Disk Evolution in Young Binaries: from Observations to Theory

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The formation of a binary system surrounded by disks is the most common outcome of stellar formation. Hence studying and understanding the formation and the evolution of binary systems and associated disks is a cornerstone of star formation science. Moreover, since the components within binary systems are coeval and the sizes of their disks are fixed by the tidal truncation of their companion, binary systems provide an ideal "laboratory" in which to study disk evolution under well defined boundary conditions.

Since the previous edition of Protostars and Planets, large diameter ($8-10$m) telescopes have been optimized and equipped with adaptive optics systems, providing diffraction-limited observations in the near-infrared where most of the emission of the disks can be traced. These cutting edge facilities provide observations of the inner parts of circumstellar and circumbinary disks in binary systems with unprecedented detail. It is therefore a timely exercise to review the observational results of the last five years and to attempt to interpret them in a theoretical framework.

In this paper, we review observations of several inner disk diagnostics in multiple systems, including hydrogen emission lines (indicative of ongoing accretion), $K - L$ and $K - N$ color excesses (evidence of warm inner disks), and polarization (indicative of the relative orientations of the disks around each component). We examine to what degree these properties are correlated within binary systems and how this degree of correlation depends on parameters such as separation and binary mass ratio. These findings will be interpreted both in terms of models that treat each disk as an isolated reservoir and those in which the disks are subject to re-supply from some form of circumbinary reservoir, the observational evidence for which we will also critically review. The planet forming potential of multiple star systems is discussed in terms of the relative lifetimes of disks around single stars, binary primaries and binary secondaries. Finally, we summarize several potentially revealing observational problems and future projects that could provide further insight into disk evolution in the coming decade.

1. INTRODUCTION

It is now a matter of common knowledge that the majority of stars in star forming regions are in binary or higher order multiple systems (*Ghez et al.*, 1993; *Leinert et al.*, 1993; *Reipurth and Zinnecker*, 1993; *Simon et al.*, 1995). Likewise, it is undisputed that many of the younger stars in these regions exhibit evidence for circumstellar disks and/or accretion. Putting these two facts together, an inescapable conclusion is that disks typically form and evolve in the environment of a binary/multiple star system.

This prompts a number of obvious questions. Can the distribution of dust and gas in young binaries provide a "smoking gun" for the binary formation process? Is disk evolution, and perhaps the possible formation of planets, radically affected by the binary environment and, if so, how does this depend on binary separation and mass ratio? Alternatively, if the influence of binarity on disk evolution is rather mild, we can at least use binary systems as well controlled laboratories, constituting coeval stars with disk outer radii set by tidal truncation criteria, to study disk evolution as a function of stellar mass.

However, it is not possible to address any of these issues unless we can disentangle the disk/accretion signatures produced by each component in the binary. Given that the separation distribution for binaries in the nearest populous star forming regions, such as Taurus-Aurigae, peaks at $\sim 0.3''$ ($\equiv 40$ AU; e.g., *Mathieu*, 1994), this necessitates the use

of high resolution photometry and spectroscopy. Such an enterprise has only become possible in the past decade.

We review what has been learned in recent years about the distribution of dust and gas within young binary systems. We mainly highlight observational developments since PP IV, for example, the discovery of a population of so called passive disks (*McCabe et al.*, 2006) in low mass secondaries and the use of polarimetry to constrain the orientations of disks in young binaries (e.g., *Jensen et al.*, 2004; *Monin et al.*, 2005). We also discuss circumbinary disks and profile in detail a few systems that have been the subject of intense observational scrutiny. In addition, it is timely to examine the statistical properties of resolved binaries that have been accumulating in the literature over the past decade. We have therefore combined the results from a number of relatively small scale studies in order to assemble around 60 resolved pairs and use this dataset to examine the relationship between binarity and disk evolution.

In this Chapter we progress through a description of disk/accretion *diagnostics* (and their application to resolved binary star studies; Section 2) to highlighting some recent results on disk *structure* in binaries (Section 3) to a statistical analysis of the relationship between binarity and disk *evolution* (Section 4). In Section 4.5 we briefly consider how the insights of the preceding section can be applied to the question of planet formation in binaries. Section 5 examines future prospects and potential projects to advance our understanding of disk structure and evolution in young binaries.

2. INNER DISK DIAGNOSTICS IN YOUNG BINARIES

How do we know when either circumstellar or circumbinary disks are present in a young multiple star system? It took over a decade of observations to confirm the existence of simple circumstellar disk structures after the original observational and theoretical introduction of the concept in the early 1970s (e.g., *Strom et al.*, 1971, 1972; *Lynden-Bell and Pringle*, 1974). The paradigm is yet more complicated for a binary systems with multiple disks. Over the last two decades, direct means of imaging circumstellar disks have become available to astronomers, beginning with millimeter observations in the mid-1980s and ending with the recent development of high angular resolution laser guide star adaptive optics. Most critically to this chapter, the last decade has witnessed unprecedented improvements in our ability not only to directly image disks and to indirectly infer their presence, but to detect disks around both stellar components of extremely close binary systems, as well as larger, circumbinary structures.

In this section we summarize the methods used to determine the presence of circumstellar and circumbinary disks in multiples. The section is divided into two parts: disk diagnostics and accretion diagnostics. In this manner we distinguish between observations that detect the disks themselves, directly or indirectly, and the observations that are sensitive to the presence of accretion processes, indicating that material is flowing from a disk onto the central star, and thus betraying the existence of the disk indirectly. The end of this section summarizes the database that we compiled in the process of writing this chapter.

An excellent inner disk diagnostic that we do not explore is the emission of molecular lines. This topic is reviewed in the PP V paper of *Najita et al.* as well as in *Najita et al.* (2003) and references therein. Outer disk diagnostics, such as sub-millimeter and millimeter observations, and more narrowly applied accretion diagnostics, such as forbidden line emission and ultraviolet excesses, are also neglected here because they do not appear in our analysis. These tools are either not as relevant to our component resolved studies or have not yet been widely applied to many binary observations. Relevant references may be found in *Dutrey et al.* (1996) and *Jensen et al.* (1996) (sub-millimeter and millimeter), *Hartigan and Kenyon* (2003) ([OI] emission lines), and *Gullbring et al.* (1998).

2.1. Background

Lynden-Bell and Pringle's (1974) prescient disk model for classical T Tauri stars (CTTS) accounted for a number of characteristics of these objects, including atomic emission lines and the relatively flat λF_λ distribution of light at infrared wavelengths. Pioneering infrared observations of young stars indicated the presence of a strong excess (*Mendoza* ,1966, 1968) above expected photospheric values (*Johnson*, 1966) for T Tauri stars. These were largely interpreted as indicative of either a spherical dust shell around the young stars studied (*Strom et al.*, 1971; *Strom*, 1972; *Strom et al.*, 1972) or free-free emission from circumstellar gaseous envelopes (*Breger and Dyke*, 1972; *Strom et al.*, 1975), although the suggestion of a circumstellar disk structure was raised as early as 1971 (*Strom et al.*, 1971, 1972). Early analysis of the IRAS satellite data (e.g., *Rucinski*, 1985) and direct imaging of disk-like structures around HL Tau and L 1551 IRS 5 (*Grasdalen et al.*, 1984; *Beckwith et al.*, 1984; *Strom et al.*, 1985) provided ultimately convincing evidence in support of disks.

2.2. Disk Diagnostics

2.2.1. Near- and Mid-Infrared Excesses. Optically thick but physically thin dusty circumstellar disks around T Tauri stars reprocess stellar flux and give rise to excess thermal radiation at wavelengths greater than $\sim$ 1 micron. At larger disk radii, the equilibrium dust temperature is lower; thus, different circumstellar disk regions are studied in different wavelength regimes. For low-mass stars, the $JHK(1-2\,\mu\mathrm{m})$ colors sample the inner few tenths of an AU, the L-band ($3.5\,\mu\mathrm{m}$) about twice that distance, the N-band ($10\,\mu\mathrm{m}$) the inner $\sim$1$-$2 AU. $IRAS$ and $Spitzer$ data sample radii of several to tens of AU. The exact correspondences depend on the luminosity of the central star and the disk properties and geometry (e.g., scale height of the dust, degree of flaring, particle size distribution; see e.g.,

D'Alessio 2003; *Chiang et al.* 2001; *Malbet et al.* 2001). This results in a spectral energy distribution where the disk and star contributions can be disentangled (Fig. 1). For the nearby star forming regions, binary separation distributions typically peak at $\sim 0.3''$ (*Simon et al.*,1995; *Patience et al.*, 2002); for a distance of 150 pc, this corresponds to 45 AU. Therefore, most stars in binaries should have a direct impact on the circumstellar environments of their companions, at least at radii of several to a few dozen AU from the individual stars.

