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PREDICTING PLANETS IN KNOWN EXTRASOLAR PLANETARY SYSTEMS. III. FORMING TERRESTRIAL PLANETS

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ABSTRACT

Recent results have shown that many of the known extrasolar planetary systems contain regions that are stable for both Earth-mass and Saturn-mass planets. Here we simulate the formation of terrestrial planets in four planetary systems, 55 Cancri, HD 38529, HD 37124, and HD 74156, under the assumption that these systems of giant planets are complete and that their orbits are well determined. Assuming that the giant planets formed and migrated quickly, terrestrial planets may form from a second generation of planetesimals. In each case, Moon- to Mars-sized planetary embryos are placed in between the giant planets and evolved for 100 Myr. We find that planets form relatively easily in 55 Cnc, with masses up to 0.6 $M_\oplus$ and, in some cases, substantial water content and orbits in the habitable zone. HD 38529 is likely to support an asteroid belt, but no terrestrial planets of significant mass. No terrestrial planets form in HD 37124 and HD 74156, although in some cases 1–2 lone embryos survive for 100 Myr. If migration occurred later, depleting the planetesimal disk, then massive terrestrial planets are unlikely to form in any of these systems.

Subject headings: astrobiology — methods: *n*-body simulations — planets and satellites: formation

1. INTRODUCTION

Most planets detected to date around main-sequence stars are thought to be Jovian (gaseous) in nature. This is known from their large masses, most of which are >30 $M_\oplus$ (although smaller planets have been detected; e.g., Rivera et al. 2005), and from transit measurements of the size of HD 209458b, to be 1.27 Jupiter radii (Charbonneau et al. 2000). The radial velocity technique, which is sensitive to the reflex motion of a planet's parent star, is unlikely to ever be able to detect Earth-mass planets in the habitable zones of their parent stars. The sensitivity of current surveys is 3–10 m s^{-1} (Butler et al. 1996; Baranne et al. 1996; Marcy & Butler 1998), while the reflex velocity of the Sun due to the Earth is only about 9 cm s^{-1}. This signal is not likely to be detected by radial velocity surveys in the near future. ESA's *COROT* and NASA's *Kepler* missions, to be launched in 2006 and 2007, respectively, hope to be the first to find Earth-like planets around other stars by looking for transits. NASA's *Terrestrial Planet Finder* (*TPF*) and ESA's *Darwin* missions hope to spectroscopically characterize terrestrial planets around main-sequence stars.

Recent results have shown that several known planetary systems contain regions in between the giant planets in which massless test particles remain on stable orbits for long periods of time. Barnes & Raymond (2004, hereafter Paper I) mapped out these stable regions in semimajor axis *a* and eccentricity *e* space for HD 37124, HD 38529, HD 74156, and 55 Cnc. These regions have been mapped in *a* space (assuming circular orbits) for υ And (Rivera & Lissauer 2000), GJ 876 (Rivera & Lissauer 2001), and 55 Cnc (Rivera & Haghighipour 2003).

Menou & Tabachnik (2003) examined the possibility of Earth-sized planets residing in the habitable zones of known extrasolar planetary systems (including single-planet systems), again using massless test particles. They find that roughly one-fourth of the known systems can support a planet in the habitable zone of its parent star, as defined by Kasting et al. (1993).

Raymond & Barnes (2004, hereafter Paper II) tested the stability of Saturn-mass planets in the regions of four planetary systems in which test particles had been shown in Paper I to be stable: HD 37124, HD 38529, 55 Cnc, and HD 74156. They found that, for Saturn-mass planets, the stable regions identified in Paper I shrank to a small fraction of the test-particle stable region.

Barnes & Quinn (2004) tested the stability of seven known planetary systems and found that several are on the edge of stability: a small change in orbital elements can lead to a catastrophic disruption of the system. This idea led to the "packed planetary systems" (PPS) hypothesis, first suggested by Laskar (1996), and presented in Paper I. The PPS model suggests that all planetary systems contain as many planets as they can support without becoming unstable, and implies that if a stable region exists within a planetary system, then it should contain an additional planet. The systems studied in Paper II are not on the edge of stability, and therefore have enough "dynamical space" to harbor additional unseen planets.

Papers I and II dealt solely with the dynamic stability of hypothetical additional planets in planetary systems. In this paper we examine the formation process of terrestrial planets in such a system. Giant planets close to their parent stars (e.g., "hot jupiters") are thought to form farther out in the protoplanetary disk and migrate inward via torques with the gas disk (e.g., Lin et al. 1996). In order for a terrestrial planet to coexist with a close-in giant planet, the terrestrial planet must either (1) form quickly and survive the inward gas giant migration, or (2) form from material remaining after the giant planet has migrated through.

