YOUNG BINARY STARS AND ASSOCIATED DISKS

ROBERT D. MATHIEU
University of Wisconsin - Madison

ANDREA M. GHEZ
University of California, Los Angeles

ERIC L. N. JENSEN
Swarthmore College

MICHAL SIMON
State University of New York, Stony Brook

Abstract - The typical product of the star formation process is a multiple star system, most commonly a binary star. Binaries have provided the first dynamical measures of the masses of pre-main-sequence (PMS) stars. These measurements have established that T Tauri-like stars are indeed of solar mass or less, and have provided preliminary support for the mass calibrations of theoretical PMS evolutionary tracks. Surprisingly, in some star-forming regions PMS binary frequencies have been found to be higher than among main-sequence solar-type stars. The binary frequency in the Taurus star-forming region is a factor two in excess of the field, although other regions show no excess. Observations suggest that the difference in PMS and main-sequence binary frequencies is not an evolutionary effect, and thus recent attention has focussed on correlations between binary frequency and initial conditions (e.g., stellar density or cloud temperatures). Accretion disks are common among young binary stars. Binaries with separations between 1 AU and 100 AU have substantially less submillimeter emission than closer or wider binaries, suggesting that such binaries have dynamically truncated their associated disks. Direct evidence of dynamical clearing has been seen in several binaries, most notably GG Tau. Remarkably, PMS binaries of all separations show evidence of long-lived circumstellar disks and continued accretion at stellar surfaces. This strongly suggests that the circumstellar disks are replenished from circumbinary disks or envelopes, perhaps through recently hypothesized accretion streams across dynamically cleared gaps. The frequent presence of either circumstellar or circumbinary disks suggests that planet formation can occur in binary environments. That planets may form around stars in wide binaries is already established by their discovery. Circumbinary disk masses around very short period binaries are ample to form planetary systems such as our own. The nature of planetary systems among the most frequent binaries, with separations between 10 AU and 100 AU, is less clear given the observed reduction in disk mass. However, even these

systems have disks with masses adequate for the formation of terrestrial-like planets.

I. INTRODUCTION

During the last decade we have gone from *suspecting* that most pre-main-sequence (PMS) stars are binary stars to *knowing* that most PMS stars are binary stars. Advances in high-angular-resolution infrared imaging technology have enabled large surveys for binaries in a variety of star-forming regions. The consistent result is that binary stars are abundant among young stars, indeed perhaps remarkably so.

The implications of this for star and planet formation research are enormous. From an observational point of view we ignore the presence of companion stars at our own peril. A companion star may substantially contaminate the light attributed to the primary, thereby leading to incorrect luminosity, temperature and extinction measurements, erroneous age and mass estimates, incorrect disk models, and so on. From a theoretical point of view, we must recognize that binary star formation is the primary branch of the star formation process. While our presence in orbit around a single star will always drive interest in single-star formation, a general understanding of star formation must focus on multiple star formation. Similarly, the typical environment for planet formation may be a binary star. The ubiquity of binary systems suggests that the question of planet formation in binary systems is critical for setting the overall frequency of planets.

In this contribution we will focus on those observations of PMS binaries as they relate to (1) probes of evolutionary models, (2) binary star populations, and (3) protoplanetary disks and the potential for planet formation. Typically, consideration will be restricted to binaries with primaries having masses less than 3 $M_{\odot}$ (with primaries of solar mass or less predominating) and ages of less than 10 million years. Observations of such PMS binaries have been comprehensively reviewed by Mathieu (1994; see also review papers in Milone and Mermilliod 1996), and thus we will concentrate our attention on observations made since then. Many theoretical issues of binary formation are addressed in Bodenheimer et al./ (this volume).

II. PRE-MAIN-SEQUENCE STELLAR PROPERTIES

Typically, the masses and ages of young stars are inferred from comparisons with PMS evolutionary tracks. The mass and age calibrations of such tracks are largely untested against observations. Young binary stars provide powerful tools for assessing the validity of these models. In particular, their orbital motions yield *direct* measures of their stellar masses, while under assumptions of coeval formation the derived ages of binary components test relative age calibrations of the tracks.

High-angular-resolution observations from both speckle interferometry and the Hubble Space Telescope Fine Guidance Sensors have begun to contribute significantly to the determination of astrometric orbits (Ghez et al. 1995; Thiébaut et al. 1995; Simon et al. 1996). These studies clearly show relative motion of the two stars in many PMS binaries, and show curvature in the relative motions of several. These motions are larger than the velocity dispersions in star-forming regions (SFRs) and thus generally argue for an orbital origin.

Ghez et al. (1995) treated the observed relative motions statistically to obtain a typical system mass among a set of astrometric binaries. Their results are shown in Fig. 1. The trend in the data of increasing relative velocity with decreasing separation also strongly suggests orbital motion. The comparison curves represent the expected values of relative velocity as a function of binary separation for a set of binary stars observed at random orientations. While any given datum reflects only the state of a binary at a certain moment in its orbit, and thus cannot reliably provide binary mass, the median mass of 1.7 $M_{\odot}$ found from the ensemble should be a valid estimate of the typical binary total mass. This value empirically supports the theoretical conclusion that most PMS stars have solar masses or less.

Eclipsing binaries are particularly powerful routes to the measurement of *both* stellar masses and radii. Until recently only EK Cep had been studied in detail (Popper 1987; Claret et al. 1995; Martín and Rebolo 1993). Unfortunately the PMS secondary of this system is very near the ZAMS and thus places little constraint on evolutionary tracks. A second eclipsing binary, TY CrA, recently has been intensively studied by two groups (Casey et al. 1998, Corporon et al. 1996, and references therein). This system consists of a Herbig Be star of 3.16 $M_{\odot}$ on the main sequence and a cool (4900 K) 1.64 $M_{\odot}$ secondary star. The 2.1 $R_{\odot}$ radius of the secondary, along with its association with the R CrA dark cloud and lithium absorption, identify it as PMS. Comparison with evolutionary models places it at the base of its Hayashi track, with an age of 3 Myr (Fig. 2). Casey et al. tested three sets of evolutionary tracks— Swenson et al. (1994; Fig. 2), Claret (1995), and D'Antona and Mazzitelli (1994)—against the TY CrA secondary. In all three cases solar-composition 1.64 $M_{\odot}$ tracks are consistent with the observed physical parameters. Thus the secondary star represents the first quantitative dynamical test of PMS evolutionary tracks, which they pass without contradiction. Unfortunately, the accuracies of the derived physical parameters were not adequate to distinguish critically *among* evolutionary tracks. Discovery and study of additional PMS eclipsing binaries are sorely needed.