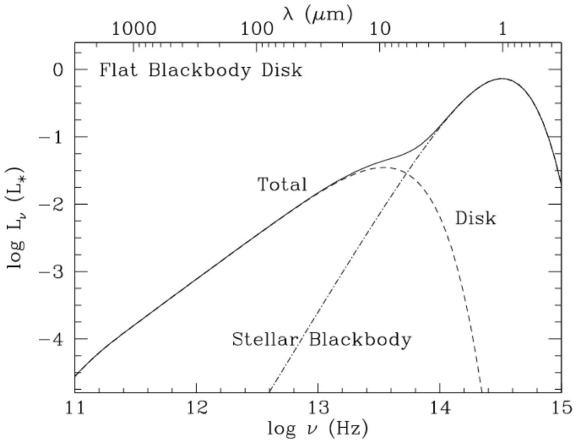

Fig. 1.— SED of a flat reprocessing disk from *Chiang and Goldreich* (1997). The dashed line corresponds to the disk emission, the dot-dash line to the stellar photosphere, and the solid line shows the total flux.

The shortest wavelength JHK colors, although useful (e.g., *Hillenbrand*, 1998), are susceptible to contamination from reflected light and are highly sensitive to the disk inner gap size (e.g., *Haisch et al.*, 2000). L-band data, where the contribution from the T Tauri stellar photosphere decreases, offers a far more reliable indicator of the innermost circumstellar dust (e.g., *Haisch et al.*) and reveals a much larger proportion of stars with disks. In the 1993 proceedings from Protostars and Planets III, *Edwards et al.* summarized the relationships between the K−L disk colors and the winds off of, and accretion flows on to, T Tauri stars. This establishment of the usefulness of K−L colors as a disk diagnostic coincided with early studies of binary colors (*Leinert and Haas*, 1989; *Ghez et al.*, 1991). Since the mid-1990s this diagnostic has been widely used as a convenient indicator of circumstellar disks in small separation binaries (e.g., *Tessier et al.*, 1994; *Chelli et al.*, 1995; *Geoffray and Monin*, 2001; *White and Ghez*, 2001; *Prato et al.*, 2003; *McCabe et al.*, 2006). At 8−10 m class telescopes, an angular resolution of $\sim$0.1″ is achievable in the L-band.

N-band observations are sensitive to dusty disk material that may surround a young star even in the absence of an innermost disk and a corresponding near-infrared excess (e.g., *Koerner et al.*, 2000; *Prato et al.*, 2001). For more than 30 years, observations have been made of young stars at 10 and 20 μm (e.g., *Strom et al.*, 1972; *Knacke et al.*, 1973; *Strom et al.*, 1975; *Rydgren et al.*, 1976; *Skrutskie et al.*, 1990; *Stassun et al.*, 2001), but, with few exceptions (e.g., *Ghez et al., 1994*) high angular resolution mid-infrared observations required the development of a new generation of cameras in the late 1990's for the largest existing (8−10 m class) telescopes. The Keck telescopes, for example, provide a 0.25″ diffraction limit at 10 μm. Over 80% of the known, angularly resolved, young binary N-band measurements, and most of the angularly resolved Q-band ($\sim$ 20 μm) measurements, have only recently been published in *McCabe et al.* (2006). Although far-infrared space-based observations do not provide the requisite angular resolution to distinguish between close binary components ($Spitzer's$ diffraction limit at 160 μm is about half a minute of arc), ALMA will provide unprecedented resolution in the far-infrared/sub-millimeter regime (see section 5).

2.2.2. Polarization. Linear polarization maps of young stars typically show an axisymmetric, or "centrosymmetric" pattern. By the late 1980's, these observations were interpreted by *Bastien and Ménard* (1988, 1990) as the result, in part, of light scattering from optically thick circumstellar disks. A prescient remark from the PP III paper of *Basri and Bertout* (1993) notes that "High resolution near-infrared polarization maps are, however, becoming possible with the advent of 256x256 detectors and AO..." Indeed, by the late 1990's, stunning detail in the polarization maps of *Close et al.* (1998), *Potter et al.* (2000), and *Kuhn et al.* (2001) illustrated the power of polarization observations for the study of circumstellar and circumbinary disks. *Monin et al.* (1998) applied the tool of polarization to a sample of wide (8−40″) binaries in Taurus. Most recently, *Jensen et al.* (2004) and *Monin et al.* (2005) mapped polarization around more than 3 dozen small separation ($\sim$1−10″) binaries (Section 3.1). Given that polarization observations can identify the orientation of a circumstellar disk, this provides a unique way in which to test the alignment of disks in binary systems.

2.3. Accretion Diagnostics: Permitted atomic line emission

The prolific work in the 1940's of Joy (e.g., *Joy and van Biesbroeck*, 1944) and later of Herbig (e.g., *Herbig*, 1948) on T Tauri type emission line stars laid the foundations for the study of emission lines in young binaries. Although the source of hydrogen emission lines in young stars was variously attributed as the result of free-free emission, chromospheric activity, and stellar winds (e.g., *Strom et al.*, 1975; *Herbig*, 1989; *Edwards et al.*, 1987), by the late 1980's *Bertout et al.* (1988) and others had established a model for magnetospheric accretion. *Strom et al.* (1989) canonized the nominal 10 Å distinction in Hα ($\lambda = 6563$ Å) line emission between weak-lined (WTT) and classical (CTT) T Tauri stars, which is still - somewhat indiscriminately - used today, albeit with slight modifications (e.g., *Martín*, 1998).

As the high frequency of young star binaries became es-

tablished in the mid-1990's, hydrogren emission lines were recognized as a useful approach for the study of circumstellar material around each star in the system (e.g., *Hartigan et al.*, 1994; *Brandner and Zinnecker*, 1997; *Prato and Simon*, 1997; *Duchêne et al.*, 1999; *White and Ghez*, 2001; *Prato et al.*, 2003). Infrared Brγ ($\lambda = 2.16\ \mu$m) observations (*Prato and Simon*, 1997; *Muzerolle et al.*, 1998; *Prato et al., 2003*) provide a means of measuring emission lines with the best possible seeing at longer wavelengths, as well as a method of detecting infrared components not readily seen in visible light.

2.4. The Young Star Binary Database

Observations of young binaries that resolve the circumstellar disk and accretion diagnostics of each component involve access to large telescopes with adaptive optics capabilities or space based observatories. Limited access to such facilities has meant that the results of such studies have often been published in papers describing a relatively small number of objects, from which it has proved impossible to derive statistically secure results. We have therefore combined many studies into a single database. In order to qualify for inclusion in the database, it is only necessary for the binary components to be angularly resolved and located in a region with a distance estimate such that the separation of the pair in the plane of the sky is known. Because we restrict the database to resolved systems, we exclude systems with semi-major axis $a < 14$ AU. In order to avoid contamination with chance projections we also exclude systems with $a > 1400$ AU. These limits correspond to binaries in the angular separation range of $0.1 - 10.0''$ at the 140 pc distance of Taurus.

Although the information available is incomplete for a number of objects, we have $\sim$60 systems where the spectral type of each component is known, as well as the presence or absence of disks and/or accretion for each component. We shall return to the statistical properties of these systems, and the implications for disk evolution in binaries, in Section 4. The database is available at http://www.
lowell.edu/users/lprato/compil_binaires_cmc5.html.
We welcome additions, revisions, and comments.

3. DISK STRUCTURE IN YOUNG BINARIES

3.1. Disk orientations in binary systems

A binary system with disks possesses many more degrees of freedom than an isolated star. Both stars can have a disk, they orbit around each other, and the entire system can be surrounded by a circumbinary disk. This defines 4 planes: 2 circumstellar disks, the stellar binary orbit, and the circumbinary disk. In a single young star system, only one plane is potentially present, that of one disk. In this section we examine some recent observational and theoretical results that shed light on the respective orientations of the multiple planes present in a binary.

