Terrestrial Planet Formation in Binary Star Systems

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1 Introduction

More than half of all main sequence stars have at least one stellar companion (Duquennoy & Mayor 1991), yet most planet formation models have examined the process occurring about an isolated single star. Of the first 130 planets detected outside of our Solar System, 19 have been confirmed to travel on so-called S-type orbits that encircle one component of a main-sequence binary star system (Eggenberger et al. 2004), including 3 in systems with stellar semimajor axes, a_B, of only ~ 20 AU. A Jupiter-like planet has been discovered in a triple star system: HD 188753 Ab was detected in a 3.3 day S-type orbit around a 1.06 $M_\odot$ star, which has a close binary star system (with a total mass of ~ 1.63 $M_\odot$) that orbits as close as ~ 6 AU to the star-planet system (Konacki et al. 2005). One giant planet has been confirmed in a P-type orbit that encircles both members of a binary star system: the radio pulsar PSR 1620-26, which is comprised of a neutron star and a white dwarf (Lyne et al. 1988; Sigurdsson 1993; Sigurdsson et al. 2003). The effect of the stellar perturbations on the formation of these planets, however, remains largely unstudied. Both circumstellar disks and circumbinary disks have been observed in young binary star systems, and we expect that a substantial fraction of planets (which are believed to form by an accretion process from dust and gas in a disk) may form in binary star systems. The existence of Earth-like planets in orbit about one or both components of main-sequence binary stars has yet to be determined, though ground- and space-based efforts to search for extrasolar terrestrial planets are currently in development.

This paper reports on numerical simulations of the final stages of terrestrial planet formation around one or both components of main-sequence binary star systems using two symplectic algorithms that we developed for this purpose (Chambers et al. 2002). These simulations use an initial disk composed of planetesimals and embryos of masses and separations virtually identical to those used in previous simulations of terrestrial planet formation in the Sun-Jupiter-Saturn System, in particular, the version that was most successful in reproducing the terrestrial planets in our Solar System (Chambers 2001). As a result, we can determine the effects of binary stars (with varying orbital parameters) on the planet formation process (despite our approximations, e.g., the lack of very small bodies and the assumption of perfectly inelastic collisions). Our simulations assume that large bodies have already accreted from a circumstellar or circumbinary disk of gas and dust, and each run begins with a 'bimodal' mass distribution of 14 large (Mars-sized) embryos embedded in a disk of 140 smaller (lunar-sized) planetesimals between ~ 0.3 AU – 2 AU from the central star or from the center of mass of the inner binary. The radii of solid bodies are calculated assuming a density of $\rho = 3$ g cm^{-3}, and the evolution of the accreting bodies are followed for 200 Myr – 1 Gyr. Because these N-body systems are chaotic in nature, we performed multiple (5 – 30) integrations of each binary star system with a slight change in the initial conditions of one body in the disk. This tactic allows us to sample the range of possible outcomes for effectively equivalent initial conditions, and the result is a distribution of final planetary systems.

We examine planetary accretion in two binary star configurations: [1] Around one component of widely separated binary stars, with minimum separations $q_B = a_B(1 - e_B)$ between 5 AU and 10 AU, where a_B is the stellar separation and e_B is the binary eccentricity. [2] Around both stars of tight binaries, with maximum separations of $Q_B = a_B(1 + e_B)$ between 0.05 AU and 0.4 AU. Perturbations from binary stars outside of these ranges ($Q_B \leq 0.05$ AU for close binaries and $q_B \geq 10$ AU for wide binaries) have relatively small effects on the process of terrrestrial planet formation (for the stellar mass ratios used here). Quintana (2004) provides the most complete discussion of our research presented in this article. Herein, we present a summary of the results of our simulations of planetary growth on S-type orbits in wide binaries (§2) and on P-type orbits in close binary systems (§3). Our conclusions are given in §4.

