with well-flattened continua and deep absorption lines, automated fitting to the synthetic grid returns robust parameters within two or three iterations. For heavily veiled and/or low signal to noise spectra, the Marquardt routine results do not always converge consistently but the iterative outcomes yield a range of viable parameters, which may then be tested by visual comparison between the corresponding synthetic spectrum and the observations. Optimization of the fitting code is still in progress. Uncertainty estimates for T_{eff} are on the order of 50–100 K, for log(g), ~ 0.1 dex, for veiling, ~ 0.1, and for $v \sin i$ and RV, ~ 1 km s^{-1}. The more formal analysis to be carried out on the complete sample will yield precise errors.

In general, outcomes are highly sensitive to the flattening of the continuum. For the closest pairs, the extraction by Gaussian fitting to the spatial profiles across the spectrum can distort the continuum, requiring flattening with a third or fourth order polynomial post-reduction. This process is particularly challenging for the latest type stars in the sample given the ubiquitous line coverage arising from molecular transitions in relatively cool photospheres.

In these first pass fits, the calculation of the surface magnetic field has been neglected; magnetically sensitive lines with large Lande g factors are therefore not well-fit for stars with large B values. Furthermore, lines which appear in the observations but not in the synthetic spectra, and vice versa, have not yet been masked out, leading to mismatches between the observations and models, particularly in the short wavelength portion of the panels in Fig. 4.

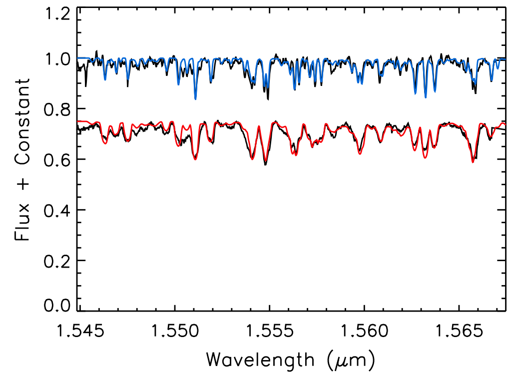
Even for cases with extreme values of veiling (DF Tau A, XZ Tau A) and large values of $v \sin i$ (DF Tau B, LkCa 7 B), relatively robust fits of the synthetic spectra to the observations were possible. One benefit of high-resolution spectroscopy (>30,000) is that even heavily veiled absorption lines from rapidly rotating stars are discernible with sufficient signal to noise to be fitted; at low spectral resolutions, these features can blend and wash out. This facilitates the determination of far more nuanced disk characteristics than has ever been possible before and, crucially, permits the simultaneous measurement of properties such as $v \sin i$ and veiling, which can be variable in active accretors.

3.7 Comparison with previous observations

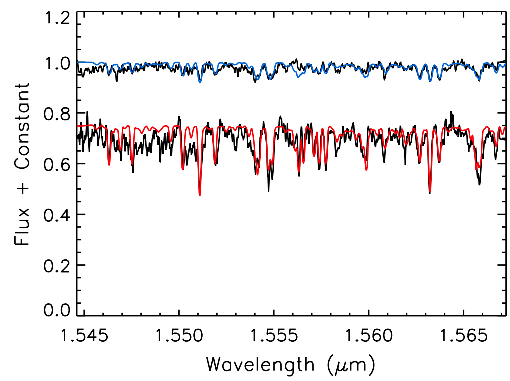
Using the same spectra shown in the top panel of Fig. 4 and comparing target data with spectra of main sequence standard stars, [53] also determined some of the fundamental parameters for DF Tau A and B. Their $v \sin i$ results are consistent with those reported here; the [53] value for veiling is weaker for the primary star, 0.6±0.1 compared to the value of 1.1 ± 0.1 shown in this work. Veiling for DF Tau B is consistent in both investigations, 0.0±0.1 [53] and 0.1 ± 0.1 (Table 2). The RV results differ by a couple to several sigma; the results reported here, 20 ± 1 (primary) and 15 ± 1 km s^{-1} (secondary), are more consistent with the phased RV curve shown in Figure 8 of [53]. No values for log(g) were reported in [53]. In this work, the T_{eff} for the two components differs by over 200 K, whereas [53] found similar spectral types for both components; this discrepancy will be investigated in more detail.