If a binary forms through the fragmentation of a disk, then the disks that form around each star are expected to be mutually aligned and also to be aligned with the binary orbit. The same is true for binaries that form through core fragmentation, provided the angular momentum vectors of the parent core material are well aligned and provided that the initial core geometry (or the result of any perturbation inducing fragmentation) does not introduce any other symmetry planes into the problem. Although *Papaloizou and Terquem* (1995) showed that tidal effects may sometimes induce subsequent misalignment of the disks and orbital planes, *Lubow and Ogilvie* (2000) show that the required conditions are unlikely to be met in practice. We shall therefore assume that a binary that is created with all its planes aligned will remain in this state throughout its Class 0, Class I and Class II phases.

If any of the above conditions are not met, however, the binary will be created with some planes misaligned. For example, *Bonnell et al.* (1992) showed that if the initial cloud is elongated and if the rotation axis is oriented arbitrarily with respect to the cloud axis, then the initial disk and binary orbital planes are misaligned: in this case, the disk planes (which reflect the angular momentum of the core) are parallel, and misaligned with the binary orbit (which reflects the symmetry of the initial core). On the other hand, all planes may be misaligned either in the case that the angular momentum distribution of the initial core is complex or that the fragmentation involves more than two bodies. There are therefore a number of routes by which misaligned systems can be created and may be manifest among Class 0 systems. This does not, however, imply that these systems will remain misaligned during subsequent evolutionary phases, owing to the fact that both tidal effects and accretion onto the protobinary can bring the system into alignment at a later stage. Therefore the detection of misaligned systems is an unambiguous sign of misaligned formation, whereas aligned systems may either have been created that way or else have subsequently evolved into this state.

At the earliest evolutionary stages, it now seems inescapable that at least some systems contain misaligned disks. In these systems, jet orientation provides an observable proxy for disk orientation since jets are always launched perpendicular to the inner disk: the detection of multiple jets emanating with different position angles from a small region is thus an unambiguous sign of misalignment (*Reipurth et al.*, 1993; *Gredel and Reipurth*, 1993; *Davis et al.*, 1994; *Bohm and Solf*, 1994; *Eislöffel et al.*, 1996). In all cases, the parent multiple systems are either unresolved or are known to be wide binaries (i.e. with $a > 100$ AU). Less directly, the observation of changes in jet position angle have been interpreted as the result of jet precession (or "wobble"; *Bate et al.*, 2000), induced by misalignment between the disk and the orbital plane of a putative companion (*Chandler et al.*, 2005; *Hodapp et al.*, 2005). The observed rates of change of jet position angle are thought to be consistent with the presence of unresolved binary companions with separations in the range several to ~ 100 AU. However, not all observed instances of changes in jet direction can necessarily be explained in these terms (*Eislöffel and*

Mundt, 1997).

The expected timescale on which strongly misaligned disks should be brought into rough alignment by tidal torques is about 20 binary orbital periods (*Bate et al.*, 2000); it is thus only in rather wide binaries (i.e. with $a > 100$ AU) that we should expect misaligment throughout their Class 0 and Class I stages. However, as the misalignment angle (δ) evolves towards zero, the rate of alignment becomes proportional to δ and hence the system may be expected to remain in a mildly misaligned state over considerably longer periods.

How are these expectations borne out by observations of Class II sources (with typical ages of a few $\times 10^6$ years)? The most obvious approach is through direct imaging of disks in PMS binaries. Unfortunately, despite the recent deployment of a range of instruments offering high angular resolution on very large telescopes, circumstellar disks in TTS multiple systems have only been imaged in few cases (HK Tau: *Stapelfeldt et al.*, 1998; HV Tau: *Monin and Bouvier*, 2000; *Stapelfeldt et al.*, 2003; LkHα 263: *Jayawardhana et al.*, 2002). In each of these systems only one disk is detectable via imaging and is seen edge-on, a favorable orientation for detection. In all three systems, the observed edge-on disk is oriented in a direction quite different from the projection of the binary orbit on the sky: therefore we see immediately that *at least some disks in binaries remain misaligned with the binary orbital plane during the Class II phase*.

Several properties of these imaged systems are noteworthy: first, they are all wide binaries ($a >$ several hundred AU) and are thus consistent with the estimate given above that disks in binaries closer than $\sim$ 100 AU should be brought into alignment during the Class 0 or Class I phase. Second, for HK Tau and LkHα 263, the companion to the star with the edge on disk is itself a close binary system. Third, in each of these systems only one disk is detectable through imaging, although there is some spectroscopic evidence that the other component does possess a disk. The fact that these other disks are not detected through direct imaging implies that they are not themselves viewed close to edge on and we can thus infer that the disks in these systems are not parallel with each other. However, since only a slight tilt of the other disk away from edge-on can abruptly reduce its detectability as the central star becomes visible directly, this observation only excludes an alignment between the disks to within ≈ 15 degrees.

Since the publication of PP IV, various studies have been performed to determine the orientation of binary disks relative to each other in the plane of the sky. Following the theoretical computations by *Bastien and Ménard* (1990), and the previous measurements of *Monin et al.* (1998), *Wolf et al.* (2001), *Jensen et al.* (2004), and *Monin et al.* (2005) have used polarimetric observations to determine the relative orientation of disks in the plane of the sky. The position angle of the integrated linear polarization of the scattered starlight is parallel to the equatorial plane of the disk, provided that its inclination is sufficiently large to mask the direct light from the star (*Monin et al.*, 2005). One caveat of this method is that it does not reveal the actual 3D orientations of disks; two disks with parallel polarization could be differently inclined along the line of sight. In principle, this other orientation angle can be obtained from $v \sin i$ and rotation period measurements, but these are quite rare and difficult to obtain in close binaries and are in any case subject to errors attributable to uncertainties in the stellar radius. However, *Wolf et al.* (2001) have shown from statistical arguments that if the relative polarization position angle difference distribution peaks at zero, then the disks tend to be parallel.

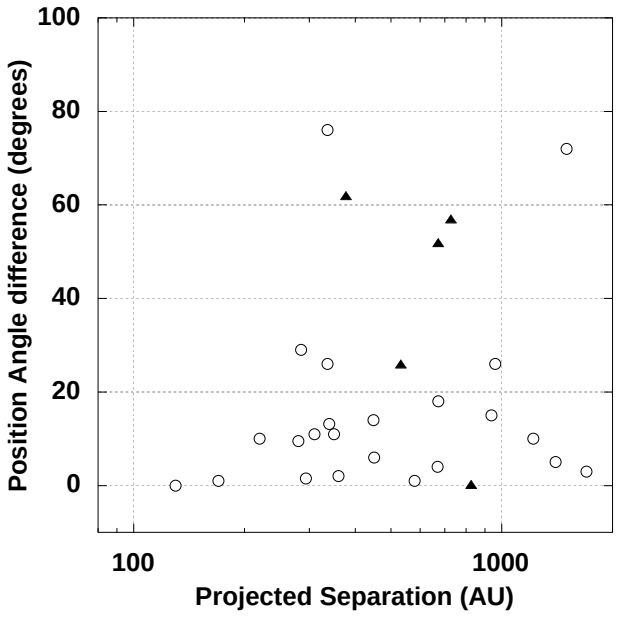

Fig. 2.— Adapted from *Jensen et al.* (2004) and *Monin et al.* (2005); binaries are plotted as empty circles and higher order multiples as filled triangles. Note the suggestion in the data that disks in triples and quadruples are proportionally less aligned than in pure binary systems.

The net result of these studies is twofold: disk polarizations tend to be close to (but not exactly) parallel in binary systems, but there exist systems with misaligned polarization, with a few objects having polarization position angle differences of $\sim 90^o$. *Jensen et al.* (2004) argue that it is unlikely that this result is compromised by dilution of the polarization signal from each disk by interstellar polarization, since, among other evidence, they note that disk polarization tends *not* to be parallel in the case that one or other of the two components is itself a close binary system (see Fig. 2 where we have merged the results from *Jensen et al.*, 2004) and *Monin et al.*, 2005). This supports the notion that the polarization differences are intrinsic, since there should be no correlation between the degree of contamination by interstellar polarization and the multiplicity of the system studied. On the other hand, there is a plausi-

ble physical reason for this result: owing to the much larger angular momentum contained in a close binary pair than a simple star-disk system, the timescale for torquing a binary into alignment with the orbital plane of the wider pair is evidently much longer than that for the alignment of a disk.