2 Wide Binary Star Systems

Quintana et al. (2002) examined the late stages of terrestrial planet formation around each star in the α Centauri AB system, the closest binary system to the Sun. This binary is comprised of the G2 star α Cen A (1.1 $M_\odot$) and the K1 star α Cen B (0.91 $M_\odot$), which have a stellar separation of $a_B = 23.4$ and an eccentricity $e_B = 0.52$. From 2 – 5 terrestrial planets were formed around either star in simulations for which the midplane of the disk was initially inclined by 30° or less relative to the binary orbital plane (Quintana et al. 2002, Quintana 2003).

We are currently conducting a more general survey of planetary growth in S-type orbits in wide binaries. All of the binary systems under study begin with equal mass stars of either 0.5 $M_\odot$ or 1 $M_\odot$, and the stellar orbital parameters (a_B, e_B) are varied such that the systems have periastron values of $q_B = 5$ AU, 7.5 AU, or 10 AU. Multiple simulations, usually 3 to 10, are performed for each binary star system with slight changes in the initial conditions in order to explore the sensitivity of the planet formation process to the initial conditions. In once case, we performed 30 integrations of a single system (with $q_B =$ 7.5 AU) to produce a full distribution of final planets in order to quantify this chaotic effect. Throughout this study, one must keep in mind the chaotic nature of N-body systems: *"Long term integrations are not ephemerides, but probes of qualitative and statistical properties of the orbits ... "* (Saha et al. 1997).

Figure 1 shows the evolution of the bimodal disk around a 1 $M_\odot$ star, with another 1 $M_\odot$ star orbiting the system at 10 AU on a circular orbit ($q_B =$ 10). By the end of the integration, 5 planets remain in orbits that span essentially the entire range of the initial disk of protoplanets. Figure 2 shows a simulation with the same binary parameters as the system shown in Figure 1, with the exception of a small change in the initial conditions of one small body in the disk. The result is a different solar system, with six planets more closely spaced within the semimajor axes of Mercury and Mars; this numerical experiment cleanly demonstrates the extreme sensitivity to initial conditions in these systems. Figure 3 shows the results from a simulation of equal mass (1 $M_\odot$) binary stars with $a_B = 10$ AU and $e_B = 0.5$ (the periastron value is 5 AU). Notice that perturbations from the stellar companion truncate the disk, and only two planets form within 0.8 AU of the central star.

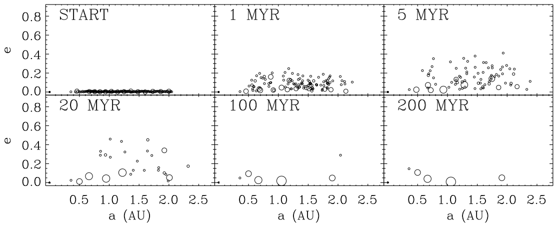

Figure 1: The temporal evolution of our standard planetesimal disk centered around and coplanar to a 1 $M_\odot$ star, with another 1 $M_\odot$ star on an initially circular orbit with $a_B = 10$ AU. The radii of the symbols are proportional to the radii of the bodies that they represent. The locations of each symbol show the orbital semimajor axes and eccentricities of the represented bodies relative to central star. Here, four planets at least as massive as the planet Mercury have formed within 2 AU, and the innermost planetesimal in the initial disk survives the integration without impact.

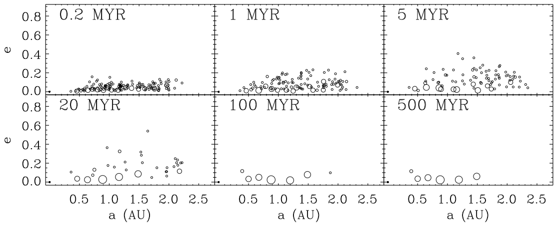

Figure 2: Results of a simulation identical to that shown in Figure 1, aside from a 5 meter shift of one small body in the disk prior to the integration. The initial masses, semimajor axes and eccentricities are the same as those shown in the first panel of Figure 1. In this case, the system forms six planets that are more closely spaced than the final system in Figure 1, demonstrating the sensitive dependence of these N-body systems on the initial conditions.

