PLANET FORMATION IN BINARY SYSTEMS: A SEPARATION-DEPENDENT MECHANISM?

G. Duchêne

Astronomy Department, University of California, Berkeley, CA 94720-3411, USA; gducene@berkeley.edu

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ABSTRACT

In this Letter, I examine several observational trends regarding protoplanetary disks, debris disks, and exoplanets in binary systems in an attempt to constrain the physical mechanisms of planet formation in such a context. Binaries wider than about 100 AU are indistinguishable from single stars in all aspects. Binaries in the 5–100 AU range, on the other hand, are associated with shorter lived but (at least in some cases) equally massive disks. Furthermore, they form planetesimals and mature planetary systems at a similar rate as wider binaries and single stars, albeit with the peculiarity that they predominantly produce high-mass planets. I posit that the location of a stellar companion influences the relative importance of the core accretion and disk fragmentation planet formation processes, with the latter mechanism being predominant in binaries tighter than 100 AU.

Key words: binaries: general – planetary systems – planets and satellites: formation – protoplanetary disks

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The exponentially growing number of known extrasolar planets now enables statistical analyses to probe their formation mechanism. Two theoretical frameworks have been proposed to account for the formation of gas giant planets: the slow and gradual core accretion model (Lissauer & Stevenson 2007), and the fast and abrupt disk fragmentation model (Durisen et al. 2009). The debate regarding their relative importance is still ongoing. Both mechanisms may contribute to planet formation, depending on the initial conditions in any given protoplanetary disk (Boley 2009, and references therein). By and large, our understanding of the planet formation process is focused on the case of a single star+disk system. Yet, roughly half of all solar-type field stars, and an even higher proportion of pre-main sequence (PMS) stars, possess a stellar companion (e.g., Duquennoy & Mayor 1991; Mathieu 1994; Duchêne et al. 2007). Since the disk and multiplicity phenomena are associated with similar ranges of distances from the central star, the dynamical influence of a companion on a disk may be dramatic. Theory and observations agree that stellar companions can open large gaps in disks, or truncate them to much smaller radii than they would otherwise have (e.g., Artymowicz & Lubow 1994; Ireland & Kraus 2008). The consequences for planet formation are still uncertain, however.

Observations of protoplanetary disks among PMS stars have revealed that tight binaries generally show substantially reduced (sub)millimeter thermal emission (Beckwith et al. 1990; Jensen et al. 1996) as well as a much rarer presence of small dust grains in regions a few AU from either component (Ghez et al. 1993; Cieza et al. 2009). Both trends can be qualitatively accounted for by companion-induced disk truncation, which can simultaneously reduce the disk’s total mass, outer radius, and viscous timescale. These observational facts have generally been interpreted as evidence that binaries tighter than ~100 AU are much less likely to support gas giant planet formation. However, follow-up imaging surveys have identified some 50 planet-host stars that possess at least one stellar companion (e.g., Patience et al. 2002; Chauvin et al. 2006; Raghavan et al. 2006; Eggenberger et al. 2007; Mugrauer & Neuhausner 2009). In particular, it is worth noting that about 20% of all known planets in binary systems have a stellar companion within less than 100 AU, so that planet formation in such an environment cannot be considered a rare occurrence.

In this Letter, I review several key statistical properties of PMS and field binary systems that provide insight on the planet formation process (Sections 2 and 3). I then discuss the implications for the main mechanisms of planet formation in binary systems as a function of their projected separation (Section 4). In this study, I only consider binaries in the 5–1400 AU separation range, for which current PMS multiplicity surveys are reasonably complete. The tightest binary system known to host a planet has a 19 AU separation. Stellar companions beyond 1400 AU are not expected to have much influence on planet formation.

2. PLANET FORMATION IN BINARIES: INITIAL CONDITIONS

2.1. Defining an Homogeneous Sample of PMS Binaries

In order to draw a broad and homogeneous view of the initial conditions for planet formation, I compiled a sample of 107 PMS binaries for which deep (sub)millimeter continuum observations and/or near- to mid-infrared colors are available in the literature (see Table 1). The (sub)millimeter data are taken from the work of Andrews & Williams (2005, 2007); for almost all targets, a 1σ sensitivity of 15 mJy or better at 850 μm and/or 1.3 mm is achieved. The median projected separation in this sample is 92 AU. I also defined a comparison sample of 222 PMS stars for which no companion has ever been detected. I focus here on the Taurus and Ophiuchus star-forming regions, the only ones for which high-resolution multiplicity, photometric and millimeter surveys have a high completeness rate. The two clouds contribute an almost equal number of binaries to the sample. Furthermore, both regions have similar stellar age distributions (median age around 1 Myr, Ophiuchus being probably slighter younger on average than Taurus) and their
mass function fully samples the 0.1–1.5 $M_\odot$ range (e.g., Luhman & Rieke 1999; Luhman 2000). Finally, Taurus represents an instance of distributed star formation, while Ophiuchus is a more clustered environment. These two clouds therefore offer a global view of the early stages of planet formation among solar-type and lower mass stars.

