Planets in Binary Star Systems

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Nader Haghighipour
Editor

Planets in Binary Star Systems

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Editor
Dr. Nader Haghighipour
Institute for Astronomy and
NASA Astrobiology Institute
University of Hawaii
2680 Woodlawn Drive
Honolulu, HI 96822
USA
nader@ifa.hawaii.edu

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Preface

In 1988, in an article on the analysis of the measurements of the variations in the radial velocities of a number of stars, Campbell, Walker, and Yang reported an interesting phenomenon; the radial velocity variations of γ Cephei seemed to suggest the existence of a Jupiter-like planet around this star. This was a very exciting and, at the same time, very surprising discovery. It was exciting because if true, it would have marked the detection of the first planet outside of our solar system. It was surprising because the planet-hosting star is the primary of a binary system with a separation less than 19 AU, a distance comparable to the planetary distances in our solar system.

The moderately close orbit of the stellar companion of γ Cephei raised questions about the reality of its planet. The skepticism over the interpretation of the results (which was primarily based on the idea that binary star systems with small separations would not be favorable places for planet formation) became so strong that in a subsequent paper in 1992, Walker and his colleagues suggested that the planet in the γ Cephei binary might not be real, and the variations in the radial velocity of this star might have been due to its chromospheric activities.

Despite the 1992 article, the search for planets in binaries did not stop. Gamma Cephei was continuously monitored and more precise measurements of its radial velocity variations were obtained. In 2003, 15 years after the first announcement of the planet of this system, these efforts fruited, and in an article in *Astrophysical Journal*, Hatzes and his colleagues confirmed the existence of a Jupiter-like planet around the primary of γ Cephei. The planet became real, and so became many challenges that it introduced to the planetary science.

The 2003 confirmation of γ Cephei's planet, and the subsequent detection of giant planets in three other moderately close binary stars, GL 86, HD 41004 and HD 196885, marked the beginning of a new era on theoretical and observational research on planets in dual-star systems. During the past few years, much research has been carried out in this area, and a large number of excellent articles have been published on different aspects of observational and theoretical studies of planets in moderately close binaries. The depth of these articles, combined with their great diversity and the rich history of literature on the dynamical evolution of planets in dual-star systems has turned the field of planets in binaries into a well-established and an independent branch of exoplanetary science. This book is intended to introduce this field to the community. In doing so, this volume presents the reader with the current state of the research on the detection and formation of planets in binary stars, written by teams of experts on these topics. The first half of the book focuses on the observational evidence for the birthplace of planets in binary systems, and techniques of detecting planets in and around dual-stars. The second half discusses the status of theoretical research on the formation of planets in binaries, from planetesimals, to planetary embryos, and eventually to giant and terrestrial planets. The last chapter presents a complete review of the dynamics of planets in binary star systems and the possibility of habitable planet formation in these environments.

In making of this book, I had the privilege of collaborating with an outstanding team of authors and referees. I am grateful to the authors for their participation in this project and for their responsiveness during the editorial phase. I am also indebted to the referees, Richard Durisen, Eric Jensen, John Johnson, Greg Laughlin, Mercedes Lopez-Morales, Fred Rasio, Kevin Rauch, John Rayner, Steinn Sigurdsson, Gordon Walker, Russel White, and Jason Wright, for accepting to review chapters of this book, and for their constructive comments and suggestions. Each chapter in this book has been reviewed by at least one of these reviewers and myself. I am also thankful to the NASA Astrobiology Institute at the University of Hawaii for their continuous support during this project, and to the NASA Astrobiology Central for their financial support for the production of this book.

IfA/UH-NAI Nader Haghighipour
University of Hawaii
September 2009

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Chapter 1
Disks Around Young Binary Stars

Lisa Prato and Alycia J. Weinberger

1.1 Introduction

Multiple star systems provide a complicated mix of conditions for planet formation. Whereas circumstellar disks around single stars are likely routine sites for planet formation, binary systems can have circumprimary (around the more massive star), circumsecondary (around the less massive star), and circumbinary (around both stars) disks. These heterogeneous locations can provide opportunities as well as hazards.

The frequency and separation of young binary populations are perhaps most important when examined in light of the impact of companion stars on the potential for planet formation. Even for star-forming regions in which the binary frequency is similar to that of the local field population, roughly two thirds of all member stars form in multiple systems. For a certain range of stellar separations, the presence of a companion star will clearly impact the formation, structure, and evolution of circumstellar disks, and, hence any potential planet formation. Another aspect of planet formation in young binaries is that we can assume that the stars in a binary are relatively coeval. Differences in the planet forming properties between two stars of similar age in the same local environment provide key information for understanding what *stellar* properties are more or less favorable for planets. Thus, the two stars in a young binary provide a built-in control sample.

It is an observational fact that among young stars in many nearby star forming regions (SFRs) an excess binary population exists (Ghez et al. 1993; Leinert et al. 1993; Simon et al. 1993 and reviews in Mathieu et al. 2007; Duchêne et al. 2007). This overabundance of young doubles, in comparison to field stars in the solar

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L. Prato (✉)
Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001
e-mail: lprato@lowell.edu

A.J. Weinberger
Department of Terrestrial Magnetism and NASA Astrobiology Institute,
Carnegie Institution of Washington, 5241 Broad Branch Road NW, Washington, DC 20015
e-mail: weinberger@dtm.ciw.edu

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neighborhood (Duquennoy and Mayor 1991), anti-correlates with the property of stellar density (Prosser et al. 1994; Petr et al. 1998; Patience et al. 2002; Beck et al. 2003). Thus, the denser clusters, in which most stars form, contain a lower fraction of bound multiple systems, comparable to the fraction found among field stars. The maximum separation of bound systems is also related to the stellar density. Based on analysis of a two-point correlation function, the transition between the binary and large-scale clustering regimes, and hence the cutoff separation for the likelihood of a bound pair, increases from 400 AU (Orion Trapezium) to 5,000 AU (Ophiuchus) to 12,000 AU (Taurus), while the average stellar surface density decreases (Simon 1997). Studies of large samples of binaries in a wide variety of star-forming regions are key to unravelling the nature of binary formation mechanisms and the impact of environment on multiplicity fraction, distribution, and evolution.

An insoluble problem among main-sequence field stars is the possibility of prior dynamical evolution of the system (Portegies Zwart and McMillan 2005). The interactions between young stars and their associated circumstellar and circumbinary disks may set in motion such evolution. Examining systems while they are still young tells us about the initial *potential* for planet formation. Field star observations tell us if this potential was realized.

For very small-separation binaries, models indicate that planet formation should be possible in a circumbinary disk (Quintana and Lissauer 2006). Several examples of close young binaries with circumbinary disks are well known, such as DQ Tau (Mathieu et al. 1997), UZ Tau E (Prato et al. 2002; Martín et al. 2005) and HD 98800 B (Koerner et al. 2000; Prato et al. 2001). Figures 1.1 and 1.2 show the system of HD 98800. These pairs have separations of approximately 30 solar-radii to 1 AU (Basri et al. 1997; Prato et al. 2002; Boden et al. 2005). The GG Tau and UY Aur binaries, with stellar separations of tens of AU, are surrounded by angularly large and therefore well-studied circumbinary disks (McCabe et al. 2002; Close et al. 1998). *Spitzer* Space Telescope observations of main-sequence pairs revealed circumbinary debris disk material in 12 systems with stellar separations of several solar-radii to ∼5 AU (Trilling et al. 2007). However, in spite of these promising disk observations and model predictions, no planet has yet been detected orbiting a small separation, main-sequence binary (although a 2.4 $M_{\rm Jup}$ minimum-mass planet orbits the G6V star HD 202206 and its 0.83 AU substellar companion; Udry et al. 2002). This dearth of detections may simply reflect the difficulties inherent in radial velocity (RV) searches for planets around binaries and the fact that binaries are typically eliminated from RV samples (Eggenberger et al. 2004; Konacki 2005).

