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DISK TRUNCATION AND PLANET FORMATION IN γ CEPHEI

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ABSTRACT

The γ Cephei system is one of the most closely bound binary planet hosts known to date. The companion (γ Cep B) to the planet-hosting star (γ Cep A) should have truncated any protoplanetary disk around γ Cep A, possibly limiting planet formation in the disk. We explore this problem by calculating the truncation radii of protoplanetary disk models around γ Cep A to determine whether or not there is sufficient material remaining in the disk to form a planet. We vary the accretion rate and viscosity parameter of the disk models to cover a range of reasonable possibilities for the disk properties and determine that for accretion rates of $\geq 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$ and low viscosity parameter, sufficient material in gas and solids exist for planet formation via core accretion to be possible. Disk instability is less favored, as this can only occur in the most massive disk model with an extremely high accretion rate.

Subject headings: accretion, accretion disks — binaries: close — planetary systems — planetary systems: formation — planetary systems: protoplanetary disks — stars: individual (γ Cephei)

Online material: color figures

1. INTRODUCTION

Over the last decade, several stellar and substellar companions of exoplanet host stars have been found, mostly in seeing-limited wide field imaging surveys (e.g., Mugrauer et al. 2007b; Raghavan et al. 2006; Chauvin et al. 2006). The projected separations are a few tens to several thousand AU, with companion masses ~0.08–1.1 $M_\odot$. Eggenberger & Udry (2007) suggest that exoplanets may be less common in binaries closer than 120 AU. This apparent lack of close companions to exoplanet host stars may indicate that planet formation is hampered by the gravitational influence of a close massive companion. However, further investigations are needed to confirm this result.

One of the closest planet host binaries presently known is γ Cep. The planet orbits the primary γ Cep A on a 906 day orbit and has $m \sin(i) \sim 1.7\ M_{\mathrm{Jup}}$ (Campbell et al. 1988; Hatzes et al. 2003). The stellar companion orbits at a semimajor axis of 20 AU with an eccentricity of 0.4 (Hatzes et al. 2003; Torres 2007). Given that massive companions can disrupt the protoplanetary disks in which planets form, how feasible is the in situ formation of a planet around γ Cep A?

Haghighipour (2006) considered the dynamical stability of γ Cep in order to put limits on possibility of the existence of another planet in the system. Thébault et al. (2004) considered the problem of planet formation via core accretion in this system using *N*-body simulations, assuming a density profile consistent with the minimum-mass solar nebula (MMSN) model of Hayashi (1981) which is steeper than that produced by viscous accretion disk models. Paardekooper et al. (2008) revisited the problem including gas drag and determined that giant planet formation by core accretion is feasible in γ Cep, although they did not address the evolution of the gas in the disk or the truncation radius of the disk in detail. Kley & Nelson (2008) assumed a specific disk model and examined the fate of planet cores inserted into the disk. Rather than do a detailed hydrodynamic simulation of a planet embedded in the disk, our objectives are to model the protoplanetary disk in γ Cep as a viscous accretion disk and to explore which disk parameters allow planet formation to occur given that the disk is truncated by the stellar companion.

This analysis is similar to that done in Jang-Condell (2007) (hereafter Paper I) for the extremely close triple system HD 188753. Paper I concluded that HD 188753 was unlikely to support a disk sufficiently massive to support planet formation. Indeed, the initial claim of a Jupiter-mass planet in HD 188753 (Konacki 2005) has since been refuted (Eggenberger et al. 2007). This does not rule out the possibility that the planet could form around a single star or in a wide binary and then undergo dynamical evolution, such as through close encounters with another star (Portegies Zwart & McMillan 2005; Pfahl 2005), but this is outside the scope of this Letter.

2. MODEL DESCRIPTION

We adopt orbital parameters for the γ Cep system from Neuhäuser et al. (2007) as follows: primary mass 1.40 $M_\odot$, secondary mass 0.409 $M_\odot$, eccentricity 0.41, and semimajor axis 20.18 AU. We ignore the orbit of the planet, since we are interested in preplanetary conditions of the disk around the 1.4 $M_\odot$ primary. We assume that the stars have not undergone significant mass loss or orbital evolution since their formation, so we can model the properties for γ Cep A based on a pre–main-sequence stellar model for a 1.4 $M_\odot$ star. Since the typical age of a T Tauri star is 1 Myr, we assume this age for our model.