The probability of a planet surviving in the terrestrial region in scenario (1) is small. Mandell & Sigurdsson (2003) showed that in some cases terrestrial planets can survive the migration of a Jupiter-like planet through the terrestrial zone. The fraction of planets that survive such a migration is a function of the rate of migration (faster migration implies higher survival rate), and ranges between 15% and 40%. However, only a small fraction (7%–16%) of the surviving planets end up with orbits in the habitable zone,

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TABLE 1
Orbital Parameters of Selected Planetary Systems

System	Planet	M (M_J)	a (AU)	e	ϖ (deg)	T (JD)	$M_\star$[a] ($M_\odot$)	[Fe/H]
HD 37124[b]	b	0.86	0.54	0.1	97.0	2,451,227	0.91	−0.32
	c	1.01	2.95	0.4	265.0	2,451,828		
HD 38529	b	0.78	0.129	0.29	87.7	2,450,005.8	1.39	0.313
	c	12.8	3.68	0.36	14.7	2,450,073.8		
55 Cnc[c]	b	0.84	0.115	0.02	99.0	2,450,001.479	1.03	0.29
	c	0.21	0.241	0.339	61.0	2,450,031.4		
	d	4.05	5.9	0.16	201.0	2,452,785		
HD 74156[d]	b	1.61	0.28	0.647	185.0	2,451,981.38	1.05	0.13
	c	8.21	3.82	0.354	272.0	2,451,012.0		

[a] Stellar masses $M_\star$ and metallicities [Fe/H] are from the extrasolar planets encyclopedia, http://www.obspm.fr/planets.
[b] Best-fit values for HD 37124 from Butler et al. (2003). The current best fit for planet c is $a = 2.50$ AU, $e = 0.69$ (http://www.exoplanets.org).
[c] Another planet, 55 Cnc e, was discovered in this system in late 2004 (McArthur et al. 2004).
[d] Best-fit values for HD 74156 as of 2002 Aug 22. The current best fit for planet c is $a = 3.40$ AU, $e = 0.58$ (Naef et al. 2004).

meaning that only 1%–4% of terrestrial planets in the habitable zone are likely to remain on similar orbits after a migration event. A much more likely outcome is that the planet is scattered onto a highly eccentric orbit with a large semimajor axis (Fig. 3 from Mandell & Sigurdsson 2003).

Can terrestrial planets form from local material after a giant planet migrates through? Armitage (2003) showed that in many cases the postmigration disk of planetesimals is depleted beyond repair. However, if giant planet migration occurs quickly and early enough in the disk's lifetime, then enough time remains for a second generation of planetesimals to form (Armitage 2003). Raymond et al. (2005a) argued that terrestrial accretion can therefore occur in the presence of one or more close-in giant planets via scenario (2). Indeed, several recent results have shown that giant planets may form in less than 1 Myr via either the bottom-up, core-accretion scenario (Rice & Armitage 2003; Alibert et al. 2004; Hubickyj et al. 2005) or the top-down, fragmentation scenario (Boss 1997; Mayer et al. 2002). Migration begins immediately after (or even during) formation (Lufkin et al. 2004) and takes $\sim 10^5$ yr or less for planets larger than 0.1 Jupiter masses (M_J) (D'Angelo et al. 2003, and references therein).

Raymond et al. (2005a) show that potentially habitable terrestrial planets can form in the presence of a close-in giant planet, assuming that a substantial disk remains and re-forms after migration. The orbit and composition of these planets are strongly affected by the position of the giant planet. Hot/warm jupiters at larger orbital radii (up to 0.5 AU) cause the terrestrial planets to be iron-poor and, in some cases, drier than closer-in giant planets, and may reduce the chances of habitable planet formation.

Here we simulate the final stages in terrestrial planet formation from disks of planetary embryos in four known systems: HD 37124 (Butler et al. 2003), HD 38539 (Fischer et al. 2001, 2003), 55 Cnc (Marcy et al. 2002), and HD 74156 (Naef et al. 2004), the same four systems we examined in Paper II. We assume that embryos form via oligarchic growth (e.g., Kokubo & Ida 2000), and allow these bodies to accrete under their mutual gravity and the gravity of the known planets for 100–200 Myr. We explore systems in which rapid, early migration has occurred, thus leaving behind a substantial planetesimal disk (Armitage 2003). We also look at cases in which migration has occurred late in the disk lifetime, leaving behind a disk with little mass in planetesimals. In addition, we make simple comparisons with previous simulations (e.g., Raymond et al. 2004). In § 2 we describe our numerical method and initial conditions. We present the results of our simulations in § 3, and conclude in § 4.