Models also indicate a favorable outcome for planet formation in the circumstellar disks of wide binaries (Quintana et al. 2007). Reservoirs for this process, the optically thick, circumstellar disks around component stars, are routinely observed in binary systems with separations as small as ∼14 AU (Hartigan and Kenyon 2003). A *Spitzer* study of dust evolution in the circumstellar disks of wide binaries shows no difference in the initial processing stages, such as grain growth and crystallization, between the binary and single stars (Pascucci et al. 2008). More than

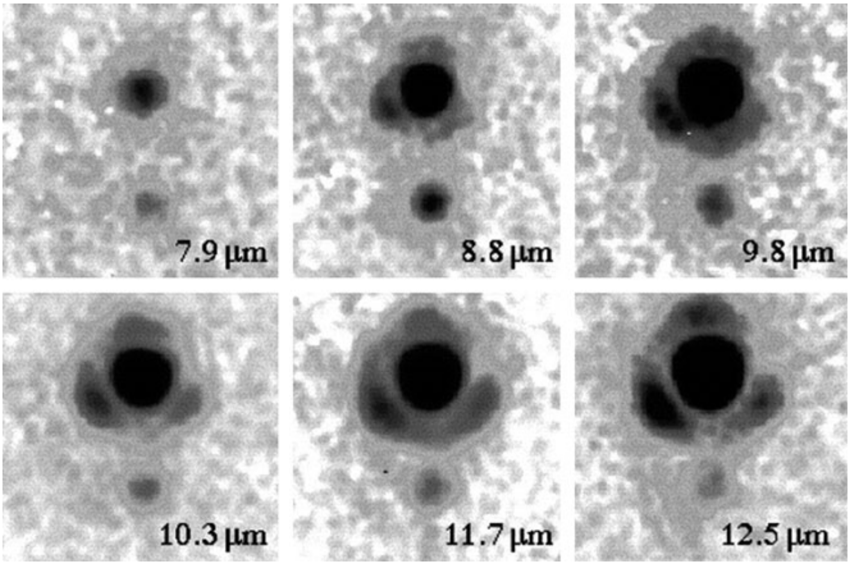

Fig. 1.1 Keck/MIRLIN imaging of the thermal infrared emission from the HD 98800 quadruple system oriented with up axis aligned due north. The spectroscopic binaries HD 98800A and HD 98800B are clearly resolved from each other and are identified, respectively, with northern and southern point sources separated by 0.8 arc sec (38 AU). Emission from HD 98800A steadily decreases with wavelength as λ^{-2} and is no longer detected in the 20 µm images. In contrast, radiation from the optical secondary, HD 98800B, increases dramatically out to 24.5 µm. Figure from Prato et al. (2001)

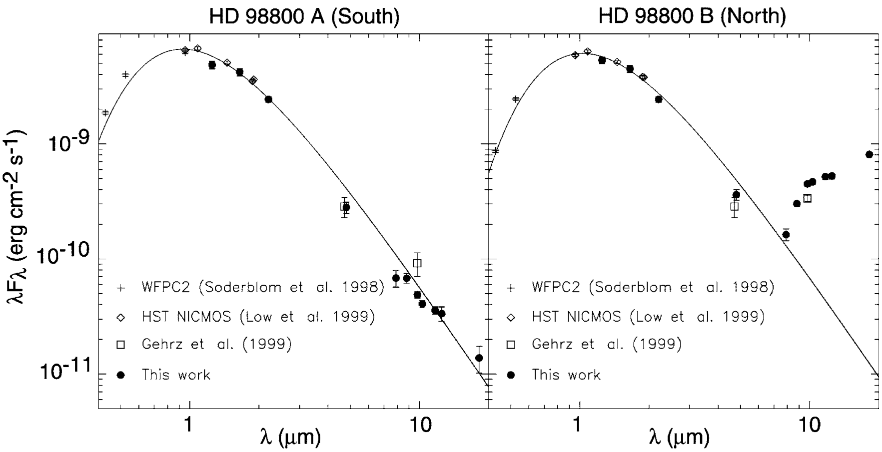

Fig. 1.2 Spectral energy distributions for HD 98800 A (*left*) and HD 98800 B (*right*). For HD 98800 A, no excess emission is evident out to the longest observed wavelength of 18.2 m; the 3932 K blackbody is plotted for reference. The 3562 K blackbody fit to HD 98800 B is also shown. Figure from Prato et al. (2001)

30 extrasolar planets (∼20%) have been reported around one component in binaries with separations of tens of AU up to thousands of AU (Eggenberger et al. 2004; Raghavan et al. 2006) – circumstellar planet formation seems to be common in multiple systems.

Inevitable truncation of the outer portions of circumstellar disks in binaries with separations of a few to several tens of AU likely delineates a "planet-free" zone, at least for formation. Subsequent dynamical evolution in multiple systems could still bring planets into this region (Jang-Condell 2007). Interestingly, this fiducial separation is similar to that of the peak in the separation distribution for binaries in most SFRs (Patience et al. 2002). This planet-free regime of binary separation is also notably the least well-studied; components at such separations are too distant to be observed as spectroscopic binaries (orbital induced RV variations are on the order of star spot induced RV variations; Saar et al. 1998), yet too close to be easily angularly resolved. For example, two solar-mass stars in a circular orbit with a 10 AU semi-major axis would have a period of 22.4 years, and a maximum orbital velocity of ∼1 km/s. At the 140 pc distance typical to the nearest SFRs, the maximum angular separation would be $0.07''$, slightly greater than the diffraction limit at a 10 m telescope in the near-infrared. Furthermore, angular resolution is more straightforward in a relatively face on orbit, but at the cost of modulation of the observed radial velocity by a $\sin i$ factor, where i is the angle between the plane of the sky and that of the orbit; a timescale of decades is required to observe a full cycle of radial velocity modulation in such a system.

A recent *Spitzer* study of the η Chamaeleontis cluster suggested that circumstellar disks were absent in 80% of the close binary systems while present around 80% of the single stars, although the study had a very small sample size and did not spatially resolve the binaries (Bouwman et al. 2006). At this point, such studies are suggestive, rather than definitive, of faster disk removal in close binaries.

It is not surprising that few data sets that go beyond initial binary identification exist, although there are some exceptions such as Hartigan and Kenyon (2003). We loosely define the binary separation regime most interesting, under-studied, and potentially treacherous to the formation and longevity of circumstellar disks, and therefore to the formation of planets, as spanning a few AU to 30 AU. This definition is naturally modulo eccentricity and mass-ratio, properties that could reinforce circumstellar disk destruction on short timescales.

In this chapter, we will discuss the current state of observations of disks in young multiple systems with an emphasis on circumstellar structures. Disks in solar analogue and low-mass stellar systems will be primarily considered. The topics covered in this review are (i) the evolution of inner disks in binaries (Section 1.2), (ii) the evolution of outer disks and the determination of disk masses as derived from submillimeter astronomy (Section 1.3), (iii) the orientation of disks in binary systems (Section 1.4), and (iv) the structure of debris disks in such environments (Section 1.5). We will present these topics through the lens of the potential for planet formation in these systems. In summary, Section 1.6 will present a discussion of future experiments and observations required to move knowledge in this field forward.