2.1. *Disk Model*

The calculation for the disk models is described in detail in Paper I and Jang-Condell & Sasselov (2003, 2004). We assume an α-disk model, where the viscosity ν is given by $\nu = \alpha c_s h$ where c_s is the sound speed, h is the thermal scale height of the disk, and α is a dimensionless parameter (Shakura & Sunyaev 1973; Pringle 1981). The disk temperature is set by

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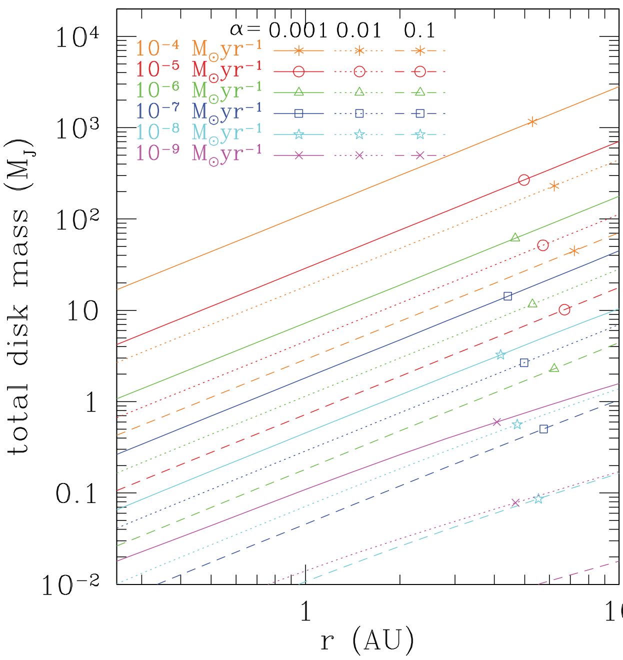

FIG. 1.—Enclosed disk mass vs. radius for disk models for γ Cep, in units of $M_{\rm Jup}$. The accretion rate is indicated by color and symbol type: orange asterisks for 10^{-4}, red circles for 10^{-5}, green triangles for 10^{-6}, blue squares for 10^{-7}, cyan stars for 10^{-8}, and magenta crosses for 10^{-9} $M_\odot$ yr^{-1}. Models with α of 0.001, 0.01, and 0.01 are indicated by solid, dotted, and dashed lines, respectively. The locations of the points mark the truncation radius and maximum disk mass for each disk model.

stellar irradiation at the surface and viscous heating at the midplane. The radial and vertical density and temperature structure of the disk are calculated iteratively for self-consistency. We adopt effective temperature $T_* = 4500$ K and radius $R_* = 3.0\ R_\odot$, corresponding to a $M_* = 1.4\ M_\odot$, 1 Myr old star with metallicity $Z = 0.02$ (Siess et al. 2000).

The two remaining free parameters for our disk models are the mass accretion rate onto the star $\dot{M}$ and the viscosity parameter α. The exact values for these parameters are unknown for γ Cep, and it is likely that these values evolved over time, so we explore a range of values for both $\dot{M}$ and α to determine which, if any, set of parameters allows for planet formation to occur. As in Paper I, we calculate a grid of disk models, with $\alpha \in \{0.001, 0.01, 0.1\}$ and $\dot{M} \in \{10^{-9}, 10^{-8}, 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}\}\ M_\odot$ yr^{-1}. These parameters are roughly consistent with observations of T Tauri stars (e.g., Gullbring et al. 1998; Hartmann et al. 1998), including the extremely high and transient accretion rates of FU Ori phenomena (Calvet et al. 2000; Hartmann & Kenyon 1996). In practice, the models are calculated out to 256 AU, but we consider only the material interior to the truncation radius to be available for planet formation. We refer to a given disk model by the coordinate pair (α, $\dot{M}$), so that model (0.01, 10^{-7}) refers to the run with $\alpha = 0.01$ and $\dot{M} = 10^{-7}\ M_\odot$ yr^{-1}.

2.2. *Disk Truncation*

The truncation radii of gaseous disks depend on the viscosity and temperature of the gas (Artymowicz & Lubow 1994, hereafter AL94), as opposed to planetesimal disks, whose truncation radii can be calculated from last stable orbits of test particles (Pichardo et al. 2005). The truncation radius of each disk model is calculated following AL94, as in Paper I. In AL94, the truncation radius of a circumstellar disk in a close binary is where resonant and viscous torques balance. This depends on the mass ratio of the binary (μ), the semimajor axis of the orbit (a), the eccentricity of the orbit (e), and the Reynolds number of the disk (Re). For γ Cep, μ, a, and e have all been determined observationally. The remaining parameter, Re, depends on the structure of the disk, which has long since dissipated.