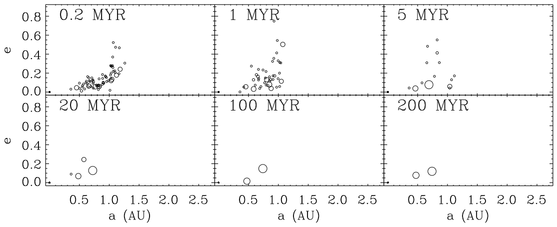

Figure 3: A simulation of the disk around one member of a binary star system with $a_B = 10$ AU, $e_B = 0.5$ ($q_B = 5$ AU), and equal mass stars of 1 $M_\odot$. The initial masses, semimajor axes and eccentricities are the same as those shown in the first panel of Figure 1. The effect of the stellar companion is clear in this case, as the initial disk is truncated early in the integration, and only two planets form within 0.8 AU.

Our exploration of parameter space shows how binary orbital parameters affect planet formation. The presence of a (relatively close) binary companion acts to limit the number of terrestrial planets formed, as shown by Figure 4. In our ensemble of $\sim$ 90 wide binary simulations, from 1 – 6 planets formed within 2.15 AU of the central star in binary systems with $q_B = 10$ AU, from 1 – 5 planets formed within 1.65 AU for systems with $q_B = 7.5$ AU, and from 1 – 3

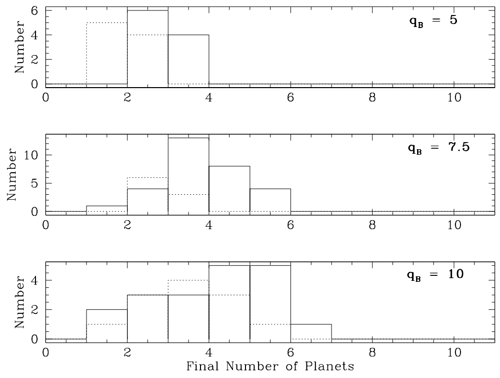

Figure 4: Distributions of the number of planets formed in 20 wide binary simulations with q_B = 5 AU (top panel), in 40 simulations with q_B = 7.5 AU (middle panel), and in 30 simulations with q_B = 10 AU (bottom panel). The dotted lines indicate the simulations of systems with $M_1 = M_2 = 0.5$ $M_\odot$, whereas the solid lines represent systems with $M_1 = M_2$ = 1.0 $M_\odot$. Notice that at least 1 terrestrial planet formed in all of our simulations, and a greater number of planets typically formed in binary systems with 1.0 $M_\odot$ stars.

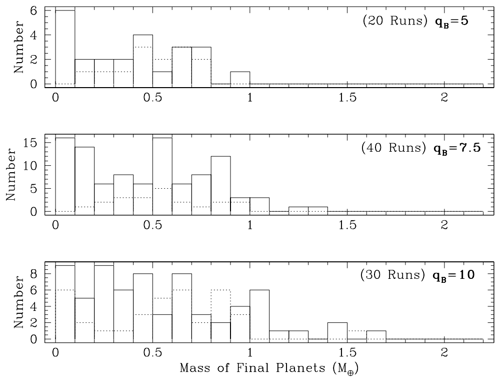

Figure 5: Distributions of the final masses of planets formed in wide binary simulations with q_B = 5 AU (top panel), simulations with q_B = 7.5 AU (middle panel), and simulations with q_B = 10 AU (bottom panel). The dotted lines indicate the simulations of systems with $M_1 = M_2 = 0.5$ $M_\odot$, whereas the solid lines represent systems with $M_1 = M_2 = 1.0$ $M_\odot$. Notice that binary stars with periastron q_B = 5 AU inhibit the growth of Earth-mass planets beyond 1 AU.