1.2 Inner Disks

Hydrogen emission line diagnostics (Hα or Brγ) and near-infrared colors are effective determinants of weak-lined (no or little inner disk material) and classical (optically thick inner disk) young stars (see Prato and Simon 1997; Martín 1998). Substantial line emission and near-infrared excesses attest to the presence of gas and warm dust located in the inner ~1 AU of a circumstellar disk around a G–M spectral type young star. The inner few AU of a circumstellar disk delineate the likely site of terrestrial planet formation and giant planet migration, and thus are particularly important. Inner disks are thought to evolve quickly from optically thick to thin states; few systems have been found in the intermediate "transition" state. In an overview of about a dozen Taurus SFR transition objects, Najita et al. (2007) find that although their mass accretion rates are typically an order of magnitude lower than those of classical T Tauri stars, their median disk masses are about four times larger, consistent with a scenario in which an object with a massive disk is in transition because a Jovian-mass planet is opening a large gap and effectively starving the inner disk (D'Alessio et al. 2005). Several of Najita et al.'s transition systems are binaries (Najita et al. 2007), one with projected separation ~120 AU (FQ Tau) and two with projected separations ~30 AU (FO Tau and V773 Tau (Fig. 1.3); the A component of the latter is also a 51 day period spectroscopic binary; Welty 1995). These separations are relatively wide and easily allow for the presence of inner disks. If the interpretation of on-going planet formation is

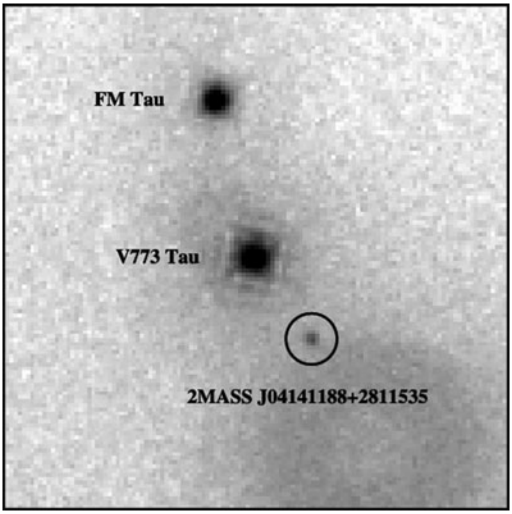

Fig. 1.3 X-ray image of V773 Tau in the 0.5–2 keV energy band obtained with XMM-Newton/UV Monitor image in the U-band of the young brown dwarf 2MASS J0414. This image is centered on the weak-line T Tauri star V773 Tau located only 24″ away from the brown dwarf. The Classical T Tauri star FM Tau is also visible. 2MASS J0414 is located on the PSF wings of V773 Tau, where no X-ray counterpart was found with the source detection algorithm. Figure from Grosso et al. (2007)

correct, these binaries illustrate the feasibility of this process in multiple systems. Confirmation of this hypothesis is, however, a challenge. One potential approach is to use high-resolution spectroscopy coupled with adaptive optics observations in order to angularly resolve these visual pairs and study the accretion signatures for the individual stars. A sufficiently massive planet could reveal its presence with radial velocity shifted hydrogen emission lines.

On the basis of the line emission and color diagnostics described above, Monin et al. (2007) classified a sample of young binaries with separations of ∼15–1,500 AU. In an extensive search of the young star binary literature, only ∼60 systems were found for which both component spectral types were known, and for which angularly resolved Hα, Brγ, K–L, or K–N (K $=$ 2.2 μm, L $=$ 3.4 μm, and N $=$ 10 μm) color data were available. These few dozen systems are drawn from a variety of star-forming regions, and thus do not represent a homogeneous sample. This dramatically underscores the unavoidable small number statistics inherent in any analysis of this sample, and the pressing need for a substantial observational effort in this area.

In spite of the small sample size, Monin et al.'s analysis revealed intriguing results and trends (see Figure 4 of Monin et al. 2007). One surprising and relatively robust outcome is that mixed pairs, in which the components appear to be in different evolutionary stages, are not as rare as once thought (Prato and Simon 1997; Hartigan and Kenyon 2003, composing 38% of the sample, exclusive of pure weak-lined systems (Table 1, Monin et al. 2007)). Less statistically notable are the suggestions that mixed systems are more common among the larger separation pairs and that a slight majority of these systems are detected among the lower mass-ratio pairs. There is also a hint in the available data that the frequency of mixed pairs may vary between star forming regions; this was previously suggested by Prato and Monin (2001) (see their Table 1). Unfortunately, because of the sparse data, these results are all at the 2σ level at best. Because the young star binary distribution peaks at subarcsecond angular separations, producing statistically large (hundreds of stars) samples in the nearby SFRs will require years of work at relatively large facilities which supply adaptive optics capabilities.

The determination of the stellar properties associated with long-lived, inner circumstellar disks allows us to predict what kind of stars are most likely to host planets. For example, if disk-locking is the main mechanism for controlling stellar angular momentum, stellar rotation rates over time will depend on inner disk masses. A young, slowly rotating star locked to a massive inner disk is therefore a likely candidate for future planet formation. Angularly resolved high-resolution spectroscopy of close young binaries yields $v \sin i$ measurements, providing insight into either the alignment of stellar rotation axes, or component stellar rotation rates. This degeneracy can be resolved with time series observations designed to determine component rotation periods. If rotation axes are aligned, discrepant rotation periods suggest star-disk locking in only one component, or some other differential source of angular momentum loss. Binary formation with discrepant component rotation is difficult to explain but also cannot be ruled out. Figure 1.4 shows a young binary with component $v \sin i$'s discrepant by a

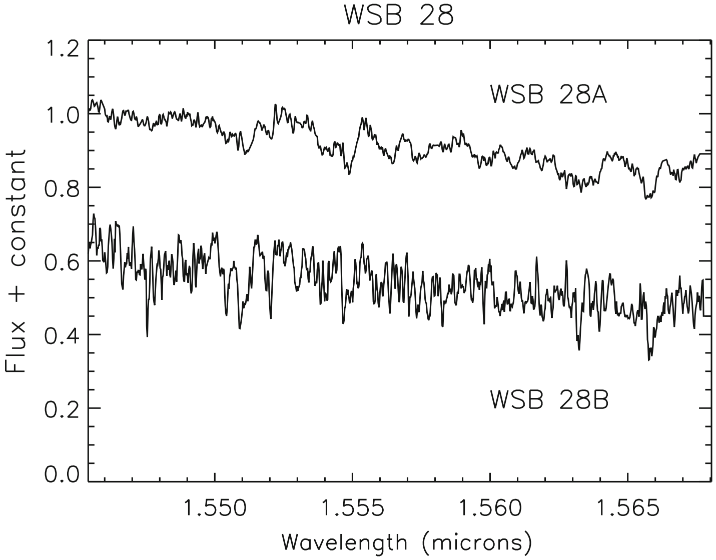

Fig. 1.4 R = 30,000 spectra of the components in the young binary WSB 28. The v sin i's are discrepant by a factor of 2–3, indicating either unaligned rotation axes or significantly different rotation periods. Veiling from circumstellar material cannot account for the shallow features in the M3 primary because this component is not associated with any circumstellar material, although the M7 secondary is (McCabe et al. 2006)

factor of 2–3. Intriguingly, this ~700 AU separation Ophiuchus binary, an M3 and an M7, is a mixed system (Prato et al. 2003). The rapidly rotating primary is not associated with dusty circumstellar material; however, the low mass companion is (McCabe et al. 2006), as we might expect from a disk-locking scenario. Similar discrepancies have also been observed in other systems, including the 30 AU separation young hierarchical triple, Elias 12, in Taurus (Schaefer 2004; Schaefer et al. 2006).