Stellar masses can also be measured via orbital motions of disk gas.

The circumstellar disks of the single stars DM Tau and GM Aur, and the circumbinary disks of GG Tau and UY Aur have been used in this way (Dutrey et al. 1994; Duvert et al. 1998; Guilloteau and Dutrey 1998; Dutrey et al. 1996; Guilloteau et al. 1999). In well-positioned systems, the relative precision of this technique can be less than 10%, so that uncertainty in the distance to a given system is the limiting factor in the determination of its mass.

The *relative* mass calibrations of evolutionary models can be tested with careful analyses of PMS double-lined binaries, which provide very accurate dynamical mass ratios. Adopting the observations and analysis procedures of Lee (1992), Figueiredo (1997) has used the PMS binary 162814−2427 to test sets of PMS evolutionary models with different input physics; Lee also studied four other double-lined systems. Both Lee and Figueiredo find that the relative mass calibrations of evolutionary tracks are consistent with the observed mass ratios of the binaries, presuming coeval formation of the component stars. However, Figueiredo notes that the observational uncertainties are considerably higher than the theoretical ones. *More generally, it should be appreciated that even given accurate mass determinations meaningful comparison with theory is severely limited by uncertainties in the effective temperatures and luminosities of the weighed stars.* (See Fig. 3 for an example of one aspect of the temperature difficulty.)

Recently, Prato (1998) has extended this observational test into the near-infrared. Infrared observations permit the detection of cooler companions than does the optical, which has the advantages of 1) converting single-lined systems into double-lined systems and thus expanding the sample and 2) providing double-lined systems with large mass ratios which give more leverage in testing the models. Prato has obtained H-band high-resolution spectroscopy of the previously single-lined system NTT 155913-2233, and detected an M5 companion to the K5 primary. The derived mass ratio is about 2, the largest mass ratio yet measured among PMS binaries. Interestingly only the Swenson et al. (1994) models are roughly (within 1 σ) consistent with the binary system. The components are neither coeval nor consistent with the mass limits using the D'Antona and Mazzitelli tracks.

Similarly, White et al. (1999) conducted a test of evolutionary models by requiring that the components of the quadruple GG Tau be the same age. This system is particularly useful as its components span a wide range in mass and extend across the stellar/substellar boundary, a region where both the evolutionary models and the PMS temperature scale are very uncertain. Of the evolutionary models tested, they find the Baraffe et al. (1998) models yield the most consistent ages using a temperature scale intermediate between that of giants and dwarfs for PMS M stars (Fig. 3). With this model, the coldest component of the GG Tau system, GG Tau Bb, is substellar with a mass of 50 M_{Jup}.

At present we have no empirical measure of the absolute ages of PMS stars, and thus age determination relies on the application of evolutionary models to the temperatures and luminosities of the stars. As stressed by Simon et al. (1993), applying this procedure to the combined light of binaries must lead to biased results, primarily toward younger ages due to enhanced luminosity. Typical errors are of order a factor 2, although errors as large as an order of magnitude are possible (Brandner and Zinnecker 1997, Ghez et al. 1997b).

Assuming a given evolutionary model, the inferred relative ages of the components of binaries provide an empirical test of coevality, which is useful for distinguishing between different modes of binary star formation. Hartigan et al. (1994) determined the ages of components of wide binaries, and found that in roughly one-third of the cases the secondary was significantly younger than the primary. Brandner and Zinnecker (1997) did not find any such age differences in a sample of somewhat closer binaries. Ghez et al. (1997) noted that many of the binary components in the Hartigan et al. sample were themselves binaries, leading to biased age estimates. When they considered the subset of the Hartigan et al. sample not known to be triples, all of the binary components were coeval to within the uncertainties.

III. YOUNG BINARY POPULATIONS

The early multiplicity surveys of the Taurus and Ophiuchus dark cloud complexes revealed an apparent difference in the binary star fractions of PMS and main-sequence stars (Ghez et al. 1993; Leinert et al. 1993; Simon et al. 1995). This difference was found to be particularly pronounced within the separation range of 1 AU to 150 AU, where the young stars were found to be twice as likely to be members of a binary system as the older stars observed by Duquennoy and Mayor (1991, DM91). Interpretations of this unexpected finding have included (1) observational selection effects, especially differences in detection limits between the surveys and differences in sample populations (e.g., relative fractions of classical T Tauris stars (CTTS) and weak-lined T Tauri stars (WTTS)), (2) formation differences among SFRs (e.g., Reipurth and Zinnecker 1993), (3) varying period distributions (Leinert et al.), or (4) the disruption of primordial multiple star systems over time (Ghez et al. 1993). Alternatively, Mathieu (1996) questioned whether the excesses were statistically significant. The variety of interpretations led to many subsequent surveys in order to increase both the sample sizes and the numbers of SFRs studied (see Table 1). These surveys have shed light on many of the questions raised.

A. Is the excess of young companion stars real?

The question of whether or not the excess frequency of PMS binaries is real can be divided into two parts. First, is the high fraction of binary stars in Taurus and Ophiuchus statistically significant? Second, is this really different from the binary fraction in the solar neighborhood? The issue of the latter question is incompleteness, and raises the related question of how incomplete surveys should be compared.

Addressing the first question requires observation of larger samples of stars. Köhler and Leinert (1998) roughly doubled the sample studied in the Taurus SFR by surveying 75 new PMS stars discovered by *ROSAT*, most of which are classified as WTTS.† Their survey is comparable in sensitivity to the previous infrared speckle work done in Taurus (flux ratio $\Delta K \sim 3$ mag) and results in a binary frequency (BF, number of multiples divided by number of systems, hereinafter and in Table 1) consistent with the earlier surveys, reinforcing the conclusion that Taurus does indeed have a remarkably high BF.