All of the above discussion relates to binaries that are wide enough to be imaged (typically wider than 100 AU). However, in the case of spectroscopic binaries, there is the possibility of determining the system inclination from the orbital solution and then comparing this with the inclination determined from direct imaging of the circumbinary disk (albeit on a much larger scale). In the small number of systems where this has proved possible, the evidence is for alignment between the plane of the spectroscopic binary and its circumbinary disk (see *Mathieu et al.*, 1997; *Prato et al.*, 2001; *Prato et al.*, 2002; *Simon et al.*, 2000).

Finally, among *main-sequence* solar type binaries, it is found that the stellar orbital planes are aligned with the binary orbit for binaries closer than 40 AU (Hale 1994), as one would expect, given the short predicted alignment timescales for closer binaries.

In summary, we have plenty of examples (through imaging and polarization studies) of misaligned systems among wider binaries (i.e. with $a > 100$ AU or so), implying that at least some of these systems must be formed in a misaligned state. By the Class II phase, it would appear that binaries in this separation range constitute a mixture of aligned and misaligned systems (*Monin et al.*, 2005; *Jensen et al.*, 2004). This may imply that wider binaries are formed in both aligned and misaligned states, or, alternatively, that all such binaries are born in the misaligned state and are brought into alignment through tidal torques (which should operate on a roughly 10^6 year timescale for binaries of this separation). In the case of closer binaries, where direct imaging is not possible, observational evidence for disk alignment can be derived only in the case of spectroscopic binaries with imaged circumbinary disks and also through the fossil evidence contained in stellar spin vectors within main-sequence binaries. Both these lines of evidence point to close binaries being aligned during the main disk accretion stage. This is expected, given the short predicted alignment timescales for close binaries, and therefore gives us no information about the *initial* state of alignment of these systems.

3.2. A sampling of circumbinary disks

Only a few circumbinary disks have been imaged directly. *Ménard et al.* (1993) proposed a circumbinary disk to explain NIR images of Haro 6-10, and in 1994, the circumbinary disk that still today remains the most impressive to date was found by *Dutrey et al.* (1994) around GG Tau. The majority of the currently inferred circumbinary disks are proposed to explain SED emission from warm dust in disks with a central hole where the binary resides. With the ever growing number of discoveries of PMS spectroscopic binaries, the number of putative circumbinary disks in these closer systems has increased. On the other hand, in the case of wide binaries, very few circumbinary disks have been directly imaged and, moreover, the low upper limits for circumbinary disk masses from millimetre measurements (*Jensen et al.*, 1996; see also Section 4.4) suggest that circumbinary disks are weak or absent in the majority of these systems. However, this conclusion remains provisional on two grounds. First, the very small number of circumbinary disks that have been imaged might not be as surprising as originally thought, when one considers also the relatively low rate of detection of circumstellar disks by direct imaging; only when the system geometry is very favorable can the disk be imaged easily (see section 3.1 above). Second, there is at least one case in which a circumbinary disk that has been imaged in CO lines is not detectable in dust as probed by the millimetre continuum (see discussion of SR 24 N below). We therefore cannot rule out that wide binaries either possess low mass disks that escape detection in the dust continuum (corresponding to disk masses $\leq$ a Jupiter mass) or else that some process, such as grain growth, is reducing the dust emission in these systems. Such a process may be at work in the GG Tau circumbinary disk (see Section 3.2.1 below).

In the case of wider binaries ($a > 20$ AU), the argument in favour of circumbinary disks as a necessary reservoir for the resupply of circumstellar disks has weakened since its orginal proposal by *Prato and Simon* (1997): our analysis described in Section 4 below shows that mixed systems (i.e. pairs containing both a CTTS and a WTTS) are in fact common. It is likely that, in wider binaries, circumstellar disks evolve in relative isolation, and resupply might not be a necessity. In closer binaries, resupply remains a necessity on the grounds that the circumstellar disk lifetimes in these close systems would otherwise be too short to explain the incidence of component CTT stars. In these closer systems, circumbinary disks, as evidenced by their contribution to the spectral energy distribution, remain a good candidate for the resupply reservoir. Indeed, in various objects, signatures of accretion episodes from the circumbinary environment onto the central objects, presumably via their associated circumstellar disks, have been detected. In this section we examine in more detail several circumbinary disk systems and discuss their properties in terms of disk evolution, circumbinary accretion, and potential for planet formation.

3.2.1. GG Tau. Discovered by *Simon and Guilloteau* (1992), this circumbinary disk orbits the $0.25''$ separation pair GG Tau A and has been spatially resolved in the optical, (Krist et al. 2002; 2005), near-infrared (*Roddier et al.*, 1996; *McCabe et al.*, 2002; *Duchêne et al., 2004*) and in the millimeter (continuum and ^{12}CO, e.g., *Guilloteau et al.*, 1999). *Beust and Dutrey* (2005) investigated the GG Tau A orbit and the inner ring gap and find that a binary orbital solution with $a = 62$ AU and $e = 0.35$ could be consistent with the data; in this study, the presence of the circumbinary disk is used to add dynamical constraints to the central binary system. Using a collection of images at various wavelengths, *Duchêne et al.* (2004) have shown that grain

growth is at work in the midplane of the GG Tau circumbinary ring within a stratified structure. This shows that the processes leading to planet formation might be at work in circumbinary disks as well as in circumstellar disks.

3.2.2. SR 24 N. The binary separation in this system is of the same order as GG Tau's, 32 AU. *Andrews and Williams* (2005) have observed a 250 AU structure in this system, probably a circumbinary disk. An interesting feature of their observations is that this disk shows no emission in the continuum, possibly as the result of a central gap inside the disk, and is seen only in CO line emission. This suggests that other wide circumbinary disks could have been missed by continuum observations, and thus could be more frequent than previously thought. K-L measurements by *McCabe et al.* (2006) indicate that both components of SR24N are themselves CTTS.

3.2.3. GW Ori. GW Ori is a spectroscopic binary with an orbital period of 242 days (*Mathieu et al.*, 1991) and a separation slightly more than 1 AU. These authors used a circumbinary disk model to reproduce the mid-infrared excess at $20\,\mu$m: GW Ori is one of those spectroscopic binaries in which a large emitting region is needed to explain the sub-mm flux. With an estimated stellar separation of ~ 1 AU, this requires an extended circumbinary structure. The presence of circumbinary material was even confirmed by *Mathieu et al.* (1995) who found that independently of any specific disk model, the extended (≈ 500 AU) sub-mm emission of GW Ori was circumbinary in origin.

3.2.4. DQ Tau. Like GW Ori, this 0.1 AU separation spectroscopic binary possesses excess emission at longer wavelengths, indicating the presence of circumbinary material around the central stars. Further observations have revealed evidence for accretion bursts near the binary periastron in the form of photometric variability (*Mathieu et al.*, 1997) and increased veiling (*Basri et al.*, 1997). These results are consistent with the prediction by *Artymowicz and Lubow* (1996), who showed that accretion streams are likely to link the inner edge of the circumbinary disk to the stars. Thus DQ Tau is an example of a binary where replenishment from a circumbinary structure is at work.

3.2.5. V4046 Sgr. This pair has an orbital period of 2.4 days and an eccentricity close to zero. *Artymovicz and Lubow* (1996)'s models of accretion from the circumbinary environment predict that mass ratio, q (M_2/M_1), $\sim$1, low-eccentricity binaries should not experience accretion bursts. However, *Stempels and Gahm* (2004) have recently observed spectroscopic features that can be explained by the presence of gas concentrations in corotation with the central binary. These gas accumulations might provide further evidence for accretion from the circumbinary environment.

3.2.6. AK Sco. AK Sco is an eccentric spectroscopic binary with q$\sim$1 and a separation of 0.14 AU. The circumbinary disk needed to explain the spectral energy distribution possesses an inner hole of radius $\sim$0.4 AU within which the binary resides. This is consistent with the prediction of *Artymowicz and Lubow* (1996) for the inner rim of a circumbinary disk in such a system. Like DQ Tau, it also shows evidence of accretion bursts related to the orbital motion, but not near periastron (*Alencar et al.*, 2003). Indeed, the Hα equivalent width peaks at the orbital phase when the stars are farthest apart.

These puzzling results show that the search for clear signs of circumbinary accretion onto the central system of young binaries is on-going. However, if circumbinary environment replenishment occurs only when the binaries are sufficiently close, imaging such systems will be very difficult. Future interferometric measurements might allow us to disentangle the various possible modes of accretion.