### 2.2. Inner Disk Presence and Survival

I first address the question of the presence of dust in the planet-forming region, namely the innermost few AU around each component, within binary systems. To probe the presence of an optically thick dusty inner disk, I used near- to mid-infrared colors. I selected the following standard thresholds to conclude that a circumstellar disk is present: $[3.6] - [8.0] \geq 0.8$ mag, $K - N \geq 1.75$ mag, $K - L \geq 0.35$ mag, $\alpha_{2-14 \mu m} > -1.7$ (e.g., Cieza et al. 2009; McCabe et al. 2006; Bontemps et al. 2001). About 80% of the PMS binaries considered here have Spitzer/IRAC colors, which are used whenever available.

Cieza et al. (2009) have demonstrated that tighter binaries have a much lower probability of hosting circumstellar dust. The same effect is observed here in a somewhat smaller sample. The median separation of binaries with an inner disk in this sample is about 100 AU, whereas that of disk-free binaries is 40 AU. The simplest interpretation of this trend is that disks in tight binaries are dissipated much faster than in wide systems (Cieza et al. 2009, A. L. Krauss et al. 2010, in preparation). To extend upon this previous analysis, I used the two-sided Fischer exact test to determine the probability that wide and tight binaries have a different proportion of diskless systems, using a sliding threshold to split the sample. As shown in Figure 1, the difference is significant at the $2\sigma$ level or higher for a wide range of threshold separations. In particular, this analysis reveals that the observed reduced disk lifetime in binaries only applies to systems that are tighter than about 100 AU. On the other hand, there is no statistical difference between binaries wider than 100 AU and single stars.

### 2.3. Total Mass of the Initial Dust Reservoir

While near- and mid-infrared emission best traces the presence of dust within a few AU of star, only long-wavelength flux measurements can probe the total dust mass of protoplanetary disks (e.g., Beckwith et al. 1990). From the sample defined above, I selected those objects which show evidence of an optically thick inner disk (as defined above) and have been observed in the (sub)millimeter. The median separation in this subsample of 44 binaries is 130 AU. While the 850 $\mu$m survey of Ophiuchus is not yet as complete as that of Taurus, the existing 1.3 mm observations of PMS stars are generally less sensitive to cold dust. Since using both wavelengths yield similar conclusions but with lower significance for the 1.3 mm one, I focus here on 850 $\mu$m measurements.

As has long been known, tight binaries have a different distribution of submillimeter fluxes than wide ones, with a much lower median flux (13 mJy versus 50 mJy at 850 $\mu$m using a 100 AU separation threshold) and only very few high-flux systems (Jensen et al. 1996; Andrews & Williams 2005). I compared the distributions of 850 $\mu$m fluxes for tight and wide binaries defined by the same sliding threshold as above using the conservative survival analysis Peto–Pentrice Generalized Wilcoxon test to account for upper limits. I find that wide and tight binaries are different at the $2\sigma$ level or higher if the separation threshold is in the 75–300 AU range (see Figure 1). I therefore conclude that binaries with a projected separation smaller than 300 AU have a substantially reduced submillimeter flux. On the other hand, the distribution of 850 $\mu$m fluxes for wide binaries is indistinguishable from that of single stars.

In past studies, it has been assumed that a reduced (sub)millimeter flux necessarily implies a reduced total dust mass independently of the disk properties (for instance, see the prescription used by Andrews & Williams 2005). While this is true in general, it is unclear whether this assumption is valid for severely truncated disks for which optical depth effects may become important. The model constructed by Jensen et al. (1996) seems to support this hypothesis, but these authors assumed that tight binaries are always surrounded by a massive circumbinary structure, which we now know is rare. To revisit this issue, I have computed a grid of radiative transfer models using the MCFOST code (Pinte et al. 2006) to compute the 850 $\mu$m flux of a disk with a typical $\Sigma(r) \propto r^{-1}$ surface density profile, an 0.1 AU inner radius and a flaring power law $H(r) \propto r^{1.125}$. Emission from the central star is modeled as a 4000 K, 2 $L_\odot$ photosphere, and a distance of 140 pc is assumed. The dust is assumed to be made of astronomical silicates with a $a^{-3.5}$ power-law size distribution ranging from 0.03 $\mu$m to 1 mm. The only variables in the model are the disk outer radius, $R_{\text{out}}$, and the total dust mass, $M_{\text{dust}}$. Figure 2 demonstrates that the proportionality between total dust mass and submillimeter flux observed for large disks breaks down for $R_{\text{out}} \lesssim$ 30 AU as the disk becomes optically thick to its own emission.