To determine the inclination of a stellar rotation axis, the system $v \sin i$ must first be measured. The sine of the inclination is proportional to $v \sin i$ multiplied by the period and divided by the stellar radius. The radius must be estimated based on models appropriate for the measured stellar parameters and is relatively uncertain but probably by a factor of less than two. For young binaries, the determination of the period is very challenging. Small separation systems require adaptive optics observations to resolve them, but most facilities offering this capability would be unlikely to schedule high cadence observations over a 10–20 day block conducive to rotation period determination. Furthermore, currently available adaptive optics systems function in the infrared regime, not ideal for measurements of flux modulation from star spots as the spot contrast and therefore signal amplitude is reduced at longer wavelengths. Larger separation systems (>1–$2''$) might be observed readily at 1–2 m telescopes which can be allocated for long term, multiple night programs. However, most stars in the nearest SFRs are relatively late type and are therefore faint, posing special challenges, particularly for large flux ratio binaries such as

WSB 28 (Fig. 1.4). The primary in this $\sim 5''$ pair has an I-band magnitude of ~ 13. The Gunn z filter, relatively similar to I-band, component flux ratio listed in Reipurth and Zinnecker (1993) is 0.06. Thus, the secondary's I magnitude is ~ 16. These observations are not impossible, but will require careful planning.

How much of an impact might selection effects have on the results presented here? Certainly small mass-ratio systems are more difficult to detect as well as to characterize, particularly in the most interesting small separation regime (Section 1.1). Systems classified as weak-lined T Tauris, unresolved, might also harbor truncated inner disks around the secondary stars. Such small structures could go undetected as the result of dilution from a relatively bright primary. Circumstellar disks with central holes that show excesses in the mid-infrared but not in the near-infrared, and which do not show signatures of accretion, may also be present but are effectively undetectable. Even if sensitive but low-angular resolution *Spitzer* observations could reveal the presence of such a structure, there is little recourse for ground-based mid-infrared follow up at sufficiently high sensitivity and angular resolution to determine structure and location. Only four of the circumstellar disks in the young binary sample of McCabe et al. (2006) (T Tau N and S, UZ Tau E, and RW Aur A) are brighter than the $N = 4$ mag limit of the VLTI mid-infrared instrument MIDI.

We must also take into account that the completeness of our knowledge of binary populations varies markedly between different star-forming regions, possibly leading to an inaccurate determination of differences in mixed pair fractions, etc., between regions. Although Taurus, given its small size and ready accessibility in the northern skies, is arguably the most thoroughly studied region, its faintest members are only now being surveyed for multiplicity (Konopacky et al. 2007). Ultimately, however, it is not enough to take a simple census of binary frequency and to characterize systems by their unresolved properties. Knowledge of the configuration of the circumstellar and circumbinary dust and gas is required to truly assess the planet-forming potential of young stars, and to determine if SFRs as a whole possess environments particularly conducive, or not, to planet formation. Global properties such as initial molecular cloud angular momentum, the presence of high mass, photoionizing sources, stellar density, etc., may all influence disk and thereby planet formation.

1.3 Outer Disks

Outer circumstellar disks, here taken to mean beyond about 10 AU, may also host planet formation. In addition, they provide an important reservoir of material that feeds the inner disk as well as a critical source of angular momentum transfer for interior material. The cool gas and dust in outer disks, including circumbinary disks, are best surveyed using far-infrared or submillimeter observations. Disks are usually optically thin at long wavelengths, so these observations have the additional benefit of providing total disk masses (Beckwith et al. 1990) in the region analogous to where giant planets formed in the Solar System.

Although estimates of the binary fraction were highly incomplete when the first submillimeter surveys were done, it was still clear immediately that binary stars with separations closer than 100 AU were deficient in disks (Beckwith et al. 1990; Jensen et al. 1994; Osterloh and Beckwith 1995). In a recent work, a survey of 150 young stars in Taurus (including 62 multiple stars) showed lower submillimeter fluxes, and hence disk masses, in binaries closer than $\sim$100 AU than in single stars, while wide binaries were similar to single stars in disk mass (Andrews and Williams 2005). Disks were present, albeit at these lower masses, in approximately the same fraction of multiple star as single star systems. Perhaps these disks can still form giant planets, but of lower average mass than the single stars.

The surveys described above were carried out with single dish telescopes and therefore have low spatial resolution incapable of distinguishing primary and secondary disks in the interesting separation range of $\leq$100 AU. A smaller number of objects have been surveyed with interferometers that can resolve the multiple systems. In one such survey, the primary stars of four binaries in Ophiuchus hosted higher mass disks, even when the secondaries were still accreting, while in four binaries in Taurus the circumsecondary disks were more massive (Patience et al. 2005). In these very young objects, the true "primary," i.e., more massive star of the pair, may have been misidentified in extinguished visual-wavelength data, or these trends may relate to the initial conditions. In another study of four wider systems, also in Taurus, the circumprimary disks were again the most massive (and again comparable to single stars in Taurus) (Jensen and Akeson 2003).

Models of disk dissipation generally show that the circumsecondary disk, which is expected to be truncated closer to the star than the circumprimary disk, should dissipate faster (Armitage and Clarke 1999). In single stars, however, outer disk mass is not correlated with stellar mass (Andrews and Williams 2005), therefore it is possible for circumsecondary disks to form with more mass than circumprimary disks. These initial conditions could overwhelm the difference in dissipation timescale.

Finally, it is worth noting that total disk masses for single stars or wide companions in Taurus or Ophiuchus, i.e., regions of low-mass star formation, are typically in the range 0.005–0.01 solar-masses although with wide dispersion and a substantial fraction (about 20%) of larger disk masses. For comparison, the mass of the "Minimum Mass Solar Nebula" necessary for forming our system's planets is about 0.01 $M_\odot$. Results for clusters with massive stars such as the Orion Nebula cluster (Bally et al. 1998) and NGC 2024 (Eisner and Carpenter 2003) suggest that there are fewer massive disks than in low-mass SFRs. It is possible that these disks dissipate more rapidly because of external radiation, for example. These regions of massive star formation are generally further away, so binary surveys are much less complete and single dish submillimeter measurements are less likely to resolve multiple stars (Fig. 1.5). However, just as early unresolved work in Taurus showed a general trend of lower disk mass with binarity, we expect this same trend to hold in regions of more massive star formation, as well.

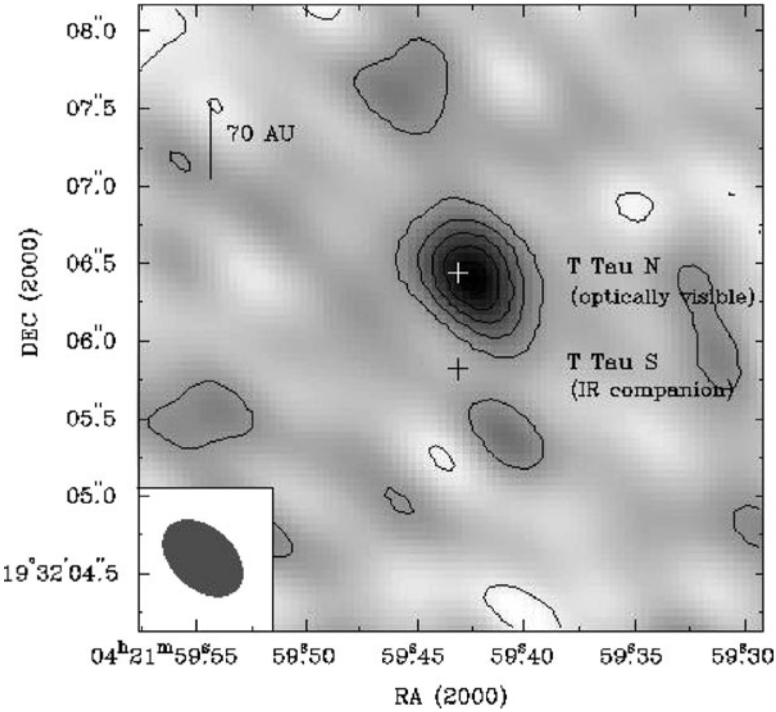

Fig. 1.5 Circumstellar disk around T Tau N. 108 GHz continuum emission using only the longest spacing array. The contour levels plotted are 2σ. The size of the error bars on the millimeter emission center position (*cross*) represents the absolute positional uncertainty for the millimeter image of 0.07 arc sec. Figure from Akeson et al. (1998)