4. DISK EVOLUTION IN YOUNG BINARIES

4.1. The Need for Resolved Observations of Young Binaries

A problem with using ensembles of T Tauri stars for discerning evolutionary trends is that one has to make judgements about the ages of the stars concerned. Some studies have used pre−main-sequence evolutionary tracks to ascribe ages to individual systems (e.g., *Hartmann et al.*, 1998; *Armitage et al.*, 2003), whereas others simply assumed that all stars in a given star forming region have a similar age (e.g., *Haisch et al.*, 2000). In each case, the assignment of age is subject to uncertainties as a result of both the uncertainties in the pre−main-sequence tracks and the additional errors introduced by placing unresolved systems, as opposed to individual stars, in the HR diagram.

In binaries, however, we know *a priori* that the components are coeval, at least to within $\sim 10^5$ years (i.e. to within a small fraction of the average ages of T Tauri stars). This statement is based on theoretical models for binary formation: the only possibility for binaries forming in a significantly non-coeval fashion is via star-disk capture. A number of studies have however shown that this is likely to be a very minor source of binary systems, even in dense environments like the Orion Nebula Cluster (*Clarke and Pringle*, 1991; *Scally and Clarke*, 2001). Therefore, without any need to rely on the accuracy of pre−main-sequence tracks, we can use binary stars as stellar pairs that are guaranteed to be coeval.

In recent years, each of the diagnostics described in section 2 has been used extensively to study the timescale and nature of evolutionary processes in protostellar disks. Typically these studies have not separated the individual components in binaries closer than an arcsecond or so. Because closer binaries constitute more than half of the systems in the best studied region, Taurus Aurigae, this means that conclusions on disk evolution based on these studies are subject to considerable uncertainties.

For example, the designation of spectral types, and hence masses, to unresolved systems is unreliable; likewise, the detection of a disk diagnostic in an unresolved system does not in itself indicate whether it is the primary or the secondary or both components that possess a disk. These two factors introduce considerable uncertainties when us-

ing such data to investigate how disk evolutionary processes depend on stellar mass.

Another potential problem resulting from using unresolved data relates to the case in which the distribution of some observed property in T Tauri systems is used to infer the *rate* at which systems pass through various evolutionary stages. Evidently, this analysis is compromised in the case that the observed property is the sum of quantities arising from the individual binary components, whose evolution may not be synchronized. For example, the distribution of T Tauri stars in the K-L, K-N two colour plane has been used to deduce the relative amounts of time that stars spend with disks that are respectively optically thick or optically thin ("transition disks") or undetectable (*Kenyon and Hartmann*, 1995). This study revealed the striking result that very few systems were located in the transition region of the two colour plane, and has motivated the quest for disk clearing models that can effect a rapid dispersal of the inner disk (*Armitage et al.*, 1999; *Clarke et al.*, 2001; *Alexander et al.*, 2005). *Prato and Simon* (1997) recognised that interpretation of this diagram is complicated by the existence of binaries and argued that the small numbers of systems with colours characteristic of transition objects implies that mixed binary pairs (i.e. one star with a disk and one without disk) must be relatively rare. Our analysis in Section 4.3 below shows that mixed pairs do in fact occur quite frequently in systems whose components have very disparate masses; in this case, however, the infrared colours of the unresolved system are then dominated by that of the primary and so such systems do not frequently end up in the transition region.

In summary, although studies of disk evolution based on unresolved systems are indeed valuable, they represent a rather blunt instrument compared with that provided by studies that resolve the individual components of binary systems. The value of this latter data can only be exploited if we first use it to answer a fundamental question: to what extent is disk evolution affected if the disk in question is located in a binary system? Depending on the answer to this question, we can *either* use the data to explore the influence of binarity on disk evolution *or* use the binary environment as just representing samples of coeval stars of various masses. We will return to this issue in section 4.3 below.

4.2. Overview of the database: separation distribution of binaries and associated selection effects

We have classified the binaries in the database for which we have been able to assess the presence of a disk in each component as CC,CW, WC and WW. Here C denotes a CTTS (accreting, disk possessing) star and W a WTTS (non-accreting, generally diskless) star. The first and second letter refer to the primary and secondary, respectively. The designation of C or W for each component is based primarily on the criterion of *Martín* (1998) for the equivalent width of Hα as a function of spectral type. In the minority of systems for which this is not available, the presence of Brγ is used instead. In the absence of information on either of these diagnostics a cut-off in near-infrared color of $K - L = 0.3$ or mid-infrared color of $K - N = 2.0$ is employed instead. We also consider two additional categories, CP and WP, in which the primary is a CTTS or a WTTS and the secondary is a "passive disk" object; a non-accreting star that while generally lacking any near-infrared excess also possesses a significant mid-infrared excess, indicating the presence of an inner dust disk hole (*McCabe et al.*, 2006).

Table 1 lists the numbers of objects of each type in the database that satisfy certain criteria. The left hand column lists the number of objects of each type that have the most complete information (i.e. binary separation and spectral type for each component). Objects in the left hand column have not been reported as possessing additional unresolved companions (at < 0.1" separation) to one of the components, a feature which would disrupt the accretion flow in that region. The second column (which includes those in the first column) covers the larger sample of systems with known separations but not necessarily spectral types for both components. Objects in this column also have no reported additional close companions. The third column lists the number of systems with additional close companions.

Table 1: Numbers of binaries in the database according to classification; see text for details.

CC	29	38	7
CW	11	14	1
CP	2	2	0
WC	4	6	1
WP	1	1	0
WW	12	21	1

To some extent, the numbers in Table 1 reflect observational selection effects. For example, it is possible that binaries with W primaries are under-represented in this sample: comparison of in Table 1 with the total numbers of stars in the Taurus aggregates that are classified as CTTS and WTTS, 100 and 70, respectively (Guieu, private communication), suggests a mild deficit of binaries with wTT primaries. Any under-representation is likely to result from the relative disincentive to make high angular resolution observations of objects which show no obvious accretion signatures in their combined spectra. We would expect this under-representation to be more acute at small separations (where resolved observations require more effort) and, in the case of WCs, in low-mass ratio objects, where the accretion signatures of the secondary are not obvious in the combined spectrum. In addition, relatively few objects have been scrutinized at N-band, so that further systems may subsequently be transferred from the CW/WW to the CP/WP category; we have been rather conservative in our

assignment of passive systems in Table 1, and so have not included several systems judged to be marginal passive candidates according to *McCabe et al.* (2006).

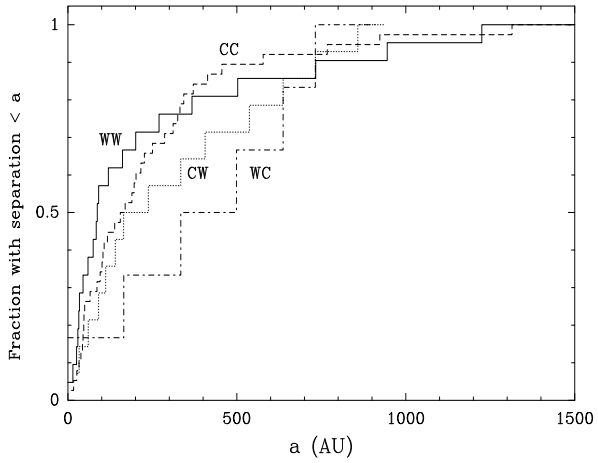

Fig. 3.— Cumulative separation distribution of the four different binary category.

In Fig. 3 we plot the cumulative separation distributions of the binaries in the central column of Table 1, with the histograms (in descending order at $a = 500$ AU) representing CCs, WWs, CWs and WCs. There is no statistically significant difference between any of these distributions: in the case of the two categories of binary with the largest subsample numbers, the CCs and the WWs, a KS test indicates that in the case that the two sub-samples were drawn from the same parent distribution, the probability that the samples would be at least as different from each other as observed is 25% . There is some theoretical expectation that disk evolution should be accelerated in closer systems (see below), which might in principle lead to an excess of WWs at small separations. Although the fraction of close binaries is somewhat higher for WWs (i.e. 57% of WWs have separation less than 100 AU compared with only 38% of CCs), this difference is not statistically significant, possibly implying that accelerated disk evolution at small separations is not occurring in the binaries in our sample, which are rarely closer than ~ 20 AU. On the other hand, as we mentioned above, there is an observational selection effect against the discovery of closer systems with a W primary, so that this might mask any evidence for accelerated disk evolution in closer binaries.