Disk truncation by an outer stellar component is dependent on the orbital parameters and mass ratio of the binary system (Artymowicz & Lubow 1994). It is therefore not possible to uniquely associate a binary separation with a tidally set value of $R_{\text{out}}$. The ratio between these quantities is typically in the broad range...
2.5–5 range. Systems whose separation is less than 100 AU are therefore expected to possess disks whose outer radius is 40 AU or less. In this configuration, total disk masses of at least $M_d$ are necessary to produce 850 $\mu$m fluxes as low as 20–30 mJy. In the sample studied here, about a third (six out of 19) of all binaries that are tighter than 100 AU and possess an inner disk have an 850 $\mu$m flux that is higher than 30 mJy. Therefore, a significant fraction of the circumstellar disks in tight binaries ($\lesssim$100 AU) are massive enough to potentially form gas giant planets, despite their much lower (sub)millimeter fluxes.

3. PLANET FORMATION IN BINARIES: END RESULTS

3.1. Distribution of Planetary Masses

Let us turn our attention to mature planetary systems. As of this writing, there are 38 exoplanets that are in a system with at least two stellar components (using 1400 AU as the upper limit for binary separation), including five systems with a stellar companions within 25 AU (Mugrauer & Neuhäuser 2009, and references therein). Most of these planet-bearing stars are of solar type. The overall detection rates of gas giant planets in binary systems and in single stars are undistinguishable (Bonavita & Desidera 2007). There is marginal evidence that planets in binaries tighter than $\sim$100 AU may be somewhat less frequent than one would assume based on the frequency of planets in wider binaries (by 6.0% $\pm$ 2.7%, Eggenberger et al. 2008). However, the small sample size, adverse selection biases, and incompleteness of current multiplicity surveys are such that it is premature to reach definitive conclusions. In any case, we can use this sample to test whether the separation of the stellar binary has any influence on planet properties.

Despite an earlier claim for a distinct period–mass distribution (Zucker & Mazeh 2002), Bonavita & Desidera (2007) have shown that there is essentially no difference in the properties of planetary systems around single stars and in binary systems. However, a previously unrecognized trend is evident in Figure 3. While planets covering two orders of magnitude in mass can be found in wide binaries (as around single stars), systems tighter than $\sim$100 AU appear to host only high-mass, $M \gtrsim M_J$, planets. To quantify this effect, I used the two-sided Fischer exact test to determine whether close and wide binaries (with the usual sliding threshold) have different proportion of high- and low-mass planets. I used 1.6 $M_J$, the median for all planets known to date, to separate low- from high-mass planets. Figure 1 confirms that binary systems tighter than about 100 AU produce a distribution of planets that is strongly biased toward the highest masses. This conclusion is significant at the 3σ level.

It is important to test whether this trend is not a mere consequence of a selection bias, as a close stellar companion can alter the detectability of a planet-induced radial velocity signal. To evaluate this possibility, I build on the “uniform detectability” sample defined by Fischer & Valenti (2005) which contains all stars for which close-in planets as low mass as 0.3 $M_J$ (well below the apparent cut-off in mass for planets in tight binaries), as well as 1 $M_J$ planets on a 4 yr orbit, could be detected. In the current sample of binary planet hosts, the proportions of stars that belong to the uniform detectability sample among binaries tighter and wider than 100 AU are indistinguishable (5/9 and 24/40, respectively). I therefore conclude that the trend discussed above is unlikely to be the consequence of a selection bias or of observational limitations.

3.2. Occurrence of Planetesimal Disks

An indirect signpost of planet formation is the debris disk phenomenon. In these systems, small dust grains are produced via the collisions of large solid bodies (Zuckerman 2001). Trilling et al. (2007) observed 69 A- and F-type known binaries with Spitzer and found debris disks in systems spanning six decades in separation. They further suggested that intermediate separation (3–30 AU) binaries are substantially less likely to host a debris disks than either tighter or wider systems, although the formal significance of this difference is marginal at best. No such trend was found by Plavchan et al. (2009), who included 24 A- through M-type binaries in their own Spitzer survey. This latter survey focused on targets that are more similar in mass to exoplanet hosts and the PMS population discussed in the previous section.

I used the two-sided Fischer test to determine whether the occurrence of debris disks is indeed different in tight and

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Footnote: This is also the median for the subsample of all planets within multiple stellar systems.
wide binaries, using the same sliding threshold as above (see Figure 1). There is no significant difference for any value of the threshold in the sample from Trilling et al. (2007), nor in a combined sample that also includes systems from Plavchan et al. (2009). The combined sample contains 52 binaries in the 5–1400 AU range, with a median separation of 50 AU, an increase of 15 sources from the sole sample of Trilling et al. (2007). In addition, the occurrence rates of debris disks in binary systems and single stars are very similar (Trilling et al. 2007). In other words, any 0.5–2 $M_\odot$ star, irrespective of the presence of a companion (within the 5–1400 AU range studied here), may experience the early phases of planet formation up to the planetesimal stage.

