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Planet Formation in Close Binaries

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Abstract. Several exoplanets have been discovered in close binaries ($a < 30$ AU) to date. The fact that planets can form in these dynamically challenging environments says that planet formation must be a robust process. Disks in these systems should be tidally truncated to within a few AU, so if they form in situ, the efficiency of planet formation must be high. While the dynamical capture of planets is also a possibility, the probability of these interactions is low, so in situ formation is the more plausible explanation. I examine the truncation of protoplanetary disks in close binary stars, studying how the disk mass is affected as it evolves from higher accretion rates to lower rates. In the gamma Cephei system, a protoplanetary disk around the primary star should be truncated to within a few AU, but enough mass still remains for planets to form. However, if the semimajor axis of the binary is too small or its eccentricity is too high, such as in HD 188753, the disk will have too little mass for planet formation to occur. I present a way to characterize the feasibility of planet formation based on binary orbital parameters such as stellar mass, companion mass, eccentricity and semi-major axis. Using this measure, we can quantify the robustness of planet formation in close binaries and better understand the overall efficiency of planet formation in general.

Keywords. planets and satellites: formation, planetary dynamics, stars: binaries

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We calculate the feasibility of planet formation in close binaries by considering the truncation radius of the initial protoplanetary disk and determine whether the disk could have supported planet formation despite its truncation. We follow the procedure carried out for HD 188753 (Jang-Condell 2007) and γ Cep (Jang-Condell *et al.* 2008) for the binary systems tabulated in Table 1.

Since the initial properties of the disk are unconstrained, we calculate a suite of disk models with $\alpha \in \{0.001, 0.01, 0.1\}$ and $\dot{M} \in \{10^{-9}, 10^{-8}, 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}\}\, M_\odot\,\mathrm{yr}^{-1}$, for a total of 18 disk models for each binary pair. The truncation radius for each disk is calculated following Artymowicz & Lubow (1994). We then enumerate how many of these 18 disks have at least 10 M_J of mass (N_M), how many contain at least 10 $M_\oplus$ of solids (N_{CA}), and how many have $Q < 1$ (N_{DI}).

In Table 1, we show these statistics for the binaries under study in this paper. In each binary in which a substellar companion exists, $N_{\mathrm{DI}} = 1$ and $N_{\mathrm{CA}} \geqslant 4$. The one disk model in which disk instability is possible has the most extreme accretion rate, which suggests that core accretion is the preferred planet formation mechanism in close binaries.

We then explore a wide range of binary parameters (M_1, μ, a, e), and tabulate values of N_{CA} and N_{DI} for each set of values. We then fit a polynomial to those values,

$$N = \sum_{i,j,k,l} c_{ijkl} \left(\frac{a}{1\ \mathrm{AU}}\right)^i e^j \mu^k \left(\frac{M_*}{M_\odot}\right)^l . \tag{0.1}$$

The coefficients may be found in Jang-Condell (2014). Based on the values for N_{CA} tabulated in Table 1, we can set $N_{\mathrm{CA}} = 4$ or possibly $N_{\mathrm{CA}} = 6$ as the limiting value for which planet formation by core accretion can occur. These contours are show in Figure 1.

Table 1. Binary systems with planets examined in this paper

	HD 188753A	γ Cep	HD 41004A	HD 41004B	HD 196885A	α Cen B
M_1	1.06 $M_\odot$	1.4 $M_\odot$	0.7 $M_\odot$	0.4 $M_\odot$	1.3 $M_\odot$	0.93 $M_\odot$
M_2	1.63 $M_\odot$	0.41 $M_\odot$	0.4 $M_\odot$	0.7 $M_\odot$	0.45 $M_\odot$	1.1 $M_\odot$
μ	0.39	0.78	0.64	0.36	0.74	0.46
a	12.3 AU	20 AU	20 AU	20 AU	21 AU	23.5 AU
e	0.5	0.41	0.4	0.4	0.42	0.52
M_p	—	$\geqslant$1.85 M_J	$\geqslant$2.5 M_J	$\geqslant$18.4 M_J	$\geqslant$2.96 M_J	$\geqslant$1.13 $M_\oplus$
a_p	—	2.1 AU	6×10^{-3} AU	7.4×10^{-4} AU	2.6 AU	0.04 AU
refs	1,2	3,4	5	5,6	7	8
N_M	6	8	7	6	8	6
$N_{\rm CA}$	0	6	6	4	6	4
$N_{\rm DI}$	0	1	1	1	1	1

References: (1) Konacki (2005), (2) Eggenberger *et al.* (2007), (3) Hatzes *et al.* (2003), (4) Endl *et al.* (2011), (5) Zucker *et al.* (2004), (6) Zucker *et al.* (2003), (7) Correia *et al.* (2008), (8) Dumusque *et al.* (2012).

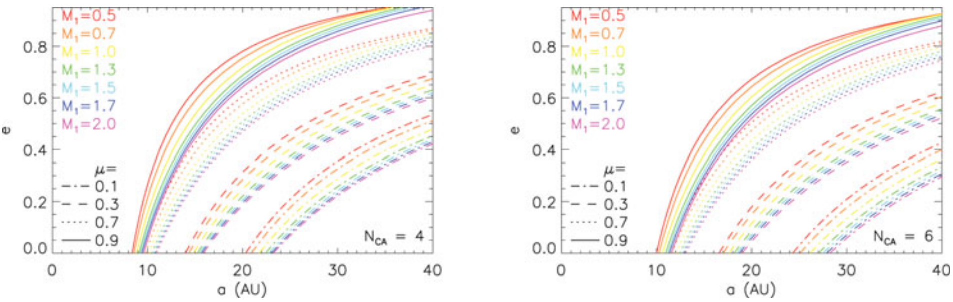

Figure 1. Binary parameters allowing giant planet core formation, using $N_{\rm CA} = 4$ (left) and $N_{\rm CA} = 6$ (right) as limits.

Then, for a given stellar mass and mass ratio ($\mu = M_1/(M_1 + M_2)$), the selected curve shows in what region of $a - e$ space planet formation by core accretion can occur.

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