All three systems shown in Fig. 4 were observed by [51]; [53] includes a discussion of the contamination of the DF Tau B component by the strong Hα emission line emanating from DF Tau A, described by [51]. As a result of this and other observations, [53] characterized DF Tau B as diskless, consistent with the result reported here (Table 2) for veiling close to zero. Comparison of differential spectral types from [51] and the T_{eff} values determined here for LkCa 7 and XZ Tau yield consistent results; because

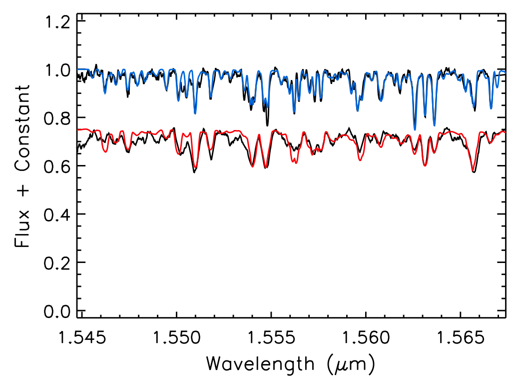
Fig. 4 Observed (black) and best fit synthetic spectra (blue = primary, red = secondary) for three young binaries in the Taurus sample. Details of the fitting procedure are described in the text. In each panel, the primary and secondary star are offset by a constant



(a) DF Tau A and B (separation 0.″1).



(b) XZ Tau A and B (separation 0.″3).



(c) LkCa 7 A and B (separation 1.″1).

the exact conversion from spectral type to $T_{\rm eff}$ is a function of the particular scale used, a direct comparison is not included here. Figure 4 and Table 1 show a modest degree a veiling for LkCa 7 A, whereas [51] did not detect any evidence for veiling or a disk around either the primary or the secondary. The greater sensitivity and lack of blended lines in the high spectral resolution data may account for this small discrepancy. Thus a small amount of material may be present around the primary, but the 0.1±0.1 result reported here for the veiling of LkCa 7 B is consistent with the absence of circumstellar material noted in [51]. Similarly, both the spectral type differential and the veiling results for XZ Tau are consistent between this work and [51].

3.8 Future work

As of July 2022 spectra of all targets for this high-resolution survey have been obtained. Subsequent steps include completion of data reduction and spectral extraction for newly observed systems, then removal of bad pixels in the final spectra and careful continuum

Table 2 Best fit binary properties

Target	Separation (″)	T_{eff} (K)	log(g) (dex)	$v \sin i$ (km s^{-1})	Veiling	RV (km s^{-1})
DF Tau A	0.1	3650	4.0	15	1.1	20
DF Tau B	.	3400	3.9	45	0.1	15
XZ Tau A	0.3	3500	3.7	29	2.2	22
XZ Tau B	.	3250	3.2	20	0.1	20
LkCa 7 A	1.1	3950	4.0	20	0.3	17
LkCa 7 B	.	3250	3.2	40	0.1	15

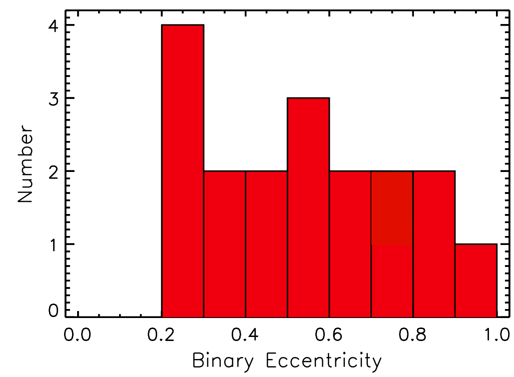


Fig. 5 The eccentricity distribution of close young binaries with sufficient orbital arcs imaging. Data are from [52, 53, 83–88] and Tang et al. (submitted)

flattening in preparation for running through the grid. Using spectral type standard stars in common with [79] that have Keck spectra observed with exactly the same methodology as the targets [e.g., 80], line depth and equivalent width ratios of Fe I and OH absorption features around 1.563 µm will be used to calibrate T_{eff} for comparison with results from the grid.