1.4 Orientation of Disks in Young Binaries

A single star plus disk system contains a single plane: that of the disk. A binary system, however, is associated with four relevant planes: a circumstellar disk around each star, the plane of the binary orbit, and the plane of any circumbinary disk. Although circumbinary disks appear to be relatively rare in young systems (Jensen and Mathieu 1997), recent observations by Trilling et al. (2007) find evidence for circumbinary debris disks around 12 small separation main-sequence binaries of relatively early spectral type, A3–F8. Whether or not these disks are aligned with the binary orbit is not known. *Alignment* of circumstellar disks does not necessarily imply coplanarity of the binary orbital plane with that of the aligned disks (Fig. 1.6). The studies of Jensen et al. (2004) and Monin et al. (2006) trace circumstellar alignment, for relatively wide, angularly resolved young binaries, using the position angle of the integrated, linear polarization of the light scattered from a circumstellar disk. Because the position angle is parallel to the plane of the disk, it provides a proxy for disk orientation (but see additional discussion in Monin et al. (2007)). Jensen et al. (2004) and Monin et al. (2006) found that most simple binary systems

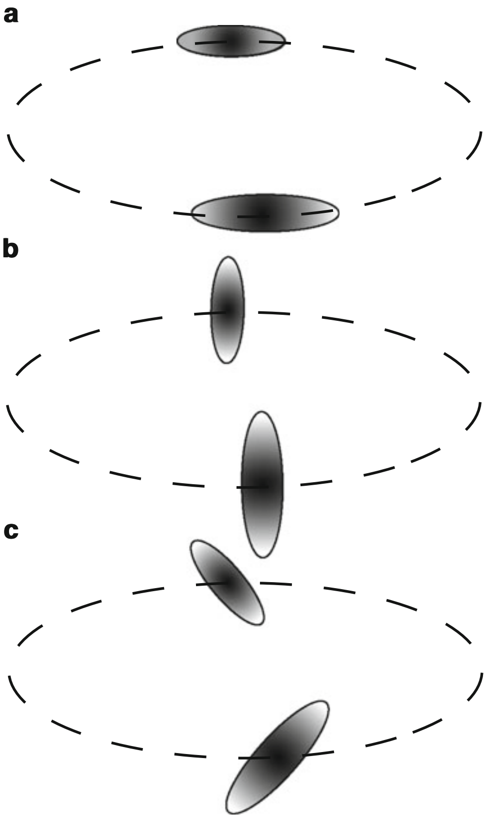

Fig. 1.6 Circumstellar disks in a simple binary orbit: (**a**) aligned and coplanar, (**b**) aligned but non-coplanar, (**c**) unaligned and non-coplanar

studied exhibit aligned disks with polarization position angles consistent to within <30 degrees, although higher order multiples show a large range of variation in polarization position angles.

The orientations of the highly collimated jets that emanate from many young star systems are also a proxy for determining disk orientations in unresolved binaries, as jets are thought to launch perpendicular to the inner circumstellar disks. Multiple misaligned jets are known to exist in a number of young systems (Monin et al. 2007 and references therein), suggesting that it is possible for small separation binaries to actually *form* with misaligned disks (Fig. 1.6, case c). Thus, formation models must account for this counterintuitive evidence.

The coplanarity of disks and binary orbits is readily studied for some well-separated pairs. Interestingly, it appears likely that circumbinary disks are aligned with close binary star orbits, e.g., for DQ Tau, UZ Tau E, and HD 98800 B (Mathieu et al. 1997; Prato et al. 2001; Prato et al. 2002). However, systems with a circumstellar disk around at least one component of a wider binary, e.g., HV Tau AB-C, HK Tau A-B, UZ Tau E-W, T Tau N-S, and HD 98800 N-S (Stapelfeldt et al. 2003, 1998; Prato et al. 2001, 2002; Akeson et al. 2002), *do not* appear to be coplanar. We note that with the possible exception of HK Tau, these systems are all higher order multiples, a condition which may well play a role in the non-coplanarity (Jensen et al. 2004). What are the implications of these observations for potential planet formation? An interesting case study is the quadruple system HD 98800. The wide pair has a separation of ~40 AU (Prato et al. 2001), a period of 300−430 years, and an inclination of ~88 degrees (Tokovinin 1999). Each component of the wide pair is a spectroscopic binary of similar properties, with K5 and K7 spectral type primaries, 262 and 315 day periods, and eccentricities of 0.484 and 0.781 for the A and B components, respectively. However, circumstellar material is only present around the HD 98800 B binary. The inclination of this stellar pair is 67 degrees (Boden et al. 2005). Recently, Akeson et al. (2007) showed that the associated circumbinary disk is likely warped by interactions with the distant A component. The primary mystery in this system, however, is the complete absence of circumbinary material surrounding HD 98800 A. Speculation by Prato et al. (2001) suggests that because of the relative orientations of the HD 98800 A and B circumbinary disks during repeated periastron passages of the wide pair over the ~10 Myr lifetime of the system, B's disk was perturbed and A's disk was completely disrupted. See the next section for more discussion of the planetesimal dynamics in this system.

The dynamics of circumbinary and even close circumstellar disks and the interrelationship between disks and orbits appears to be complex and is not yet well understood. We present these conclusions as a cautionary tale: even binaries with separations of a few tens of AU – or less – cannot be assumed to harbor aligned disks coplanar with binary orbits. In higher order multiples, misalignments may be the rule. It is possible that, in at least some cases, misalignment may have its origins in the formation dynamics of these systems.

1.5 Debris Disks and Binaries

Transitional and debris disks are generally older than the massive disks discussed earlier. Their primordial material, particularly gas, is partially or totally dissipated and remaining solids are large enough that their major destruction mechanism is collisions (either aggregation onto planets or disruptive). Giant planets must either have already formed, or will not form, in these systems, and terrestrial planets may be in their final stages of accumulation, perhaps eras akin to the late heavy bombardment in the Solar System.

To be detected in sensitivity-limited observations, debris disks must be closer to the Sun than the nearest sites of recent/ongoing star formation discussed earlier; this has the benefit that the effect of binarity on the disks can be observed in some detail. We will discuss two examples.

HD 141569 is a hierarchical triple system (Fig. 1.7) consisting of an A0-type primary star, which sports an extended disk containing small quantities of both gas and dust, and two M-type companion stars located about 1,000 AU away. The low mass stars, and presumably the whole system, are about 5 Myr old (Weinberger et al. 2000). Spiral structure at 200–500 AU in the primary's disk can be explained by either a highly eccentric ($e \geq 0.7$) binary A-BC orbit (Augereau and Papaloizou