The expanded Taurus sample has also addressed the concern that CTTS and WTTS might have differing binary frequencies. This would constitute a serious selection effect as the early surveys comprised primarily CTTS (which dominated the available catalogs such as Herbig and Bell 1988), while in fact the X-ray selected WTTS appear to outnumber the CTTS (e.g., Walter et al. 1994, Neuhäuser 1997, Walter et al. this volume). However, Köhler and Leinert (1998) find no significant difference between the CTTS and WTTS in either their BF or in their distribution of separations.

Although the measured binary frequency for PMS stars in Taurus is a factor of two larger than that measured for stars in the solar neighborhood, this does not necessarily mean that the parent populations are different. The discrepancy between the two binary frequencies could be due to a difference in sensitivity to low-mass companions. In particular, it is possible that PMS star surveys are detecting very low-mass stars that are relatively more luminous when they are young (e.g., Burrows et al. 1993, Malkov et al. 1998). Surveys of main-sequence stars generally have well-defined mass-ratio (q) sensitivity limits. In the case of the DM91 survey of solar-mass stars, the spectroscopic portion of the survey, which cover periods less than $\sim$ 10,000 days or equivalently semi-major axes less than $\sim$ 10 AU, is complete down to $q > 0.1$. DM91's sensitivity to longer periods or more widely separated systems,

† It should be noted that distances, and hence luminosities and ages, of the *ROSAT* selected stars are controversial; Briceño et al. (1997) argued that the majority are actually foreground ZAMS stars. Neuhäuser and Brandner (1998) studied the small sample of these stars that are sufficiently bright to have *HIPPARCOS* parallaxes, and found them to be younger than 1.6×10^7 years, but in front of their presumed birth place, possibly due to ejection. Nonetheless, Köhler and Leinert point out that if their sample does include foreground stars with a binary frequency like that of the nearby solarlike stars, then the binary frequency of the WTTS remaining in the Taurus SFR must be even higher than the observed value.

identified by direct imaging, is limited to $q > 0.3$. In contrast, the limits of PMS star surveys, which have generally been carried out at a single wavelength (typically 2.2 μm), are harder to characterize in terms of mass and thus are generally described in terms of limiting flux ratios or flux densities. Estimates of the secondary star masses from these single wavelength measurements involve a number of assumptions. In particular, one has to assume that the two stars have the same age, the same line-of-sight extinction, and no infrared excess (e.g., Meyer and Beckwith 1998). Follow-up studies, which resolve the binary stars at multiple wavelengths, show that most systems have $q > 0.3$ (Hartigan et al. 1994; Brandner and Zinnecker 1997; Ghez et al. 1997b), suggesting that the high young-star BF is unlikely to arise from a multitude of binary star systems with $q < 0.3$. Still, the lack of understanding of the true mass limits of the young surveys and the limited depth of DM91's main-sequence survey at comparable separations is a major weakness in the discussion of the relative BFs of the PMS and main-sequence stars.

B. Does the binary population evolve in time?

If the PMS and main-sequence binary frequencies do differ, a possible explanation is the disruption of primordial multiple star systems over time (Ghez et al. 1993). This has led several groups to pursue observations of binary frequencies in open clusters with different ages. Four clusters have now been studied intensively by Bouvier and his collaborators using adaptive optics and by Patience and her collaborators using speckle imaging: α Per ($\sim$ 50–70 Myr), Pleiades ($\sim$ 80–120 Myr), Hyades ($\sim$ 600 Myr) and Praesepe ($\sim$ 600 Myr).

The K-band speckle imaging survey of the Hyades (Patience et al. 1998a), α Per and Praesepe (Patience et al. 1998b) span a wide range of spectral types (A0–K5). These studies have a uniform mass ratio limit over their separation range, which fortuitously matches that of DM91; thus their uncorrected BF for F7–G9 stars is directly comparable to DM91's sample. They find the cluster binary frequencies to be both statistically consistent with the solar neighborhood population and to be significantly lower than the BF in Taurus. The near-infrared adaptive-optics studies of G and K stars in the Pleiades (Bouvier et al. 1997) and Praesepe (Bouvier et al., in preparation) have less uniform mass ratio limits, ranging from 0.6 to less than 0.1 over the separation range ($0''.08$–$6''.9$) studied. Over the separation range reaching $q = 0.3$ ($0''.3$–$6''.9$) and limiting the BF to $q > 0.3$ ratios results in a BF of 0.14 for the Pleiades, comparable to that reported by DM91 in this range (0.17); Praesepe produces similar results. The lack of change in BFs within this age sequence of clusters indicates that evolution is not a strong effect, at least after $\sim$ 50–70 Myr.

C. Does the binary formation outcome vary among the SFRs?

The apparent overabundance of young companions in Taurus with respect to the solar neighborhood can also be explained if Taurus-like SFRs are not the origin of most stars in our solar neighborhood. This would require other SFRs to be less efficient at either forming or maintaining binary stars, *and* to be the dominant contributors to the field population. Consistent with this line of reasoning, the majority of field stars have been suggested to originate in dense stellar clusters in giant molecular clouds and not in low-stellar-density regions such as the Taurus dark cloud complex (e.g., Lada et al. 1991). Furthermore, high-density SFRs might plausibly have lower binary fractions, either by inhibiting binary formation or by promoting their rapid destruction (e.g. through encounters (Kroupa 1995) or erosion of circumstellar disks (Hall 1997)).

Orion, the closest giant molecular cloud, is three times as distant as Taurus, and thus systems similar to the closest binaries resolved in Taurus are not currently resolved in Orion. Nonetheless there is still a large overlap in the separation/period range studied so far. Petr et al. (1998) and Simon et al. (1999) have studied the innermost region of the Orion Trapezium cluster using high-resolution imaging techniques at K. They find a BF similar to that of the nearby solar-like stars (Table 1), although the uncertainty is large owing to the small number in the sample. Padgett et al. (1997) used V- and I-band *HST* images of the Trapezium, and also of NGC 2024, 2068, and 2071, to investigate the BF. In both samples, they measured a BF somewhat higher than that of the solar-like stars, but only at a $\sim 1\sigma$ level. While these estimates are lower bounds because they do not correct for incompleteness, taken together with Prosser et al.'s (1994) results they suggest that the BF in the clusters of the Orion OB association is similar to that of the nearby solar-like stars, at least in the range of separations surveyed to date.