The Reynolds number is defined as Re $= r v_\phi/\nu$ where r is distance from the star, $v_\phi \equiv (GM_*/r)^{1/2}$ is the orbital velocity, and $\nu \equiv \alpha c_s h$ is the viscosity of the disk. Since $c_s/v_\phi = h/r$ and $c_s = (kT/\bar{m})^{1/2}$,

$$\mathrm{Re} = \frac{v_\phi^2}{\alpha c_s^2} = \frac{\bar{m} G M_*}{\alpha k T r}. \qquad (1)$$

Setting $e = 0.41$ for γ Cep, we read off truncation radii in units of semimajor axis of the circumprimary disk versus Re from Figures 5 and 6 in AL94, for $\mu = 0.3$ and 0.1, respectively. For γ Cep, $\mu = 0.22$, so we interpolate in μ to find the final truncation radius versus Re relation. This relation is plotted with the long-dashed black line in Figure 2, for a semimajor axis of 20.18 AU.

We assume that the disks are dynamically truncated and that irradiation from the stellar companion is negligible compared to heating from viscous accretion and the central star. This irradiation would most likely further decrease the likelihood of planet formation since it would provide an additional heat source at the outer edge of the disk, inhibiting planet formation by either core accretion or disk instability. In the absence of additional accretion of material past the companion's orbit onto the disk, the disk should be viscously spreading both inward and outward. Thus, the calculated truncated disk masses should be considered upper limits.

3. RESULTS

In Figure 1 we plot the mass profiles of the disk models. The line colors and types (solid/dotted/dashed) indicate $\dot{M}$ and α-parameter for each disk model, respectively (see legend for details). Disk mass increases with increasing $\dot{M}$ and decreasing α. The truncation radius for each disk model is indicated by a symbol on the line, which also indicates the maximum disk mass for each model.

Figure 2 shows Re versus radius for each disk model, coded the same as in Figure 1. The Reynolds number in each disk model depends on the input parameters, but stays fairly flat with radius. The black long-dashed line shows the truncation radius versus Re relation calculated following AL94. From the intersection of the long-dashed line with each model profile, we determine a unique truncation radius for each disk model, marked by symbols.

The truncation radii are in the range of 4–7 AU, roughly consistent with the 4–5 AU truncation radius assumed by Thébault et al. (2004) albeit a bit larger. This is expected because viscous torques of a gaseous disk allow it to extend farther than a particle-only disk. If we consider 1.6 $M_{\rm Jup}$, the mass of the planet γ Cep Ab, to be the minimum mass necessary for in situ planet formation, a majority of the disk models satisfy this criterion.

4. DISCUSSION: CORE ACCRETION VERSUS DISK INSTABILITY

Having determined that a truncated disk around γ Cep A can easily contain enough material to form one or several Ju-

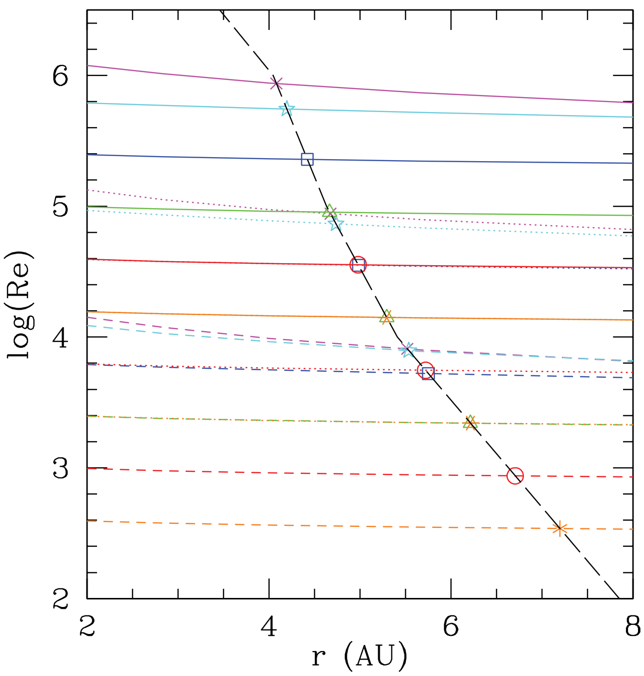

FIG. 2.—Reynolds number vs. radius for each of the disk models, marked the same as in Fig. 1. The black long-dashed line shows the truncation radius vs. Reynolds number relation for the γ Cep binary. The truncation radius for each model is at the intersection with this line.

piter mass planets, we now turn our attention to whether planet formation may take place via core accretion or gravitational instability.