Fig. 3 also demonstrates that mixed pairs (WCs, and, to a lesser extent, CWs) are more concentrated at larger separations, although again the relatively small numbers of these systems yields a statistically insignificant result. The KS probability of either the mixed binary samples having a different separation distribution from the CC or WW samples is never less than 25%. We are less inclined to ascribe this tendency to an observational selection effect, since there is no reason why WCs should be under-represented at small radii compared with WWs, or why CWs should be underrepresented compared with CCs at small separations.

The numbers of mixed systems (CWs or WCs) compared with CCs is a measure of the difference in lifetimes of the disks around each component. Synchronized evolution would imply mixed systems should be very rare, whereas a large difference in lifetimes would imply that mixed systems should be abundant. Including also the 4 passive systems as mixed systems, the total numbers of CCs compared with mixed systems is 37 compared with 24; we have avoided the complicating factor of close companions by using the systems in the middle column of Table 1. This implies that the average lifetime of the shorter lived disk is $\sim 60\%$ of the longer lived disk. A further point to make about the mixed systems is that the number of mixed systems with a CTTS primary compared with a WTTS primary is 17 compared with 7. Evidently, there is a tendency for the primary's disk to be longer lived, although this is not universally the case.

We therefore conclude that when one combines all the available data from the literature, mixed systems are much less rare than was previously thought. It would appear that the reason that we need to revise our conclusions is that the incidence of mixed systems varies between different star forming regions (see also *Prato and Monin*, 2001). Thus among the CCs and WWs in the middle column of Table 1, around half are located in Taurus. However, only 20% of the mixed systems are located in Taurus. Thus early studies (e.g., *Prato and Simon*, 1997) whose targets were mainly in Taurus contained relatively few mixed systems. We can only speculate as to why the fraction of mixed systems should vary from region to region. One obvious possibility is if the mixed phase corresponds to a particular range of ages and if different star forming regions have different fractions of stars in the relevant age range.

4.3. The distribution of binaries in the $a - q$ plane

To make further progress, we must examine how various categories of binaries are distributed in the plane of mass ratio versus separation. This necessitates using the more restricted sub-sample listed in the left hand column of Table 1, for which we have spectral type information for each component. We have checked that the separation distribution of the sub-sample is consistent with that of the full sample; although the difference is not statistically significant, we note that there happens to be a deficit of wide (> 500 AU) CC binaries in the sub-sample compared with the full sample, which is manifest as the lack of solid dots in the right hand portion of Fig. 4.

In Fig. 4, filled circles represent the CCs, open circles the CWs, filled triangles the CPs and open triangles the WCs. We do not include the WWs in this plot since they contain no information about *differential* disk evolution. We note that we expect the selection effects to be similar for all the binaries with CTTS primaries and that we expect the selection bias against low q and low a systems to be more severe

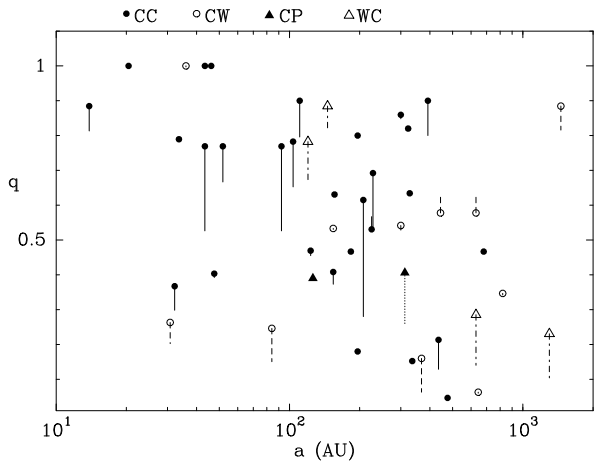

Fig. 4.— Binaries from the left hand column of Table 1 plotted in the q, a plane

for the systems with WTTS primaries.

We have placed binaries in Fig. 4 using the correlation between spectral type and mass for stars of age 1 Myr given in *Hillenbrand and White* (2004). The necessity of having an optical spectral type for each star means our sample of 29 CCs and 11 CWs has excluded any binary containing an infrared companion or Class I source. For each binary we then calculate $q_{\rm DM}$ (i.e. the mass ratio M_2/M_1) using the pre−main-sequence tracks of *D'Antona and Mazzitelli* (1994). For a subset of systems for which both spectral types are later than K3, we also compute $q_{\rm BCAH}$, using the pre−main-sequence tracks of Baraffe et al. (1998), also listed in *Hillenbrand and White* (2000). In Fig. 4, we plot $q_{\rm DM}$ in each case but link $q_{\rm DM}$ to the corresponding value of $q_{\rm BCAH}$ in the systems where both components lie in the range where $q_{\rm BCAH}$ can be computed. We use different dashes for different type of pairs. The length of the vertical lines gives some indication of the uncertainties inherent in pre−main-sequence tracks, although cannot in any sense be regarded as an errorbar on q. Despite the strong disagreement between the tracks in certain ranges of spectral type, we nevertheless find that both set of tracks are in broad agreement as to whether binary systems are high or low q. In the quantitative analysis of the q distributions described below, we use $q_{\rm DM}$ as this is the only quantity that is available for all systems in our sample.

There are several striking features in this figure. As we have already noted, it first demonstrates that mixed systems are not rare and that many of the mixed systems are binaries with low q. On theoretical grounds (see below), one might expect that systems where the secondary's disk is exhausted before the primary's (i.e. the CWs and the CPs) would be low q binaries. This is borne out with marginal statistical significance when one compares the q distribution of the CCs with the combined population of CWs and CPs. If we restrict our sample to binaries closer than 1000 AU in order to reduce the risk of picking up chance projections in our sample, we find that a KS test reveals that the two q distributions are different at the $2\ \sigma$ level. A KS test assesses the statistical significance of the *maximum* difference between the two datasets, which in this case refers to the fact that $11/28$ CCs have $q < 0.6$ whereas for CWs and CPs the combined figure is $11/13$. We also note that systems in which the primary's disk is exhausted first are relatively rare, i.e. for $a < 1000$ AU the total number of WCs and WPs is 4, compared with the 13 mixed systems with a CTTS primary in this separation range. From Fig. 4, we see that these 4 mixed systems with WTTS primaries are not found preferentially at low q, in contrast to what appears to be the case for the mixed systems with CTTS primaries. However, we caution that there may be a selection effect against the detection of low q mixed systems with WTTS primaries at small separations.

Further analysis of this figure (i.e. division of the (a, q) domain into different regimes) 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. For example, we draw attention to the fact that for binaries closer than 100 AU, this being the canonical scale of disks around young stars (*Vicente and Alves*, 2005; *McCaughrean and Rodmann*, 2005), there are *no* examples of pairs in which the primary's disk is exhausted first (i.e. WCs or WPs) and that $2/3$ of the mixed systems have $q < 0.5$ compared with only $2/10$ of the CCs having such low values of q.

This behaviour is qualitatively consistent with what is expected theoretically in the case in which the disks around each star evolve in isolation, with their outer radii set by tidal truncation in the binary potential. Tidal truncation of disks occurs at a radius equal to a factor $R_{\rm tidal}$ times the binary separation, where $R_{\rm tidal}$ is plotted in Fig. 5 (*Armitage et al.*, 1999; *Papaloizou and Pringle*, 1987).

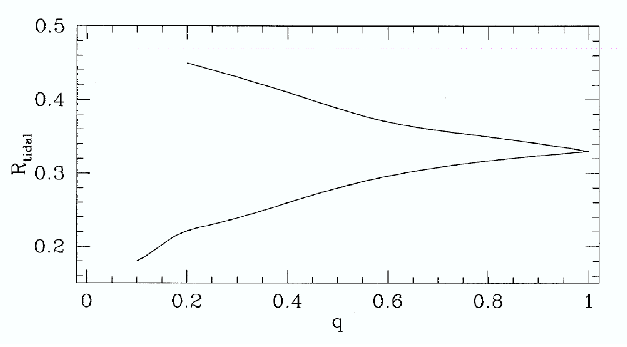

Fig. 5.— Truncation radius as a fraction of the semimajor axis of the binary orbit vs q: upper line for primary, lower line for secondary (from *Armitage et al.* 1999).