It is tempting to conclude that the high densities of the young clusters have led to lower binary frequencies than in Taurus, and more generally that binary frequency is anti-correlated with stellar density. Several other regions in Table 1 are consistent with this hypothesis (e.g., the dark cloud complexes Chamaeleon, Corona Australis, and Lupus (Ghez et al. 1997a); but see IC348 (Duchene et al. 1999a)), but the precisions of the measured BFs are lower, as are the confidences of the consequent conclusions. In addition, the present samples do not clearly discriminate between stellar density and other environmental factors. Thus Durisen and Sterzik (1994) have suggested that cloud temperature may play a key role; in the existing samples the higher stellar densities are found in OB associations which might arguably have higher temperature environments than dark cloud complexes. Isolating the critical factors in determining binary frequencies will be a challenging task.

Finally, none of these surveys covers the entire separation range of binary populations. As such, differences in measured binary frequencies could be the result of differing separation distributions, perhaps also linked to initial conditions. In this regard, Brandner and Köhler (1998) report that the binary separation distribution peaks at 90 AU among the youngest subgroup in Sco OB, and at 215 AU toward an older subgroup in the same association. As always, small sample sizes are a concern as is the possibility of contamination by field stars at the larger separations. The frequency of the shortest period binaries (e.g, P < 100 days) has also received attention. At present orbital solutions exist for nearly 30 spectroscopic binaries. In the most recent summary, Mathieu (1996) reports 7 binaries with P < 100 days among 91 PMS stars for a frequency of 8% $\pm$ 3%, the same as found for main-sequence solar-type stars. Even so, an excess comparable to those found in the high-angular-resolution surveys is not excluded by these data. Spectroscopic surveys of larger, carefully selected samples are needed. High-precision long-time-scale surveys will be especially fruitful; their sensitivity to long period systems will both increase the expected number of detections, improving statistical significance, and provide important cases for combined spectroscopic-astrometric orbital solutions.

IV. DISKS IN YOUNG BINARY STARS: STRUCTURE

The frequency of binary companions is a critical datum with respect to assessing the prospects for the formation of planets, in part because of the impact of companions on protoplanetary disks. The observational case for disks in young binaries is well established (see Mathieu 1994). Low-spatial-resolution observations of CTTS binaries reveal many of the classic signatures of disk material and accretion, such as excess emission at near-infrared through millimeter wavelengths, spectral veiling, Balmer and forbidden emission lines, and polarization. Disk material may be located around individual stellar companions (circumstellar disks) and/or entire binary star systems (circumbinary disks). Theoretical calculations of binary-disk interactions predict that companions will truncate both circumstellar and circumbinary disks, with circumstellar disks having outer radii of 0.2–0.5 times the binary semimajor axis a, and circumbinary disks having inner radii of $2a$–$3a$, with the exact values depending on eccentricity, mass ratio, and disk viscosity (Artymowicz and Lubow 1994; see also Lubow and Artymowicz, this volume). Recent observations have made significant progress towards delineating such structures of disks in binary environments, and the potential for planet formation in these disks.

A. Disk masses

Millimeter or submillimeter wavelength measurements of dust continuum emission allow a measurement of the total disk mass present in a system since at least part of the disk is optically thin at these wavelengths. The first systematic survey of millimeter emission from a large number of young stars (Beckwith et al. 1990, Beckwith and Sargent 1993) suggested that millimeter fluxes from close binaries might be lower than those from wider binaries. The subsequent discovery of many more young binaries and further millimeter and submillimeter observations allowed more detailed investigation of this question. Jensen et al. (1994, 1996a), Osterloh and Beckwith (1995), and Nurnberger et al. (1998) found that millimeter fluxes (and by extension, disk masses) are significantly lower among binaries with separations of 1–100 AU than among wider binaries or single stars. Binaries wider than 100 AU have a distribution of millimeter fluxes indistinguishable from that of single stars. Finally, there is no evidence for a diminished disk mass around many PMS spectroscopic binaries (separations of less than 1 AU), including GW Ori, UZ Tau E, AK Sco, DQ Tau and V4046 Sgr (Mathieu et al. 1995; Jensen et al. 1996a,b; Mathieu et al. 1997).

The amount of reduction in millimeter flux among the 1–100 AU binaries is consistent with their circumstellar disks being truncated at 0.2–0.5 times the binary separation, as predicted by theory. However, the surface densities of these circumstellar disks are poorly constrained. The low millimeter fluxes give typical disk-mass upper limits of a few times 10^{-3} $M_\odot$, while the presence of *IRAS* 12, 25, and 60 μm emission from most of the binaries requires the presence of at least tenuous circumstellar disks with $M_{\rm disk} \gtrsim 10^{-5}$ $M_\odot$. [†]

These observations suggest the rather intuitive picture that binaries much wider or much closer than typical disk radii do not significantly alter disk structure, while those binaries whose separations are comparable to disk radii substantially modify the associated disks. The breakpoint of roughly 100 AU is similar to the sizes of disks seen in millimeter aperture-synthesis images (e.g., Koerner and Sargent 1995) and optical/IR scattered-light images (McCaughrean et al., this volume).

Images of $\lambda = 1.3$ mm continuum emission from the young quadruple system UZ Tau empirically confirm this general picture on all three scales (Fig. 4; Jensen et al. 1996b). UZ Tau E is a spectroscopic binary with a projected semimajor axis of $a \sin i$ = 0.1 AU (Mathieu et al. 1996), and UZ Tau W is a binary with a projected separation of 50 AU (Ghez et al. 1993). The two binaries are separated by roughly 500 AU. UZ Tau E has strong 1.3 mm emission that is resolved with a radius of

[†] It should be noted that the absolute disk masses are highly uncertain due to the poorly determined dust opacities, gas-to-dust ratios, and disk surface-density profiles (e.g., Beckwith and Sargent 1993).

~ 170 AU and estimated mass of $0.06\ M_\odot$. This circumbinary disk has a size and mass similar to those seen around other young stars, and by extension, similar to the early solar nebula. It is not evidently affected either by the presence of an embedded binary with separation much smaller than its radius or by the presence of a companion (UZ Tau W) at a separation much larger than its radius. In marked contrast, UZ Tau W, with a separation comparable to a typical disk size, has millimeter emission that is greatly reduced both in flux and in spatial extent. The unresolved millimeter emission must arise from circumstellar disks around one or both of the stars in the 50 AU binary. It is noteworthy that, though the circumstellar disks are reduced in mass and size, they are still present. We note that unresolved observations of the quadruple system would see a "normal" millimeter flux, i.e. one comparable to that from single stars, whereas the distribution of disk material is in fact much more complex.