Giant planet formation by core accretion requires sufficient mass of solid material to coagulate into a dense core which can then accrete gas. We calculate the mass of dust or solid materials as in Paper I, adopting the dust composition from Pollack et al. (1994) of olivines, orthopyroxene, iron, water, troilite, refractory organics, and volatile organics. At a given radius in the disk, we assume that each species is completely condensed or vaporized, depending on whether the temperature is lower or higher, respectively, than the sublimation temperature for that species.

In Figure 3 we plot the mass of solids or dust particles in the disk as function of radius. Here, we only plot those disks that contain more than 1.6 $M_{\rm Jup}$ of material within their truncation radii. We use the same coding of colors, lines, and symbols to represent the different disks as in Figure 1, scaling the symbols sizes relative to the disk masses. The amount of solids does not simply scale with the mass of the disk because hotter disks sublimate their dust. While higher accretion rates yield more massive disks, they also yield higher temperatures. On the other hand, higher α-values yield less massive disks and higher temperatures. If we require a minimum of 20 Earth masses ($M_\oplus$) of solids to form a giant planet core, we find that the models (0.001, 10^{-6}), (0.01, 10^{-5}), (0.001, 10^{-5}), and (0.001, 10^{-7}) all have sufficient solids to form giant planets by core accretion.

The metric for planet formation by gravitational instability is the Toomre Q parameter:

$$Q = \frac{c_s \kappa}{\pi G \Sigma}. \qquad (2)$$

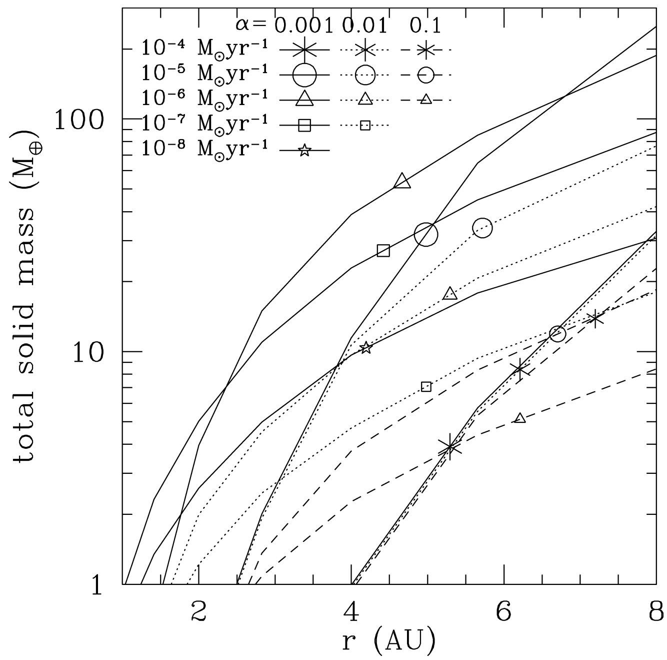

FIG. 3.—Mass of solids for each disk model. The position of the point indicates the truncation radius and maximum enclosed solid mass. The sizes of the points indicate the relative total disk mass. See Fig. 1 for key. [*See the electronic edition of the Journal for a color version of this figure.*]

In order for planet formation to proceed, $Q < 1$ is required. In Figure 4 we plot the local value of Q versus radius for our disk models. Only six of these have $Q < 10$ and model (0.001, 10^{-4}), the most massive disk, has $Q < 1$. As discussed previously, $10^{-4}\ M_\odot\ {\rm yr}^{-1}$ is an extreme accretion rate, seen only episodically in FU Ori stars. Moreover, $Q < 1$ only in very the outermost part of the disk. Therefore, we find it unlikely that γ Cep Ab formed through gravitational instability.