4. DISCUSSION AND IMPLICATIONS

This analysis has revealed a clear dichotomy between tight and wide binaries. Systems with separation $\gtrsim 100$ AU are indistinguishable from single stars as far as the initial conditions and end product of planet formation are concerned. The only caveat to this statement is the possibility of mild disk truncation in 100–300 AU systems, but most disks in these systems remain stable, and a mass reservoir is sufficient to build up giant planets. On the other hand, planet formation in binaries with separations $\lesssim 100$ AU is characterized by a much shorter clearing timescale for the protoplanetary disks and a strong bias towards high-mass planets. Despite these differences, planetesimals and mature planetary systems appear to form at roughly the same frequency as around other stars. Furthermore, while protoplanetary disks are more compact in tight systems because of truncation, a significant fraction of them possess large mass reservoirs (at least several times $M_\odot$). Taken together, these results suggest that planet formation in binaries tighter than 100 AU proceeds through a different, but not much less frequent, mechanism compared to wide binaries and single stars.

The shorter disk lifetime in tight binaries makes it extremely difficult to form gas giant planets through the core accretion model, especially if the final planets are particularly massive. Rather, this combination of observed trends supports an abrupt process to form planets in tight binaries, such as the disk fragmentation model. Indeed, this mechanism can be extremely efficient in the case of a compact, massive protoplanetary disk which is naturally prone to gravitational instability. Furthermore, gravitational perturbations induced by a close stellar companion can trigger the instability, even though the disk itself is not unstable to its own gravity (Boss 2006). On the other hand, considering the long survival timescale and slim chances of gravitational instabilities, disks located within wide binaries and around single stars are good candidates to form planets via the core accretion model in their inner regions (e.g., Boley 2009).

While a violent process is most likely responsible for the formation of planets in tight binaries, it is however unclear whether all planets in wide binaries form through a single mechanism. Indeed, it is also conceivable that high-mass planets ($\gtrsim M_\text{J}$) mostly form via disk fragmentation, while lower mass planets are preferentially the result of core accretion. This scenario would naturally alleviate the difficulty of the core accretion model to form the highest mass planets in less than a few Myr. This hypothesis has the additional advantage that it could also apply to tight binaries. Indeed, since a stellar companion located within less than 100 AU dramatically shortens the disk lifetime, core accretion is essentially prevented from occurring, accounting for the absence of low-mass ($\lesssim 2M_\text{J}$) gas giant planets in tight binaries. Planetesimals can presumably form in either scenario, accounting for the observations regarding the debris disks phenomenon. In summary, it remains to be determined whether the trends discussed here indicate an actual dichotomy between the main planet formation theories or a mere change of the relative importance of the two models as a function of the location of the stellar companion. Improving the statistical significance of the various trends discussed here and determining the exact properties of disks within tight PMS binaries will help shed further light these two possibilities.

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Table 1

Sample of Taurus and Ophiuchus Protoplanetary Disks Considered in this Study

| Target  | Alt. Name  | Sep. (AU) | IR Color (mag) | Inner Disk? | $F_{1.25\mu m}$ (mJy) | $F_{1.16\mu m}$ (mJy) | References |
|---------|------------|-----------|---------------|-------------|------------------------|------------------------|------------|
| Taurus–Auriga |  | | | | | |
| CZ Tau  |  | 46 | 3.41 | Y | < 9 | < 30 | 1.2 |
| DD Tau  |  | 79 | 1.99 | Y | < 42 | 17 | 1.2 |
| DF Tau  |  | 13 | 1.37 | Y | 8.8 | < 25 | 3.2 |
| DI Tau  |  | 17 | 0.76 | N | ... | ... | 3 |
| DK Tau  |  | 350 | 1.27 | Y | 80 | 35 | 3.2 |

Notes:

a Unless otherwise indicated by a note, the infrared color is the Spitzer/IRAC [3.6] – [8.0] color.
b References: (1) Luhman et al. 2006; (2) Andrews & Williams 2005; (3) Hartmann et al. 2005; (4) Cieza et al. 2009; (5) McCabe et al. 2006; (6) Guilloteau et al. 1999; (7) Kenyon & Hartmann 1995; (8) Duchêne et al. 2010; (9) Jensen & Akeson 2003; (10) Jensen et al. 1996; (11) Andrews & Williams 2007; (12) Bontemps et al. 2001.
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