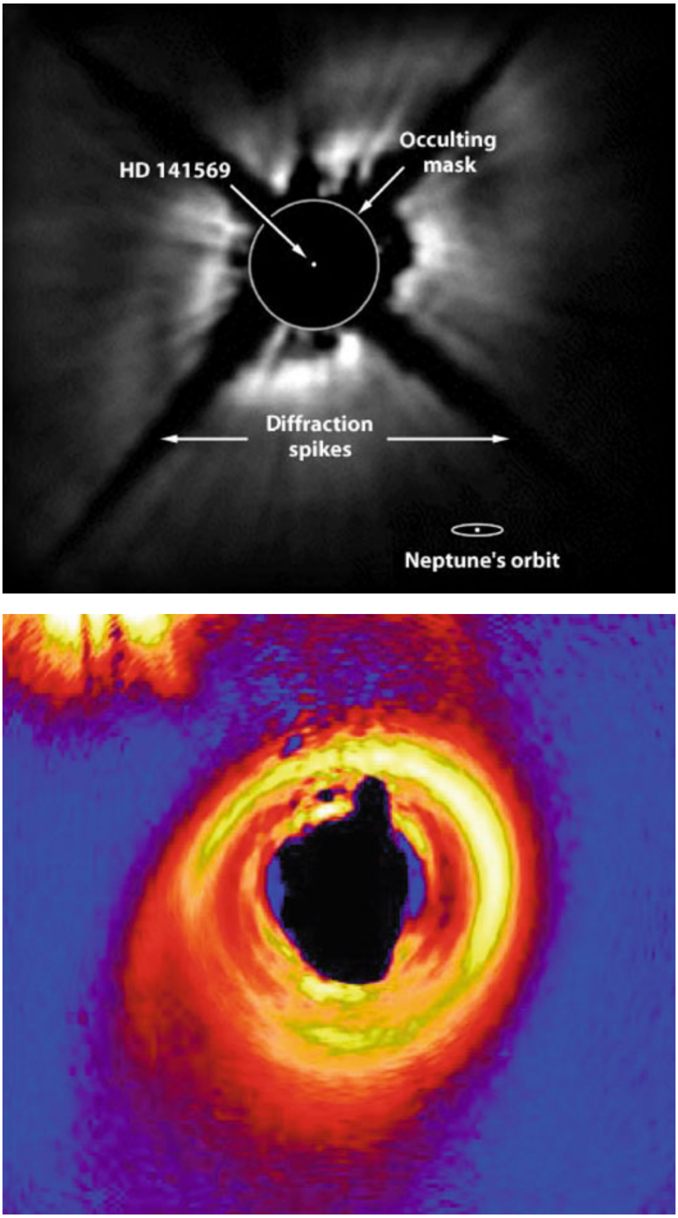

Fig. 1.7 *Top*: A near-infrared view of the disk surrounding HD 141569 recorded in 1998 by the Hubble Space Telescope. *Bottom*: Coronagraphic image of the protoplanetary disk around HD141569 taken with the Advanced Camera for Surveys (ACS) in the Hubble Space Telescope

2004; Quillen et al. 2005; Ardila et al. 2005) or a recent (~1,000 years ago) stellar flyby (Beust 2005). In both cases, the affected portion of the disk is at a radius of a few hundred AU, and structure in the disk at <150 AU must have another cause, perhaps a planet. Interestingly, the two M-type stars have no detectable disks down to the level (in $L_{\mathrm{IR,disk}}/L_*$; a measure of disk mass where $L_{\mathrm{IR,disk}}$ is the luminosity of the disk and L_* is that of its central star) of the primary's disk. This could be attributed to the small separation of their orbit, ~150 AU.

HD 98800 is a member of the ~8 Myr old TW Hya Association and the interesting arrangement of its fours stars and dust disk is described in the previous section and in Low et al. (1999), Koerner et al. (2000), and Prato et al. (2001). The system has characteristics of both a circumbinary and circumstellar disk. The HD 98800 B binary is eccentric (e = 0.78) with a semi-major axis of 1 AU (Boden et al. 2005). Based on its temperature, the inner edge of the dust disk sits at 1.2 – 2.1 AU (Prato et al. 2001). This is just barely consistent with estimates of the dynamical tidal truncation (Artymowicz and Lubow 1994). The A-B orbit is also significantly eccentric (0.3–0.6) with a periastron approach of perhaps 35 AU (Tokovinin 1999). The outer edge of the dust disk is less well constrained by the infrared/submillimeter observations, but is >5 AU and could be as large as 25 AU (Koerner et al. 2000). An outer size of 10 AU would fit both the observations of the dust temperature and the expected dynamical truncation from the A-B orbit.

While both of these systems provide interesting examples of the dynamical influence of multiplicity on the disk, they also illustrate that planet formation is possible under such complicated circumstances. The small dust grains in the HD 141569 A and HD 98800 B disks are regenerated in collisions (Weinberger et al. 1999; Augereau and Papaloizou 2004; Low et al. 1999) and indicate that planetesimals did form on timescales short enough that gas could have been present simultaneously with solid bodies.

Statistics of the incidence of debris disks around binaries are consistent with the idea that wide binaries do not affect disk evolution. A survey of 69 FGK stars including binaries of separations >500 AU finds 3/8 of the debris disks are around binary members (Bryden et al. 2006). A larger survey of old A and F-type stars (Trilling et al. 2007) looked at the incidence of debris disks as a function of separation and found that there were fewer disks in 3–50 AU separation systems than in closer or wider systems (Fig. 1.8). The total numbers of disks in this *Spitzer* survey were comparable to surveys of single stars and contained just as much dust. Although *Spitzer* did not resolve the individual components, the dust temperatures imply that both circumbinary and circumstellar debris disks are common, at least amongst stars somewhat more massive than the Sun (Fig. 1.8).

1.6 Future Tests and Observations

As noted throughout this review, binary star systems do indeed host circumstellar and circumbinary disks over their entire lifetimes from pre-main sequence to mature stars. At separations larger than a few hundred AU, disk evolution around a binary

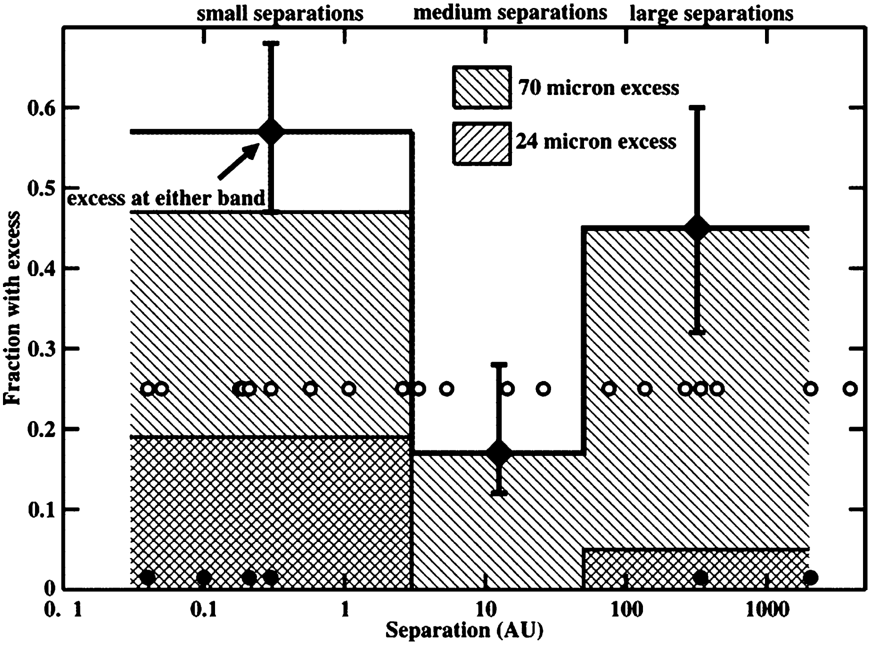

Fig. 1.8 Fraction of binary systems in each of three logarithmic bins (0–3 AU, 3–50 AU, 50–200 AU) that have 24 μm (diagonal pattern *lower left to upper right*), 70 μm (diagonal pattern *lower right to upper left*), or 24 or 70 μm excesses (clear). Binomial error bars are shown for the 24 or 70 μm excess category. Each category reads from the bottom of the plot (that is, the fraction of close binaries with 70 μm excesses is 47%). Some systems have excesses at both wavelengths, and the number of observed systems is not the same at 24 and 70 μm, so the combined fractions do not simply equal the sum of the two subcategories. The separations of the individual systems with excesses contained within each bin are indicated by the filled (24 μm) and open (70 μm) circles (with arbitrary y-axis values). Medium-separation systems have fewer excesses than small- or large-separation systems. Figure from Trilling et al. (2007)

component may proceed no differently than if the stars were not bound together. However, a tremendous observational effort is required to explore the most populous binary separation regime, and that of most scientific interest with respect to the impact of multiplicity on planet formation – a few to ~30 AU separations (Fig. 1.9).