B. Circumbinary disks and disk clearing

The millimeter surveys indicate that *massive* circumbinary disks are rare in binaries wider than a few tens of AU. As noted above, most binaries with separations of 1–100 AU are undetected at millimeter wavelengths, placing stringent limits on any circumbinary material. In addition, Dutrey et al. (1996) made $\lambda = 2.7$ mm interferometric observations of 18 binaries in Taurus-Auriga and detected circumbinary emission from only one, UY Aur. (Note that the circumbinary disk around GG Tau had been previously discovered and was not included in this study.) In the widest binaries, stable circumbinary material would lie at orbital distances of many hundreds of AU and may be difficult to detect due to cold temperatures and low surface densities. Nonetheless, substantial circumbinary disks would have been detectable among binaries with separations of tens of AU.

The exceptions are notable, though. Both GG Tau (projected separation 40 AU) and UY Aur (projected separation 120 AU) have circumbinary material that is clearly seen in both millimeter interferometric maps (Dutrey et al. 1994; Duvert et al. 1998; Guilloteau et al. 1999) and near-infrared adaptive-optics images (Roddier et al. 1996; Close et al. 1999; see also McCaughrean et al., this volume). The material in both of these circumbinary disks clearly shows Keplerian rotation. In GG Tau, the circumbinary disk is resolved in both CO and continuum emission (Fig. 5). Detailed observations demonstrate that its circumbinary disk has two components: a narrow ring with sharp edges including about 80% of the mass and an extended disk reaching as far as 800 AU. The extended disk is cooler than the ring, consistent with heating by the star and circumbinary disk. The total circumbinary mass is $0.12\ M_\odot$, about 10% of the stellar mass. In contrast, the circumbinary disk in UY Aur is resolved only in CO; its continuum emission is compact and is therefore presumed to be associated with only one of the binary components.

CO observations show both circumbinary disks clearly separated from circumstellar disks by regions of very low surface density, indicative of disk clearing. Furthermore, the circumbinary disks have inner radii consistent with theory under reasonable assumptions about the binary orientation. The near-infrared scattered-light adaptive optics images also suggest the presence of radial structures in these gaps that could arise from small amounts of infalling material; however, in the case of GG Tau these structures are not confirmed by optical HST images (J. Krist, personal communication). A third example of a directly detected circumbinary disk is found in an optical scattered light image of the main-sequence B5 star, BD+31°643, which has a projected binary star separation of ~200 AU (Kalas and Jewitt 1997).

As noted in Section IV.A., many PMS spectroscopic binaries have strong millimeter emission that, given their small semimajor axes, requires the presence of massive circumbinary disks. High spatial resolution interferometric maps of UZ Tau E (Fig. 4) resolve the millimeter emission, confirming that a massive disk surrounds the binary. Mid-infrared emission further reveals the presence of circumbinary material around yet more close binaries. The measured masses of the circumbinary disks of DQ Tau (0.02 $M_{\odot}$), UZ Tau E (0.06 $M_{\odot}$) and GW Ori (0.3 $M_{\odot}$) all exceed the minimum mass of the solar nebula. All have semimajor axes $\lesssim 1$ AU, and therefore these systems could have stable planetary orbits in their circumbinary disks at distances as small as ≈ 3 AU.

Such close binary systems are also excellent probes of disk clearing. The innermost regions of disks are, as yet, inaccessible to imaging at the distances of the nearest star-forming regions. However, these hot inner disks contribute essentially all of the near-infrared ($\lambda \simeq 2.2$–$5\ \mu$m) excess emission in the spectral energy distributions of young stellar objects. Thus, the lack of a near-infrared excess indicates a lack of hot disk material. Jensen and Mathieu (1997) studied the spectral energy distributions of all known young spectroscopic binaries with disks in order to search for disk clearing. Indeed, some of the binaries (V4046 Sgr, 162814−2427) have *no* near-infrared excess emission but substantial mid- and far-infrared excesses, the signature of cleared inner disks. The inferred sizes of these inner holes are consistent with the sizes expected given the binary orbits. †

Surprisingly, however, a number of binaries (UZ Tau E, DQ Tau,

† It is worth noting that care must be taken in interpreting small depressions in SEDs as evidence for cleared inner disks, particularly when no known companion is present, as these dips can also be caused by dust grain opacity and vertical temperature structure effects in a circumstellar disk (Boss and Yorke 1993, 1996).

AK Sco) show relatively smooth power-law spectral energy distributions, as expected from a continuous accretion disk. The near-infrared opacity of dust is very large, so that relatively little material is required to produce the observed near-infrared emission. This leaves open the possibility that these inner disks have been dynamically cleared, but not with 100% efficiency. Such a situation could arise if material were to leak steadily from circumbinary disks into a cleared gap. Recent near-infrared CO observations of DQ Tau also reveal the presence of hot gas near the stars (Carr et al., in preparation).

C. Circumstellar disks

The existence of circumstellar disks has always been implicit in the discovery of binaries among CTTS, presuming that CTTS diagnostics are indeed indicative of accretion at stellar surfaces. The outstanding issue is whether circumstellar disks surround both primary and secondary stars, and how their relative accretion rates compare.

These questions can be answered best through observations capable of resolving the binary systems. As an example, recent observations of HK Tau by speckle imaging (Koresko 1998) and HST/WFPC2 (Stapelfeldt et al. 1998) provide direct evidence of a circumsecondary disk in a wide PMS binary star. (The HST image is shown in Fig. 1d of McCaughrean et al., this volume.) In both observations the secondary is observed as two elongated reflection nebulosities separated by a dark lane, well matched to scattered light models of an optically thick circumstellar disk seen close to edge-on. The disk has a radius of ~ 100 AU, roughly one-third the projected separation of the binary. Statistical arguments for the true orbital elements suggest that dynamical truncation of the circumsecondary disk is a possibility (Stapelfeldt et al.). Likewise, mid-infrared observations of the somewhat more evolved A0 star HR 4796A reveal a circumprimary disk, still present at an age of ~ 8 Myr despite the presence of a companion star located 500 AU away (Koerner et al. 1998; Jayawardhana et al. 1998). If the companion has an eccentric orbit and is currently near apastron, it could influence the disk outer radius, but the observed confinement of the disk material in a narrow annulus roughly 60–80 AU from the primary is puzzling, perhaps suggesting the presence of one or more unseen companions (Schneider et al. 1999). An additional influence of a distant companion star can be to warp the disk (Terquem and Bertout 1993, Larwood et al. 1996). Telesco et al. (1999) note that their images of HR 4796 hint at a warp in the disk. Finally, the secondaries of both HR 4796 and HK Tau show indirect evidence of a circumstellar disk, and thus these systems appear to support both circumprimary and circumsecondary disks.