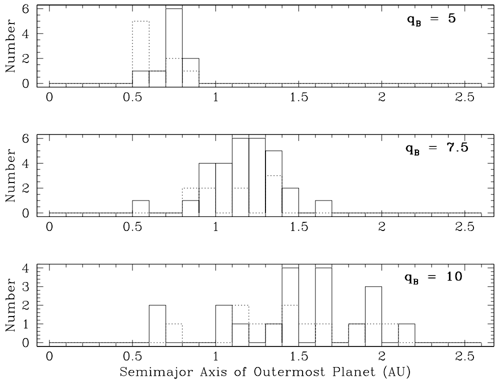

Figure 6: Distribution of the semimajor axis of the outermost planet formed in wide binary simulations with q_B = 5 AU (top panel), simulations with q_B = 7.5 AU (middle panel), and simulations with q_B = 10 AU (bottom panel). The dotted lines represent the simulations of systems with $M_1 = M_2 = 0.5$ $M_\odot$, and the solid lines represent systems with $M_1 = M_2 =$ 1.0 $M_\odot$. Notice that binary stars with q_B = 5 AU (regardless of the stellar masses) truncate the disk such that the radial extent of the final planet systems remain within 0.9 AU of the central star.

planets formed within 0.87 AU when $q_B = 5$ AU. For each value of q_B, fewer planets tend to form in binary systems with larger values of (a_B, e_B). Even though these systems are chaotic, and hence display sensitive dependence on initial conditions, the evolution of the bodies in the disk display similar accretion timescales and trends for a given system. As a result, the distribution of outcomes is well-defined.

Similarly, the presence of binary companions also affects the mass of forming planets, as shown in Figure 5. For binary systems with periastron q_B = 10 AU, the tail of high mass terrestrial planets extends up to 1.62 Earth masses ($M_\oplus$), which is $\sim$ 60% of the initial disk mass. The mass of the largest planet formed decreased with decreasing binary periastron, with the most massive planet of 0.98 $M_\oplus$ for binary periastron q_B = 5 AU (the remaining planets that formed in q_B = 5 AU simulations were all $\lesssim 0.8$ $M_\oplus$).

Finally, binary companions limit the extent of the terrestrial planet region in nascent solar systems. As shown in Figure 6, wider binaries allow for larger systems of terrestrial planets. In these simulations, the initial disk of planetesimals extends out to 2.05 AU, so we do not expect terrestrial planets to form much beyond this radius. For binary periastron q_B = 10 AU, the semimajor axis of the outermost planet typically lies near 2 AU, i.e., the system explores the entire available parameter space for planet formation. With smaller binary periastron values, the resulting extent of the terrestrial planet region is diminished. When binary periastron decreases to 5 AU, the typical system has a radial extent of about 0.75 AU and no planets form beyond 0.9 AU.

These results are consistent with our previous simulations of the long-term stability of Earth-like planets in orbit about a 1 $M_\odot$ star: This work found that long-term stability is most sensitive to the periastron q_B of the stellar companion (e.g., David et al. 2003) and suggested that Earth-like planets can remain on stable orbits for timescales on the order of the current age of the Solar System provided that $q_B \gtrsim 7$ AU. According to observations of the distributions of binary orbital parameters (Duquennoy & Mayor 1991), about 50% of binary systems meet this constraint.

3 Close Binary Star Systems

We have performed a complementary set of simulations of the late stages of terrestrial planet formation within a circumbinary disk surrounding various short-period binary systems (Quintana & Lissauer 2005). The initial disk of planetary embryos is the same as that used for simulating accretion within our Solar System, in the α Centauri AB binary system, and in our wide binary systems described in §2. The combined mass of the binary stars is equal to 1 $M_\odot$, with the stellar mass ratio μ (the ratio of the secondary star's mass to the total stellar mass) equal to either 0.2 or 0.5. Binary star separations in the range a_B = 0.05 AU – 0.4 AU are examined, while e_B begins at 0, 1/3, 0.5, or 0.8 such that the stellar apastron is 0.05 AU $\leq Q_B \leq$ 0.4 AU. Not all combinations of these stellar parameters, however, are used. For most of the simulations, the midplane of the circumbinary disk begins coplanar to the stellar orbit, but for several systems a relative inclination of $i = 30°$ is investigated. Giant planets are included, as they are in most simulations of our Solar System.