Evidently, for binaries at fixed separation, the secondary's disk is always tidally truncated to a smaller radius, but the difference only becomes significant for q less than about 0.5. In the case of disks that are not continually

replenished from an external reservoir, the tidal limitation of the disks around secondaries at a smaller radius leads to a more rapid accretion of the secondary's disk (*Armitage et al.*, 1999). This can be readily understood, as disk accretion depends on viscous redistribution of angular momentum, which, in a freely expanding disk, occurs on a longer and longer timescale as the disk spreads outwards. If a disk is tidally truncated, however, angular momentum is tidally transferred to the binary orbit at the point that the disk grows to the tidal truncation radius. Hence the disk dispersal timescale is roughly given by the disk's viscous timescale at the tidal truncation radius. For a disk with surface density profile of the form R^{-a}, the viscous timescale at radius R scales roughly as R^{2-a}. Hence, for a in the range $1-1.5$ (*Beckwith and Sargent*, 1991; *Hartmann et al.*, 1998), we have that the viscous timescale at the tidal radius R_T scales as $R_T^{0.5-1}$. Putting this scaling together with Fig. 4, we can therefore see that for binaries with $q > 0.5$, the viscous timescales at R_T are sufficiently similar that the disks should evolve more or less synchronously. The phase during which the secondary has exhausted its disk, but the primary has not, is relatively brief. On the other hand, for lower qs in the range observed, we expect the viscous timescales at R_T for the two components to differ by order unity. This means that the time spent by a system as a CW is comparable with the time spent as a CC, and hence, as observed, the two sorts of system should occur in roughly equal numbers.

At larger separations, $a > 100$ AU, the picture is apparently rather different since now mixed systems with WTTS primaries start to appear. This suggests that we are now entering a regime where the tidal truncation condition exerted by the binary is no longer the critical factor in determining which disk is exhausted first, a result that is perfectly comprehensible in the limit that the binary separation is much larger than typical disk sizes. We also note that the data for the wider binaries (where the disks evolve without obvious reference to their location in a binary) provides good evidence that disk lifetime is not a strong function of stellar mass. As an example, Sz 30 and Sz 108 are mixed systems with identical separations (630 AU) and similar spectral types for each component (M0.5-M2 and M0-M4.5 respectively). Nevertheless, in the former system it is the secondary that has lost its disk and in the latter it is the primary. Because we cannot appeal to non-coevality to explain this difference, we must assume that the lifetime of isolated disks is not a strong function of stellar mass in the range $0.1-1M_{\odot}$, and, hence, that presumably the initial conditions in the disk (such as initial mass or radius) instead dictate disk lifetime.

4.4. Implications for disk resupply

Early studies of binaries in which accretion diagnostics were separated for each component concluded that mixed systems are rare (see discussion in *Prato and Monin*, 2001), leading *Prato and Simon* (1997) to argue that the disks around each component must be sustained and then dissipated in a synchronised manner. It is hard to understand synchronised dispersal unless it is effected by some external agent. On the other hand, a low fraction of mixed systems can be explained if both components are fed from a common reservoir over most of the disk lifetime and if, once the reservoir is exhausted, the dispersal of both disks is relatively rapid. This explanation was favoured by *Prato and Simon* on the grounds that continued replenishment is the only way to explain the presence of accretion diagnostics in the closest binaries ($a <$ a few AU), for which the viscous timescale of their (highly truncated) disks is much less than the system age. In these closest binaries, there is good evidence for circumbinary disks (*Jensen and Mathieu*, 1997), which can plausibly continue to feed the central binary (*Mathieu et al.*, 1997). In wider binaries, however, i.e. a in the range a few to ~ 100 AU, upper limits on circumbinary disk masses are ~ 5 Jupiter masses (*Jensen et al.*, 1996) and therefore inadequate to provide substantial replenishment of circumstellar disks. In these wider systems, it is instead necessary to invoke replenishment through infall from an extended envelope. Possible evidence for such an envelope is provided by the millimeter study of young binaries by *Jensen and Akeson* (2003) who found that their interferometric measurements contained $46-85\%$ of the flux found in previous, single dish measurements (*Beckwith et al.*, 1990). *Jensen and Akeson* therefore speculated that the additional flux originated in an envelope on scales of > 700 AU, with the caution that the flux difference could be due to a flux calibration issue. However, as it is possible to conceal large quantities of cold dust at large distances from the binary without contributing significantly to the millimetre flux (*Lay et al.*, 1994), it is impossible to use this observation to constrain whether the extended emission contains a viable mass for re-supplying the binaries' circumstellar disks.

Our analysis here however indicates that mixed systems are, in fact, common, and thus does not require continued replenishment of disks for the binaries in our sample (which mostly have separations > 20 AU). Our results do not require there to be no replenishment, but imply that such replenishment must occur over a minor fraction of the disks' lifetimes or else be concentrated on to the primary's disk at late times. This latter possibility is in conflict with numerical simulations of infall onto proto-binaries (*Artymowicz*, 1983; *Bate*, 1997; although see *Ochi et al.*, 2005 for a recent contrary view on this issue). The simplest interpretation of our results, however, is that the disks evolve in isolation and that disk tidal truncation in the binary potential results in the secondary disk being dissipated somewhat prior to the primary's disk.

4.5. Implications for planet formation in binaries

How do these findings bear on the probability that planets are located in binary systems? The presence of a binary companion may render the existence of planets less likely

in two ways. First, binarity restricts the regions of orbital parameter space in which planets can exist in stable, circumstellar orbits, ruling out orbital radii that are within a factor of the binary separation, modulo the mass ratio q. For example, *Holman and Weigert* (1999) have conducted a study of the long term orbital stability of planets in binary systems and find that a companion star orbiting beyond more than 5 times the planetary orbital radius does not strongly threaten the planet's orbital stability. Second, if binarity reduces disk lifetimes (in the primary or secondary or both) then it may reduce the probability of planet formation, since there may be insufficient time for slow processes (such as those involved in the core accretion model) to operate before the disk is dispersed. For example, *Thebault et al.* (2004) find that the formation of the observed planet at 2 AU in the 18 AU binary γ Cephei requires the presence of a long lived and massive gas disk. In the absence of such gas, secular perturbations by the binary companion generate too high a velocity dispersion among the planetesimals for runaway accretion to proceed.

The present study, however, finds that the influence of binarity on circumstellar disk lifetime is rather mild in the systems with separations > 20 AU. The fact that the separation distribution of diskless binaries is indistinguishable from that of binaries with disks suggests that disk dispersal is not strongly accelerated for the closer binaries in this sample. Concerning differential evolution between the disks around primaries and secondaries, we found that the overall statistics of mixed systems versus CC systems implied that the shorter lived disk (usually the secondary's) had a mean lifetime of $\sim 60\%$ that of the longer lived disk. Unless there are processes in planet formation for which a factor 2 difference in disk lifetime is critical, we conclude that *circumstellar planet formation is not likely to be strongly suppressed in the case of binary secondaries.* We therefore expect planets to be formed around both components in binary systems wider than $\sim$ 20 AU. The recent numerical simulations of *Lissauer et al.* (2004) and *Quintana et al.* (2005) (see also *Barbieri et al.*, 2002) are in good agreement with this result.

The observational situation regarding the detection of planets in binary systems is strongly skewed by the selection criteria used in Doppler reflex motion surveys, as these tend to exclude known binaries on the grounds that binary orbital motion makes it harder to detect a planetary companion. Among the more than a hundred and fifty G to M stars hosting planetary companions, only 25 are binary or multiple systems, hosting a total of 31 planets (exoplanets.org; *Eggenberger et al.*, 2004, 2006; *Mugrauer et al.*, 2005). Therefore, only around 15% of known planets are in binary or multiple systems.

Fig. 6 and 7 show the orbital properties of the binary systems known to host Doppler reflex motion planets. As expected, the sample is strongly biased towards larger separations: planet search programs do not typically monitor binaries with separations less than $\sim 2''$, corresponding to separations in the range > 2 AU at the distances of the target stars (*Valenti and Fischer*, 2005). Because the median binary separation for G stars is 30 AU (*Duquennoy and Mayor*, 1991), it is evident that a large fraction of binaries have been excluded from such surveys. There is also the possibility of an observational bias towards low q on the grounds that low-mass companions are more likely to have been overlooked when initially selecting the radial velocity targets.