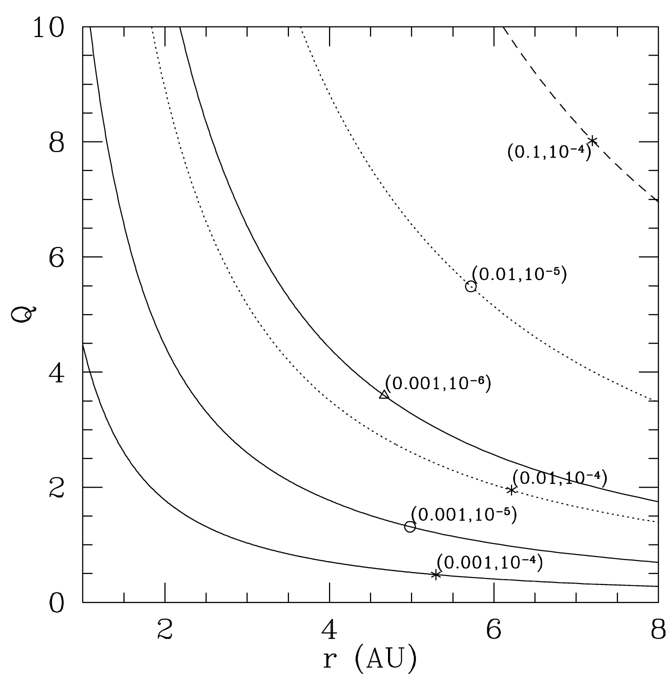

FIG. 4.—Toomre Q parameter for each disk model, as indicated by the labels. The point on each line indicates the truncation radius. Models not shown on this plot have $Q > 10$ interior to their truncation radii. [*See the electronic edition of the Journal for a color version of this figure.*]

These results may be further generalized to suggest that planet formation in any close binary is more likely to occur through core accretion than disk instability. This is because disk instability happens only in the most massive disks. While the amount of solids is also dependent to some extent on the mass of the disk, the minimum disk mass for core accretion is still below that required for disk instability.

5. CONCLUSIONS AND FUTURE WORK

We assessed the feasibility of in situ planet formation in γ Cep by examining the properties of a protoplanetary disk around the primary star, given the current orbital parameters of the binary star. We examined a range of accretion rates and viscosity parameters and determined the truncation radius for each disk model. We find that γ Cep A can host a truncated disk of sufficient mass to form a giant planet with reasonable accretion rates and viscosity parameters, so in situ planet formation is possible. There are sufficient solids in the truncated disk for core accretion to occur for accretion rates higher than $10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$ and low values of the viscosity parameter, α. This is a relatively high accretion rate, which may indicate that giant planet formation must take place very early on, within 10^5–10^6 years, since it appears that accretion rates of T Tauri stars decrease with age (e.g., Sicilia-Aguilar et al. 2006). Giant planet formation by disk instability is unlikely to have occurred in γ Cep. Disk instability also requires an extremely high accretion rate, $\sim10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$, a rate that is typical of a transient FU Ori phenomenon. On the other hand, this may mean that FU Ori outbursts and giant planet formation by disk instability are correlated.

We have omitted effects such as shock-heating or triggered planet formation by the binary. Whether these effects inhibit (e.g., Nelson 2000) or enhance (e.g., Boss 2006) planet formation depends on whether cooling times are long or short, respectively (see also Mayer et al. 2005). Low-mass disks that are not self-gravitating are not subject to strong shocks, so our results for core accretion are unaffected (Mayer et al. 2005). This strengthens our argument that core accretion is the favored mechanism for giant planet formation in close binaries.

The analysis presented here should hold also true for wider binary systems. That is, giant planet formation is possible around any star where the stellar companion has a mass ratio $\mu \lesssim 0.2$ and has an orbit wider than γ Cep B, with disk instability becoming increasingly feasible in wider systems. The handful of triple systems with exoplanets that have been discovered to date are all hierarchical, where the exoplanet host star and a close stellar pair revolve around a common barycenter. In these cases, the close stellar pair can be treated dynamically as a single object. The closest planet host triple system with confirmed exoplanets presently known is HD 65216 A+BC, at ~250 AU (Mugrauer et al. 2007b). Thus, we conclude that there is no barrier to planet formation in the known planet-hosting triple systems.

In Paper I the same analysis was carried out for a hypothesized planet in HD 188753, a multiple system which at first glance is only slightly closer than γ Cep: a semimajor axis of 12.3 AU and eccentricity of 0.5. In situ planet formation in HD 188753 was ruled out, whereas it is deemed feasible for γ Cep. Somewhere between the parameters of these two systems lies the transition between possibility and impossibility of planet formation in close binaries. We will explore this parameter space and put limits on the closeness of planet host binaries in a future paper.

Another interesting case is a system where the massive companion is a white dwarf. Known white dwarf planet hosts include Gl 86 B with a projected separation of only 20 AU; and HD 27442 with a subgiant primary and white dwarf secondary (Mugrauer et al. 2007a). Stellar evolution and mass loss generally widens the orbits of binary stars, so it is likely that these systems were originally much closer (e.g., Debes & Sigurdsson 2002). In order to determine whether in situ planet formation could have taken place in these systems, the original orbital configuration must first be determined and the disk truncation radii based on that. We will address this issue in a future paper.

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