With concerted observational attention, it seems a solvable problem to measure the dissipation timescales of primary and secondary disks. Ongoing spatially resolved spectroscopy with adaptive optics systems on large telescopes will assess the accretion parameters and optical depths of inner circumstellar disks in close binaries. Ground based interferometers will get detailed orbits for close binaries which can then be compared to disk sizes for empirical verification of dynamical estimates of tidal disruption and dissipation (Boden et al. 2005).

Progress on the determination of masses and orientations of circumstellar disks in young binaries, which cannot not be accomplished with the limited sensitivity and spatial resolution of the current generation of millimeter interferometers, will

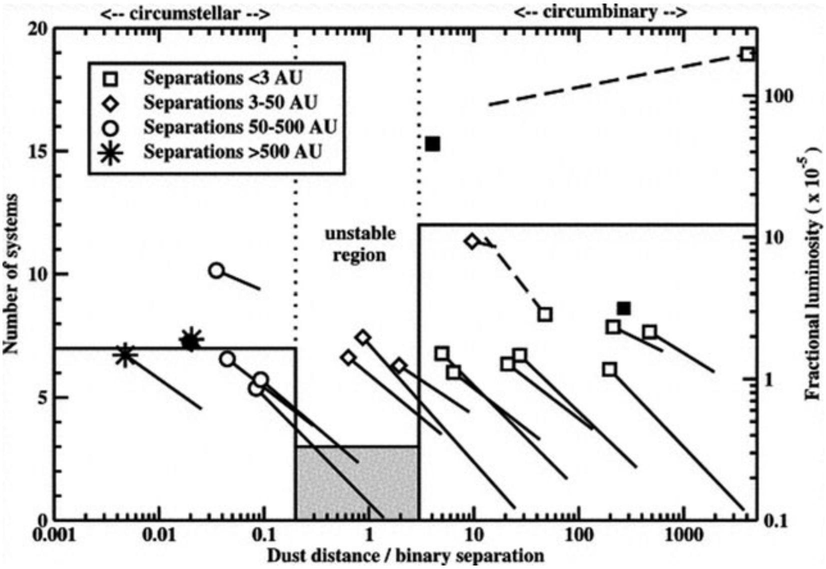

Fig. 1.9 Histogram of dust distance in units of binary separation (*left axis*) and fractional luminosity as a function of dust distance in units of binary separation (*right axis*). *Left axis: dashed vertical lines* show the approximate boundaries of the unstable zone (*histogram bar shaded gray*). Dust in three systems is found to reside within this dynamically unstable region. *Right axis:* there is no strong trend between fractional luminosity and dust location. Binary systems with small, medium, large, and very large physical separations are indicated. Not surprisingly, circumbinary disks are generally found in small-separation systems and circumstellar disks are found in large-separation systems. Dust in unstable regions is found only in medium separation systems. Fractional luminosities for the maximum-temperature cases are indicated by the symbols. "Tails" on the symbols indicate the locus of solutions, from maximum-temperature solutions (symbols) to 50 K (minimum reasonable) solutions at the other ends of the tails. Figure from Trilling et al. (2007)

advance markedly with the advent of the Atacama Large Millimeter Array (ALMA). Scheduled to begin full operation in 2012 and providing sub-arcsecond resolution and high sensitivity, ALMA will be able to probe component disk masses not only in nearby Taurus and Ophiuchus but also in clusters containing massive stars.

Imaging the dynamical effects of binarity on individual nearby disks will take advantage of ongoing, improving capabilities, such as more sensitive adaptive optics on 8–10 m ground-based telescopes. Furthermore, the James Webb Space Telescope (JWST), due to be launched in 2013, represents a leap in the quality of direct imaging in the near- and mid-infrared. A 6.5 m telescope, JWST will provide coronagraphic imaging at 1–23 μm for detailed disk studies.

The quantitative, detailed study of disks in young binaries has grown rapidly over the last decade, following quickly, and to some degree simultaneously, on the results of the initial discovery surveys. The upcoming decade promises to provide a number of powerful new and innovative tools and approaches for this field. Although many of the observations necessary to progress into the most interesting (and common) small binary separation regime require time at high-demand facilities, we emphasize that this work merits the investment: binary stars, and particularly young binary stars, dominate the stellar census. The particulars of planet formation in these systems determine the range of planetary system architectures present in the Galaxy.

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Chapter 2
Probing the Impact of Stellar Duplicity on Planet Occurrence with Spectroscopic and Imaging Observations

Anne Eggenberger and Stéphane Udry

2.1 Introduction

Over the past 14 years, Doppler spectroscopy has been very successful in detecting and characterizing extrasolar planets, providing us with a wealth of information on these distant worlds (e.g., Marcy et al. 2005a; Udry and Santos 2007b; Udry et al. 2007a). One important and considerably unexpected fact these new data have taught us is that diversity is the rule in the planetary world. Diversity is found not only in the characteristics and orbital properties of the ∼340 planets detected thus far,[1] but also in the types of environments in which they reside and are able to form. This observation has prompted a serious revision of the theories of planet formation (e.g., Lissauer and Stevenson 2007; Durisen et al. 2007; Nagasawa et al. 2007), leading to the idea that planet formation may be a richer and more robust process than originally thought.

It is well known that nearby G, K, and M dwarfs are more likely found in pairs or in multiple systems. Specifically, 57% of the G dwarf primaries within 22 pc of the Sun have at least one stellar companion (Duquennoy and Mayor 1991). The multiplicity among K dwarfs is very similar (Halbwachs et al. 2003; Eggenberger et al. 2004b), and among nearby M dwarfs is close to 30% (Fischer and Marcy 1992; Delfosse et al. 2004). Altogether, these figures imply that more than half of the nearby F7–M4 dwarfs are in binaries or in higher order systems. Since these stars constitute the bulk of the targets searched for extrasolar planets via

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[1] See the Extrasolar Planet Encyclopedia, http://exoplanet.eu/, for an up-to-date list.

A. Eggenberger (✉)
Observatoire de Genève, Université de Genève, 51 ch. des Maillettes, 1290 Sauverny, Switzerland
and
Laboratoire d'Astrophysique de Grenoble, UMR 5571 CNRS/Université J. Fourier,
BP 53, 38041 Grenoble Cedex 9, France
e-mail: anne.eggenberger@obs.ujf-grenoble.fr

S. Udry
Observatoire de Genève, Université de Genève, 51 ch. des Maillettes, 1290 Sauverny, Switzerland
e-mail: stephane.udry@obs.unige.ch

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Doppler spectroscopy, the question of the existence of planets in binary and multiple star systems is fundamental and cannot be avoided when one tries to assess the overall frequency of planets.

From the theoretical perspective, the existence of planets in binary and multiple star systems is not guaranteed a priori as the presence of a stellar companion may disrupt both planet formation and long-term stability. On the other hand, young binary systems often possess more than one protoplanetary disk (Monin et al. 2007 and references therein), meaning that planets may form around any of the two stellar components (circumstellar planets) and/or around the pair as a whole (circumbinary planets). Although theoretically both circumstellar and circumbinary planets should exist (Barbieri et al. 2002; Mayer et al. 2005; Boss 2006; Thébault et al. 2006; Quintana and Lissauer 2006; Haghighipour and Raymond 2007; Quintana et al. 2007; Pierens and Nelson 2007), our present planet search programs are essentially aimed at detecting circumstellar planets, and only these will be considered in this chapter. Our discussion will furthermore be focused on giant planets, which are less challenging to detect by means of the Doppler spectroscopy technique than lower mass objects.