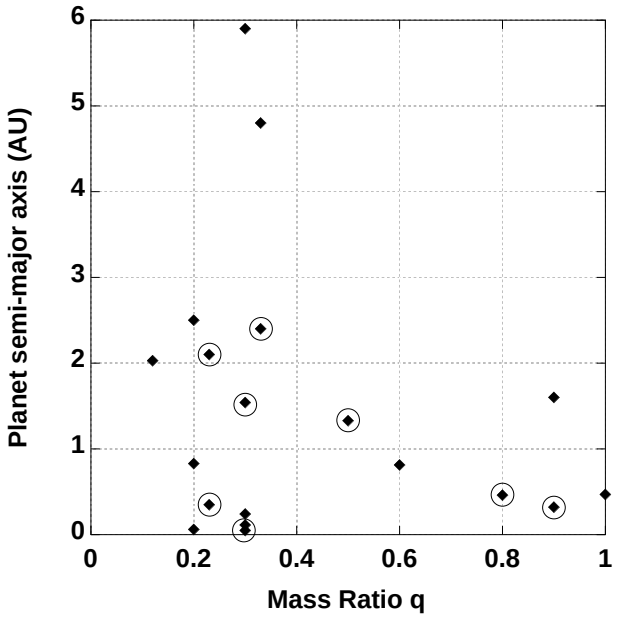

Fig. 6.— Distance from the planet to its central star (component of a binary) vs mass ratio. The encircled points are the ones for binaries with separation less than 500 AU.

It is immediately obvious from Fig. 7 that the ratio of binary semi-major axis to planet semi-major axis (a_b/a_p) is extremely large, generally in the range $100 - 1000$ and in all cases > 10. It is therefore unsurprising, on the grounds of orbital stability, that planets are found in these systems. Moreover, the binaries in Fig. 7 are in the same separation range that we have studied in Section 4.2, where we found little apparent dependence of disk lifetime on binary separation. We would therefore not expect planet formation to be suppressed in these systems on the basis of reduced disk lifetime.

We stress that the current data cannot be used to determine whether planets are preferentially found around binary primaries or secondaries, since in almost all cases it is only the primary that has been a radial velocity target. In only two systems is the planet detected around the secondary component (16 Cyg and HD 178911). Likewise, it would be premature to derive the statistics of *circumbinary planets*. To date, there is one system, HD 202206, that might be described as containing a circumbinary planet, although the mass ratio of the central binary is extremely low: the central companion is itself in the brown dwarf/planetary regime (*Correia et al.*, 2005). From a theoretical point of

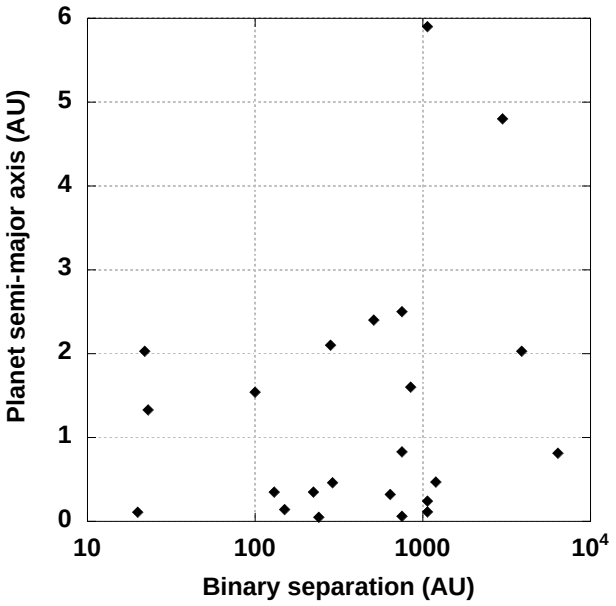

Fig. 7.— Distance from the planet to its central star (component of a binary) vs binary separation

view, *Moriwaki and Nakagawa* (2004) have claimed that in the case of a binary of separation 1 AU, planetesimal accretion should be able to proceed undisturbed at radii greater than $\sim$ 13 AU from the barycentre. This relatively large region in which planet formation might be expected to be suppressed in the circumbinary disk means that it may be problematic to detect planets through radial velocity measurements around all but the closest binaries. *Quintana et al.* (2005) calculate, however, that for binary separations of $<$0.2 AU, the growth of planetesimals into a system of terrestrial planets is statistically indistinguishable from similar simulations for single stars. Surveys for planets around single-lined, spectroscopic binaries (e.g., *Eggenberger et al.*, 2005) have only recently begun. When data are available, they should provide interesting constraints.

5. FUTURE DIRECTIONS

The most formidable obstacle to furthering our understanding of disk evolution in young binaries is the relatively small size of our database. Although our compilation of around 60 binaries with complete spectral type and disk diagnostic information for each component represents tremendous progress in the last decade, it is nevertheless too small a sample for us to be able to divide it into subcategories according to, for example, separation and subsequently derive statistically significant results. There are however good prospects for increasing the sample size. In our database of $\sim$170 total systems, we estimate that we can derive complete properties for approximately another half dozen systems based on extant data. An additional 28 systems with separations of $>1''$ can be characterized with a $2-3$ m class telescope in a site with good seeing, such as Mauna Kea or Cerro Tololo. A further 3 dozen systems have separations between $0.1''$ and $1.0''$. For these pairs it would be straightforward to characterize each component with low-resolution spectroscopy behind an adaptive optics system, or an integral field spectrometer unit, at a $6-10$ m class facility. The results of such observations would more than double the young binary sample. Furthermore, our database was compiled from a limited number of references and is certainly far from complete. We anticipate the ongoing compilation of additional objects and improvement in the quantity and quality of data for objects already listed.

Larger samples of binaries with known properties in a variety of star forming regions with a range of estimated ages will allow us to test the extremely intriguing notion of the regional dependence of the fraction of mixed systems. The data in this paper, as well as data obtained in the earlier studies of *Prato and Simon* (1997), *Prato and Monin* (2001), and *Hartigan and Kenyon* (2003), suggest a low fraction of mixed pairs in the Taurus region. Could this be the result of a younger age for Taurus than the other regions from which our sample is culled? Is it simply a selection effect, or a result of small number statistics? If a real and age-dependent effect, the mixed system fraction may yield a unique and sensitive approach to estimating the ages of star forming regions.

With high-resolution spectroscopy of both components in young binaries more detailed properties may be examined. For example, with multiple epoch observations hierarchical spectroscopic binaries might be identified in binary component stars. The individual rotation properties of the stars in close pairs could also be examined and compared with the circumstellar disk properties to better understand the evolution of angular momentum in young binaries (*Armitage et al.*, 1999). High-resolution observations of accretion line diagnostics, such as hydrogen emission lines, could provide a unique approach to the measurement of how accretion is apportioned between the two stars in spectroscopic binaries. Such observations at infrared wavelengths would provide a better opportunity to observe emission lines from both stars, even for systems with large continuum flux ratios (e.g., *Prato et al.*, 2002).

An interesting problem raised in *McCabe et al.* (2006) is the origin of the passive disk phenomenon. By combining resolved near- and mid-infrared observations with longer wavelength Spitzer data and astrophysical information for the binary stars themselves, i.e. masses, it will be possible to test the premise set up in *Clarke et al.* (2001) and *Takeuchi et al.* (2005), namely that a population of young systems with large inner disk holes exists around higher mass stars that have previously been identified as WTTS.

The advent of very high resolution interferometry, in both the optical-infrared as well as in the millimeter regimes, will provide an unprecedented view of the orientations of disks in binaries even at circumstellar scales. Already progress has been made using the Keck Interferometer (*Patience et al.*, 2005) and the VLTI (*Malbet et al.*, 2006). The ALMA interferometer, anticipated for first

light in the next 3−4 years at partial capacity, will provide unprecedented images of the cool, dusty disk structures.

These new generations of facilities will enable entirely new studies, which will go far beyond the issue of simple existence of disks in binary systems. Instead it will be possible to measure how *disk properties* vary as a function of binary properties such as separation, mass ratio, angular momentum, magnetic field strength, etc. For example, an instrument such as ALMA will enable us to study disk particle size distributions as a function of binary separation. Optical-infrared interferometers could provide data on inner disk structure as a function of magnetic field strength. Numerous such exciting possibilities for future study exist.

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