A more sophisticated grid analysis than shown here will include masking out lines in the observed spectra that do not appear in the synthetic spectra and vice versa. Relative absorption line equivalent widths in young star target spectra compared with standard star spectra provide starting point values for the model fit code; subsequent iterations of the fitting procedure will add in the fundamental parameters shown in Table 2 and finally the magnetic field components [72]. A Monte Carlo analysis will be used to determine parameter uncertainties. Corner plot analyses [e.g., 81] will also be applied in order to explore the distributions of the stellar properties and to test for degeneracies in pairs of stellar parameters.

The survey end-product will be a set of parameters such as those presented in Table 2, with the addition of the surface magnetic field strength measurements, for all or most of the 200+ stars in the sample (some systems have higher order multiplicity than binary). These rich data will be used to explore and compare the parameter distributions, for example primary and secondary star T_{eff} distributions as well as systematic differences in distributions between targets in different star forming regions. The relationships between the stellar and disk properties such as rotation, B field, and veiling will yield insights into factors modulating the accretion rate. It will also be possible to investigate the dependence of magnetic field strength on T_{eff}, a proxy for stellar mass to some extent, and many other relationships.

The addition of ancillary data such as *K2* and *TESS* light curves, ALMA images, near-IR colors, UV excesses, and other information when available will further enrich the results of this survey. In particular, multiperiod lightcurves [77] can provide rotation periods for both stars in some angularly unresolved binaries. Extremely high angular resolution ALMA images yield disk morphologies and—critically—disk inclinations (Tofflemire et al. in prep). For some of the closest pairs in the sample, partial orbits have been obtained from fits to years and in some cases decades of angularly resolved imaging data [e.g., 53]. Figure 5 shows the eccentricity distribution for most young binaries with relatively reliable orbital solutions; approximately half of the 18 systems plotted are in the sample described here. This figure illustrates the relatively flat distribution of eccentricities; none are smaller than 0.2. These orbital data may yield key insights into the shaping and evolution of circumstellar disks as a function of close periastron passages and are invaluable to collect at a cadence appropriate to the orbital period. The combination of spectroscopically determined properties, interferometric disk sizes and inclinations, and rotation period measurements will paint an unprecedented and detailed picture of the relationships between disks, stars, and binary orientations.

4 Summary

This contribution summarized the relatively concise literature of component-resolved spectroscopic surveys of young visual binary stars. The case was made for larger surveys at higher angular and spectroscopic resolution, and the very early results of such a survey were described and the methodology for completing the project presented.

What is next? What new contributions are needed from theorists and from observers to move this field forward? In part, the answers to these questions depend on the outcomes of the current work. Observationally, the likelihood is high that additional data will be a requirement: even a sample of 100 stars, four times greater than any previous surveys, permits only marginally statistically significant analyses. The 2.2 μm K-band capabilities of GRAVITY on the VLT could provide a spectacular near-IR complement to the ALMA results for these targets. On the theory side, modeling of stable disk-binary configurations, modulo realistic stellar properties, may yield insights into disk longevity. In terms of technical innovations to facilitate future advances, AO-fed optical spectroscopy would open an extended parameter space.

The fundamental goal of this program is to better understand disk longevity and dissipation, particularly in young binaries but hopefully through extrapolation of results, with respect to young single stars as well. The motivation is to conceive a more complete accounting of the environments which support planet formation. These survey results may yield more questions but will undoubtedly also provide some insights.

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Data Availability Statement This manuscript has associated data in a data repository. [Authors' comment: The fit parameters and the reduced spectra will all be provided on a publicly available database that has been developed at Lowell Observatory; the link will be accessible through the author's website when the database has been populated. Spectra are available from the author upon request. Reduced standard star spectra for the same H-band spectral region are currently available at http://www2.lowell.edu/users/lprato/hband/homepage.html. Raw data for this project are available through the Keck Observatory Archive.]

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