Circumstellar disks in binary stars have also been identified in observations that separate the emission for the primary and secondary stars but do not resolve the individual disks, using the same indirect measurements used to assess the presence of a disk in single stars such as infrared and ultraviolet excesses and strong emission lines. For the widest binaries, separated by $\gtrsim 50$ AU, Brandner and Zinnecker (1997), Prato and Simon (1997), Prato (1998), and Duchêne et al. (1999b) have investigated the occurrence of circumstellar disks through a spectroscopic study of the individual components' emission line (Hα and Br γ) characteristics. Of the combined 49 binaries whose combined light has been classified as CTTS, 43 include two CTTS stars, suggesting that they harbor both circumprimary and circumsecondary disks.

Observations with the HST/WFPC2 and ground-based speckle imaging have permitted investigations of circumstellar disks among 31 binaries with separations of 10 AU to 100 AU (Ghez et al. 1997b; White and Ghez 1999) using the individual components' ultraviolet and infrared excesses as proxies for the presence of circumstellar disks. These studies have also shown that for the majority of pairs with accretion both components show similar accretion signatures. Interestingly, among the remainder (29%) of the active pairs only the primary retains an accreting disk, suggesting that primaries may have somewhat longer lived disks. Moreover, the excesses of the primaries are generally larger than or comparable to those of the secondaries, indicating that the primary stars are experiencing larger accretion rates. If primary disks do indeed have longer lifetimes and higher accretion rates than do secondary disks, then the primary disks must be more massive or preferentially replenished. However, near-infrared excesses do not provide meaningful measures of disks masses, and so the specific masses of primary and secondary disks are unknown. Nonetheless, the presence of large accretion rates would suggest that massive circumstellar disks may survive in close binary systems.

High spatial resolution interferometric observations allow the millimeter emission to be localized even in binary stars with separations $\lesssim 100$ AU. Three clear cases of circumstellar disks based on their compact millimeter emission are GG Tau (Guilloteau et al. 1999), UZ Tau W (Jensen et al. 1996b; see Fig. 4, Section IV.A), and T Tau N (Akeson et al. 1998). In the case of GG Tau, Guilloteau et al. report that the emission is consistent with tidally truncated circumstellar disks of radius $R \sim 4$–20 AU and total mass $\geq 1.5 \times 10^{-4}\ M_{\odot}$.

Circumstellar disks may even exist in the closest binary star systems. As discussed in Section V, PMS spectroscopic binaries can show infrared excesses, high-amplitude photometric variability, Hα equivalent widths in excess of 100 Å, heavy veiling, and large ultraviolet excesses. These observations are indicative of accretion and material very near the stars, which may be in the form of either accretion disks or accretion flows.

Finally, an important but relatively unknown property of circumstellar disks is their spatial orientation in the binary system. Disk alignment is one of the few observable properties that can distinguish among competing models of binary formation. It is also critically important for the long-term stability of planetary systems. However, the challenge of resolving circumstellar disks has limited our knowledge of disk alignment. A notable exception is the HK Tau system (Stapelfeldt et al. 1998, Koresko 1998) where the resolved disk appears not to be coplanar with the binary orbital plane. Disk alignment also can be probed by polarimetry even in systems where the disks themselves are unresolved. Scattering off a disk introduces a net polarization, and so the polarization position angle (PA) of the combined light from disk and star indicates the PA of the disk on the sky (Koerner and Sargent 1995). Monin et al. (1998) compiled polarimetric measurements of $8''$–$37''$ binaries from the literature and measured the polarization of some closer systems. They found one system (GI/GK Tau) to have mis-aligned polarization vectors, while two other systems were consistent with being parallel. Jensen and Mathieu (in preparation) have made K-band imaging polarimetric measurements of all $> 1''$ young binaries with infrared excess in Taurus and Ophiuchus. Preliminary results show mis-aligned disks in HK Tau (with both components detected, indicating an unresolved disk around the primary) and in DK Tau. Currently this technique is limited to binaries wider than about $1''$ due to the lack of sensitive, stable polarimeters combined with adaptive optics, so it cannot probe binaries with separations much less than typical disk radii to see if the disks in closer binaries are aligned. A change in alignment properties with binary separation may shed light on whether there are different formation mechanisms for the closer and wider binaries.

V. DISKS IN YOUNG BINARY STARS: ACCRETION FLOWS

The observation of accretion diagnostics in CTTS binaries of *all* separations suggests that accretion continues at stellar surfaces, with the accreting material presumably flowing from circumstellar disks. However, the theoretical expectation has been that the balance of viscous and resonant forces at the inner edge of a circumbinary disk would prevent any flow of circumbinary material across the gap. The consequence of continued accretion at the stellar surfaces would thus ultimately be exhaustion of the circumstellar disks and the cessation of accretion. Thus one might expect the accretion timescale for binaries to differ from that of single stars, and indeed to differ between close and wide binaries. In fact there is little observational evidence for this; for example, Simon and Prato (1995) find no difference in the frequency of accretion diagnostics between single and binary stars. Such long-lived accretion from circumstellar disks is an outstanding puzzle, one which may lead to a much more dynamic view of disk evolution.

The widest binaries (>100 AU) whose circumstellar masses appear to be unaffected by their distant companions (Section IV.A) are likely to have accretion histories very similar to single stars. Thus the existence of active accretion in wide binaries is not a surprise, where here we operationally define "wide" as a separation several times greater than typical disk radii. More surprising, perhaps, is an apparent correlation in the presence of accretion onto primary and secondary stars (see above discusion of Brandner and Zinnecker (1997), Prato and Simon (1997), Prato (1998), Duchêne et al. (1999b), White and Ghez (1999)). These studies suggest that the components of binary systems typically retain their disks for similar lengths of time. Prato and Simon suggested that a common circumbinary envelope may replenish and maintain circumstellar disks around both stars, although evidence for such envelopes has not been found for many of the binaries in these studies.