Figure 7 shows the evolution of the circumbinary disk around two 0.5 $M_\odot$ stars with a_B = 0.2 AU and $e_B = i_B = 0$. Although the stellar perturbations slightly truncate the inner edge of the disk at 0.4 AU, four planets with masses and orbits similar to those in the Solar System have formed within 1.4 AU. Figure 8 shows the results of a simulation similar to that shown in Figure 7, but the stars begin with a larger stellar separation of a_B = 0.4 AU. In this case, any material within 0.8 AU is unstable, and $\sim$ 85% of the initial disk mass is perturbed from the system.

In all of the close binary simulations in which the stars travel on a circular orbit with a semimajor axis of up to 0.2 AU about their mutual center of mass, the planetary embryos grow into a system of terrestrial planets that are statistically indistinguishable from those formed about single stars (Quintana & Lissauer 2005). A larger semimajor axis and/or a substantially eccentric binary orbit perturbs the planetesimals more strongly, typically leading to systems with fewer planets, especially interior to 1 AU.

4 Conclusions

This paper reports on a set of N-body simulations of terrestrial planet formation in binary systems. Our results indicate that terrestrial planet formation is feasible around one or both components of a binary star system. Simulations of planet growth around both components of very close binary stars are almost complete and will be submitted for publication soon (§3; Quintana & Lissauer 2005). In the aforementioned article, we also discuss the scaling of results of planetary accretion simulation to systems with different stellar masses, planetesimal densities, etc.

We are continuing our investigations of terrestrial planet accretion around one component of a wider binary, by examining a wide range of stellar masses and orbits (§2), to gain more insight into which parameters are most likely to affect the planet formation process (Quintana et al. 2006). Results to date (see Figures 4 – 6) suggest that binary periastron is one of the most important variables in determining the affect of companions on planet formation in wide binary systems. When binary periastron is greater than about 10 AU, the terrestrial planet region (specifically, the innermost 2 AU of the solar system) is largely unaffected. Closer binaries (with smaller periastra) affect terrestrial planet formation by making smaller planets, fewer planets, and less extended sys-

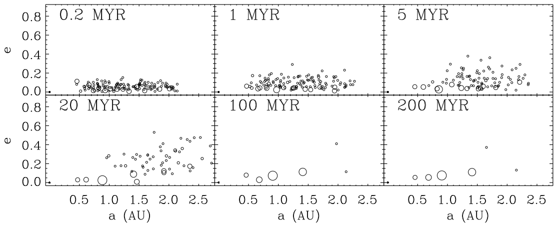

Figure 7: The evolution of a disk of proto-planets, as shown in the first panel of Figure 1, placed around a close binary with two 0.5 $M_\odot$ stars (simulation CB_.2_0_.5_c in Quintana & Lissauer 2005). The orbital parameters are a_B = 0.2 AU, $e_B = i_B = 0$ (the apastron is Q_B = 0.2 AU). In this simulation, four terrestrial planets simlar to those in our Solar System formed within 1.4 AU of the center of mass of the inner binary, while two planetesimals remain beyond 1.6 AU.

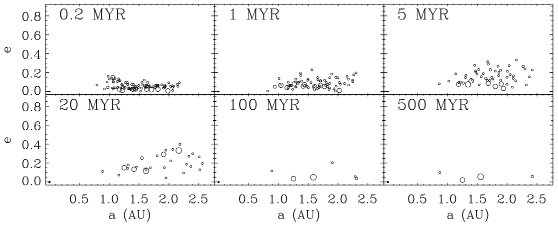

Figure 8: The evolution of a disk placed around two 0.5 $M_\odot$ stars with a larger stellar separation than the system shown in Figure 7: a_B = 0.4 AU and $e_B = i_B = 0$ (simulation CB_.4_0_.5_d in Quintana & Lissauer 2005). In this case, the inner edge of the disk is truncated up to 0.8 AU, and the four bodies that remain are composed of only 15% of the initial disk mass (most of the mass was perturbed out of the system).

tems. Fortunately, a large fraction of binary systems – roughly 40 percent (see David et al. 2003) – have binary periastron greater than 10 AU and thus do not greatly limit the formation of terrestrial planets.

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