Two different scenarios have been proposed to explain the formation of gaseous giant planets. According to the core accretion model, giant planets form in a protoplanetary disk through the accretion of solid planetesimals followed by gas capture (see, e.g., Lissauer and Stevenson (2007) for a review and references). Despite some remaining uncertainties, this scenario is commonly considered as the favored mechanism to explain the formation of giant planets. An important point in this model is that the protoplanetary cores that give rise to the giant planets may have to form beyond the snow line (i.e., beyond 1–4 AU for solar-type stars) to benefit from the presence of ices as catalysts.

An alternative way to view giant planet formation is to consider that these planets form by direct fragmentation of the protoplanetary disk. This is the so-called disk instability model (see Durisen et al. 2007 and chapter ... for a review and references). Since it is not clear yet whether real protoplanetary disks actually meet the requirements for fragmentation, and whether the fragments will live long enough to contract into permanent planets, the disk instability scenario has remained somewhat speculative. Observational tests that would help characterizing and quantifying the likelihood of forming giant planets by this method are thus desirable.

Regardless of the exact formation process, tidal perturbations from a stellar companion within $\sim$100 AU may affect planet formation by truncating, stirring, and heating a potential circumstellar protoplanetary disk (e.g., Artymowicz and Lubow 1994; Nelson 2000; Mayer et al. 2005; Pichardo et al. 2005; Boss 2006; Thébault et al. 2006). Disk truncation is a serious concern as it reduces the amount of material available for planet formation and it may cut the disk inside the snow line. This is a direct threat to planet formation in binary stars and explains why the naive outlook for planet formation in moderately close binaries is pessimistic.

The impact of disk stirring and heating on planet formation is not so easily understood and requires dedicated simulations. According to Nelson (2000), giant planet formation is inhibited in equal-mass binaries with a separation of 50 AU whatever the formation mechanism, whereas Boss (2006) claims that giant planets are able to form in binaries with periastrons as small as 25 AU. Other studies on the subject concluded that planetesimal accretion is perturbed but remains possible in various binary systems closer than 50 AU (Thébault et al. 2004, 2006), and that the two possible formation mechanisms may yield different predictions as to the occurrence of giant planets in binaries separated by 60–100 AU (Mayer et al. 2005). This last conclusion is particularly interesting since it implies that planets in 60–100 AU binaries might be used to identify the main formation mechanism for giant planets.

Assuming that planets can form in various types of binary systems, another important concern is their survival. The extensive body of literature on this subject can be summarized as follows. For low-inclination planetary orbits ($i \lesssim 39°$), the survival time is primarily determined by the binary periastron. A stellar companion with a periastron wider than approximately 5–7 times the planetary semimajor axis does not constitute a serious threat to the long-term ($\sim$5 Gyr) stability of Jovian-mass planets (e.g., Holman and Wiegert 1999; Fatuzzo et al. 2006). The survival time of planets on higher inclination orbits depends not only on the binary periastron, but also on the inclination angle (Innanen et al. 1997; Haghighipour 2006; Malmberg et al. 2007), meaning that planetary orbits become more easily unstable, even if the semimajor axis is quite large (several hundred of AU). This additional type of instability is due to the so-called Kozai mechanism, which causes synchronous oscillations of the planet eccentricity and inclination (e.g., Kozai 1962; Holman et al. 1997; Mazeh et al. 1997; Takeda and Rasio 2005).

To sum up, if giant planets are to form in binaries with a separation below $\sim$100 AU, then the most sensitive (but also less understood) issue regarding their occurrence in these systems seems to be whether or not these planets can form in the first place. This conclusion is quite appealing as it implies that quantifying the occurrence of planets in moderately close binaries may be a means of obtaining some observational constraints on the processes underlying planet formation. Yet, recent work made to explain the existence of a close-in Jovian planet around HD 188753 A emphasized the alternative possibility that moderately close double and multiple star systems originally void of giant planets may acquire one via dynamical interactions (stellar encounters or exchanges), in which case the present orbital configuration of the system would not be indicative of the planetary formation process (Pfahl 2005; Portegies Zwart and McMillan 2005). Pfahl and Muterspaugh (2006) have tried to quantify the likelihood that a binary system could acquire a giant planet in this way and concluded that dynamical processes could deposit Jovian planets in $\sim$0.1% of the binaries closer than 50 AU. Therefore, to test the possibility of forming giant planets in binaries closer than $\sim$100 AU, one needs not only to detect giant planets in these systems, but above all, to quantify their frequency.

From the observational perspective, the existence of planets in wide binaries and multiple star systems has been supported by observations almost since the first discoveries. In 1997 three planets were found to orbit the primary components of wide binaries HR 3522, HR 5185, and HR 458 (Butler et al. 1997), while another one was discovered around 16 Cyg B, the secondary component of a triple system (Cochran et al. 1997). Three years later, the detection of a giant planet around Gl 86 A (Queloz et al. 2000) brought a clear evidence that Jovian planets can also exist in the much closer spectroscopic binaries, as suggested previously by the possible detection of a giant planet around γ Cephei A (Campbell et al. 1988; Walker et al. 1992; Hatzes et al. 2003). These discoveries rapidly prompted a new interest in the study of planets in binaries, raising the possibility that planets may be common in double and multiple star systems.

When considering planets in binaries, it is important to note that most Doppler planet searches used to be, and still are, strongly biased against binaries closer than $\sim$200 AU. As a consequence, present data from these surveys provide incomplete information on the suitability of $\lesssim$200 AU binaries for planetary systems. Similarly, the actual frequency of planets in these systems remains unconstrained.

Recognizing early the importance and the interest of including binary stars in extrasolar planet studies, we have investigated the impact of stellar duplicity on planet occurrence for a few years. This investigation follows two different approaches. The first one uses Doppler spectroscopy to quantify the occurrence of giant planets in spectroscopic binaries (Eggenberger et al. 2003, 2008b). Combining the results from these surveys targeting moderately close binaries with the results from our “classical” planet searches with ELODIE (Perrier et al. 2003) and CORALIE (Queloz et al. 2000; Udry et al. 2000), we aim at quantifying the occurrence of giant planets in binaries with various separations. The second approach to our study makes use of direct imaging to probe the multiplicity status of nearby solar-type stars with and without planets. This work aims at tracing out the impact of stellar duplicity on planet occurrence and properties in binaries with typical separations between 35 and 250 AU (Udry et al. 2004; Eggenberger et al. 2004c, 2007b, 2008, 2008b).

The outline for this chapter is as follows. In Section 2.2 we present the results from classical Doppler planet searches, whose outcomes constitute the general framework within which lie more specific studies dedicated to binaries. In Section 2.3 we describe how direct imaging can be used to probe the impact of stellar duplicity on planet occurrence and to test whether the frequency of giant planets is reduced in binaries closer than $\sim$100 AU. In Section 2.4 we discuss some preliminary results from our Doppler surveys dedicated to the search for circumstellar planets in spectroscopic binaries. All these results are finally summarized in Section 2.5.

2.2 Results from Classical Doppler Planet Searches

Most of the information gathered to date on planets in binary and multiple star systems[2] has been obtained by “classical” Doppler surveys searching for planets around G and K dwarfs within 100 pc of the Sun (Udry et al. 2007a and references therein). Here, we present and discuss these observational results, together with the selection effects against binary systems that affect classical Doppler planets searches.

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[2] For the sake of conciseness, we will henceforth call “planets in binaries” the planets residing either in true binaries or in hierarchical multiple systems.