In their HST study of four CTTS and two WTTS with separations of 10 AU to 50 AU, Ghez et al. (1997b) also found that both components of three close CTTS binaries (including UZ Tau W) show infrared excesses suggestive of circumstellar disks, and that two stars have measurable ultraviolet excesses indicative of active accretion. The ultraviolet excesses from the two stars suggest that high accretion rates continue even in binary systems with separations much less than typical disk radii.

Perhaps most remarkably, the observational diagnostics for accretion are present among even the very closest binary stars. The star UZ Tau E is arguably one of the most classic of CTTS. It is a high-amplitude photometric variable (and indeed noted as one of the most active T Tauri stars by Herbig (1977)), has an emission spectrum with Hα equivalent widths in excess of 100 Å, is often heavily veiled, and has a large ultraviolet excess. Analyses have suggested accretion rates as high as 2×10^{-6} $M_{\odot}$/yr (Hartigan et al. 1995). In addition it is surrounded by a massive disk which has been resolved at millimeter wavelengths, and it has a power-law spectral energy distribution with excess emission at all infrared wavelengths. Despite these paradigmatic diagnostics for a disk accreting onto a single PMS star, UZ Tau E is a spectroscopic binary with a period of 19 days (Mathieu et al. 1996). Furthermore, with a maximum periastron separation of 0.1 AU, it is clear that the suggested accretion rate cannot be fed solely by an unreplenished circumstellar disk, although there is ample material in the circumbinary disk.

UZ Tau E is not a unique case. The CTTS AK Sco and DQ Tau have similar orbital periods and show diagnostics of accretion and material very near the stars. Indeed, the infrared spectral energy distribution of DQ Tau is one of the best examples among CTTS of a power law (Mathieu et al. 1997), typically interpreted as a continuous disk. Like UZ Tau E, both of these binaries have massive circumbinary disks. The issue is whether the circumbinary material can be tapped to supply the material accreting onto the stellar surfaces. Photometric and spectroscopic monitoring of DQ Tau may have provided a clue to the tapping mechanism. Photometric monitoring has revealed periodic brightenings with a period of 15.8 days. This is precisely the same as the orbital period, with the brightenings occurring at periastron passage. During these brightenings the system becomes bluer, the veiling increases, and emission line strengths increase (Mathieu et al. 1997; Basri et al. 1997). Together, all of these results point toward an increased mass accretion rate at periastron passage.

Basri, Mathieu and collaborators have argued that these results are consistent with the presence of accretion streams from the circumbinary disk to at least one of the stellar surfaces. Recent theoretical work of Artymowicz and Lubow (1996) and Lubow and Artymowicz (this volume) has suggested that such streams may develop if the circumbinary disks are sufficiently viscous and warm. In this scenario, the increase in luminosity is due to the deposition of kinetic energy from the infalling streams and the consequent heating of a region near the stars. For a binary with elements similar to DQ Tau, their simulations argue that the streams will be pulsed, with maximum accretion rates at periastron passage, as observed. Clearly the next observational forefront in the study of disks in binary systems is angular resolution on scales much smaller than companion separations, so that the dynamic environment within the binary orbit can be imaged.

VI. L1551 IRS5: OPENING THE WINDOW ON PROTOBINARIES

An exciting observational frontier lies in the direction of binaries in formation. Several very wide pairs have been found among embedded sources. However, perhaps the case of L1551 IRS5 best shows the prospects in the application of forefront technology to embedded sources.

L1551 IRS5 is arguably the canonical Class I system, i.e. a protostar still undergoing infall from an envelope. It has long been known to be double at centimeter wavelengths, but the interpretation as a binary system has not been secure. Recent millimeter observations demonstrate that the system is a protobinary with a projected separation of 45 AU (Looney et al. 1997, Rodriguez et al. 1998). The 7-mm VLA observations with 7 AU resolution are particularly impressive (Rodriguez et al. 1998). As shown in Fig. 6, not only is the binary clearly evident but the circumstellar emissions are marginally resolved as well. That these are in fact circumstellar disks is indicated by their flux levels being well above the extrapolation of the centimeter spectral energy distribution and by their orientation perpendicular to the centimeter outflow emission.

Combining the wealth of observations of L1551 IRS5, Looney et al. (1997) describe the system as having three main components: a large-scale envelope, a disk or extended structure with a size scale of order 150 AU, and the inner binary system with two circumstellar disks. They suggest an envelope mass and inner and outer radii of roughly 0.44 $M_{\odot}$, 30 AU and 1300 AU, respectively. The nature of the circumbinary structure remains uncertain. First resolved by Lay et al. (1994), the emission is reasonably fit with a Gaussian model with a very rough mass of 0.04 $M_{\odot}$. The VLA observations indicate circumstellar disk radii of 10 AU, with disk masses of 0.06 $M_{\odot}$ and 0.03 $M_{\odot}$. These disk masses are uncertain due to contamination by free-free emission, but Rodriguez et al. argue that this overestimate is no more than a factor of 4. As such, the disk masses remain comparable with the minimum mass required to form a planetary system like our own.

It is notable that such large circumstellar masses are found in a system with projected separation of 45 AU, given that at later evolutionary stages such binaries typically do not have detectable millimeter flux (Section IV.A). Indeed, given radii of only 10 AU the inferred disk masses are quite large. Perhaps these substantial circumstellar disks are maintained by rapid accretion from the envelope, possibly via an accretion stream from a circumbinary disk.

VII. CLOSING THOUGHTS ON PLANET FORMATION

A wide variety of investigations in the last several years have made it clear that disks are common in binary systems of all separations. There is no significant difference in the frequency of near-infrared excess emission in binaries and single stars (Moneti and Zinnecker 1991, Simon and Prato 1995, White and Ghez 1999), nor in the frequency of detected *IRAS* 12, 25, or 60 μm emission (Jensen et al. 1996a). This leaves open the very real possibility that while disks in binary systems may be constrained in *size* by the presence of a companion, the remaining circumstellar disk material may be similar in temperature and surface density to that in disks around single stars. The clear implication is that in a significant fraction of binary systems planet formation may be able to proceed relatively undisturbed. Here we look more closely at exactly which binaries may be likely or unlikely to form planetary systems based on our current knowledge.

In our own solar system, most of the planet formation has occurred in the range of 0.1–30 AU. If this holds true in other systems, what fraction of binaries could form similar planetary systems? A typical circumstellar disk radius is predicted by theory to be no more than 0.3 times the binary semimajor axis, allowing 30 AU disks in any binary wider than about 100 AU. Adopting the period distribution for main-sequence G stars (Duquennoy and Mayor 1991), this includes roughly 37% of all binary systems. Narrowing the disk radius to 5 AU (i.e., including only the terrestrial planets plus the asteroid belt) reduces the minimum binary separation to 17 AU and includes 57% of all binaries. These numbers assume that planet formation is a relatively local event, proceeding independently of conditions elsewhere in the system, which may not be the case. Nonetheless, it is clear that the possibility of planet formation in even relatively close binary systems is by no means ruled out by current data. These numbers also do not include the roughly 10% of very small separation binaries ($a \lesssim 0.3$ AU) with circumbinary disks that begin at or inside 1 AU; such systems could form circumbinary planetary systems.

In wider (hundreds of AU) systems, the question has already been answered. Four of the eight extrasolar planetary systems known to date are in members of wide binary systems, with binary separations ranging from $\sim$ 200–1000 AU(Marcy et al./, this volume).

Finally, we note that more subtle effects may be important for the long-term prospects of planets in binary systems. Little is currently known about the relative alignment of circumstellar disks and the binary orbital plane. Holman and Wiegert (1996; see also Wiegert and Holman 1997, Innanen et al. 1997) found that a planetary system around one member of a wide binary is stable for longer times if the planetary orbits and binary orbit are co-planar; in their calculations, planetary systems inclined to the binary orbit become unbound in 10^7–10^8 yr, while a coplanar planetary system survives for the full 10^9 yr integration. Investigations of disk alignment in binary systems will be important in determining the long-term stability of planets in binaries and therefore their prospects for evolving and supporting life.

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FIGURE CAPTIONS

Figure 1. The relative velocity of the binary stars' components as a function of their mean separation. The observed velocities are consistent with orbital motion since they (1) decrease with separation and (2) are generally greater for systems with higher mass primary stars ($M_1 > 1M_\odot$ and $M_1 \leq 1M_\odot$ are plotted as squares and circles respectively). The measurements are compared to that expected from a set of randomly oriented binary stars with total masses of 0.2, 1, 3, and 7 $M_\odot$. Although any individual total mass estimate is unreliable due to projection effects, the sample has an average total dynamical mass of ~1.7 $M_\odot$. (Taken from Ghez et al. 1995.)

Figure 2. Location of TY CrA primary and secondary stars in the theoretical H-R diagram. The hatched regions designate high-confidence domains for the primary and secondary based on light-curve analyses. Dotted lines are drawn at constant radii. Solid and dashed lines correspond to pre-main-sequence tracks of Swenson et al. (1994), calculated for the masses of the TY CrA components at solar (solid curve) and Hyades (dashed curve) compositions. Open boxes and triangles mark isochrone points at ages of 3×10^6 yr and 10×10^7 yr, respectively. (Taken from Casey et al. 1998.)

Figure 3. The stars of the GG Tau quadruple system compared with the theoretical evolutionary tracks of Baraffe et al. (1998; $\alpha = 1.9$). The range of plausible temperatures for each component are determined using a dwarf temperature scale (solid squares; Leggett et al. 1996) and a giant temperature scale (open diamonds; Perrin et al. 1998). Since the dwarf and giant temperature scales are nearly identical for the two hottest components, these two stars define an isochrone (dashed line) that can be used to test evolutionary models and the T Tauri temperature scale at lower masses. Of the models tested, the Baraffe et al. models yield the most consistent ages using a temperature scale intermediate between that of dwarfs and giants. These tracks and the implied coeval temperature scale (asterisks) yield a substellar mass of 0.044 $\pm$ 0.04 $M_\odot$ for the lowest mass component of GG Tau. (Taken from White et al. 1999)

Figure 4. Owens Valley Radio Observatory $\lambda = 1.3$ mm continuum map (top) of UZ Tau, a young quadruple system, along with a schematic model for the system (bottom). UZ Tau W is a 50 AU binary, separated by 500 AU from the sub-AU binary UZ Tau E. UZ Tau E has a massive circumbinary disk, seemingly undisturbed by either the central close binary or by UZ Tau W located several disk radii away in projection. In contrast UZ Tau W, a binary with a separation similar to typical disk radii, shows substantially less disk emission, though it retains *some* mass in one or two unresolved circumstellar disks. (Adapted from Jensen et al. 1996b.)

Figure 5. Left—The stellar components of the GG Tau binary are shown as stars. The circumbinary ring is evident in the light shaded region, displaying 1.3 mm continuum emission. The contours display three velocity channels of ^{13}CO 2→1 emission: 5.55 km/sec, 6.30 km/sec and 7.05 km/sec, increasing from left to right in the figure. The spatial gradient in the line emission is consistent with Keplerian motion about a binary of 1.3 (D/140 pc) $M_\odot$. The synthesized beam is $0.88'' \times 0.56''$. Right—The J-band adaptive optics image. The white ellipse is the same in both figures and represents the ring average radius. Evidently the light in the near infrared coincides with the circumbinary ring seen in millimeter light, and

is interpreted as scattered light off the inner edge of the ring. (Taken from Guilloteau et al. 1999; the J-band image is from Roddier et al. 1996.)

Figure 6. VLA image of the L1551 IRS5 region at 7 mm. The two compact sources are interpreted as protoplanetary disks in a gravitationally bound protobinary system. The masses of the individual disks are of order 0.05 $M_{\odot}$, adequate to form planetary systems like our own. However the spatially resolved projected semimajor axes are only 10 AU, perhaps due to dynamical truncation by the stars. The half-power contour of the VLA beam was $\approx 0.05''$, opening a new forefront in high-resolution observations of young binary systems. (Taken from Rodriguez et al. 1998.)

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