2. METHOD

2.1. *Initial Conditions*

As discussed above, our formation scenario assumes that the gas giants formed and migrated through the terrestrial region. The terrestrial planets formed from a subsequent, second generation of planetesimals. We place the known giant planets of the four systems examined on their best-fit (coplanar) orbits and assign them their minimum masses (see Table 1). To accurately model terrestrial accretion in the system, we need a complete understanding of the planetary system, including the location of all mean motion and secular resonances, which are determined by the true masses and relative inclinations of all planets in the system. Because of observational limitations and incompleteness, we do not know the $\sin i$ or mutual inclinations of the planets, a common limitation of many studies of extrasolar planets. We proceed under the assumption that the giant planets' orbits are coplanar and that they are the only planets in the system. If $\sin i < 1$, the giant planets' masses are larger than assumed here, and the stable zones from Papers I and II would likely become narrower. The discovery of additional planets could potentially eliminate the stable zones completely. But the goal of these papers is to use dynamics to find additional planets; indeed, the stable zones from Papers I and II are proposed as the most likely locations for additional planets in these systems.

We assume a surface density profile of solids that decreases with heliocentric distance as $r^{-3/2}$, i.e., surface density $\Sigma = \Sigma_1 r^{-3/2}$. We first perform a set of simulations assuming that a substantial amount of mass remains in the terrestrial zone after migration. In these runs, the surface density is normalized at 1 AU to a value of $\Sigma_1 = 10$ g cm^{-2}. This value is roughly 50% larger than that for the minimum-mass solar nebula model (Hayashi 1981), and is reasonable under the assumption that the surface density of solid material in the protoplanetary disk correlates with stellar metallicity. Indeed, three of the four known host stars (all but HD 37124) have higher metallicities than the Sun,[5] and all four have giant planets more massive than Jupiter. For systems in which planets accreted in the first set of simulations, we construct disks for a second set of runs. In this set, we assume that

[5] Data from http://www.exoplanets.org.

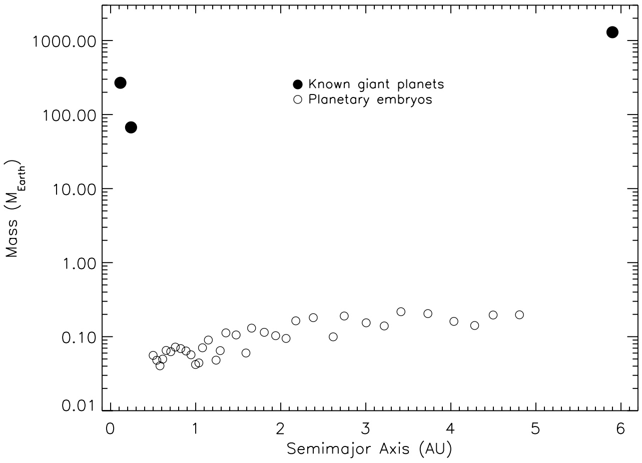

FIG. 1.—Initial conditions for a simulation of 55 Cnc, assuming a surface density of 10 g cm^{-2} at 1 AU that scales with heliocentric distance as $r^{-3/2}$.

giant planet migration severely depleted the planetesimal disk. The remaining surface density is normalized to 1.5 g cm^{-2} at 1 AU, roughly one-quarter of the density of the MMSN model. For late or slow giant planet migration, Armitage (2003) does predict a drop of 1–2 orders of magnitude in the surface density of planetesimals. However, the mass of planets that will form, via accretion, scales roughly linearly with the surface density (Wetherill 1996; Kokubo et al. 2006). Thus, we can extrapolate from our simulations with $\Sigma_1 = 1.5$ g cm^{-2} to even more depleted disks. We refer to our two sets of simulations as representative of "early migration" (with a substantial planetesimal disk) and "late migration" (with a depleted disk) scenarios.

We assume that oligarchic growth has taken place in these systems, following the formation of a second generation of planetesimals, as described in Armitage (2003). We place planetary embryos between the giant planets, following the method of Raymond et al. (2004, 2005a, 2006a). We assume that embryos form with a typical spacing of Δ mutual Hill radii, where $\Delta = 5$–10 (as in, e.g., Kokubo & Ida 2000). The mass of embryos M scales as $M \propto r^{3/4}\Delta^{3/2}\Sigma_1^{3/2}$. Thus, embryo masses are larger farther from the star. Figure 1 shows a set of early migration initial conditions for a simulation of 55 Cnc.

The number of embryos we include depends on the separation of the giant planets. For the early migration simulations, we include 12–15 embryos in HD 37124 of total mass $\sim$0.5 $M_\oplus$ (Earth masses) between 0.8 and 1.2 AU; for HD 38529, 25–29 embryos of total mass 2.7 $M_\oplus$ between 0.2 and 3.2 AU; for HD 74156, 45–50 embryos of total mass 3.2 $M_\oplus$ between 0.6 and 3.6 AU; and for 55 Cnc, 34–38 embryos totaling 3.7 $M_\oplus$ between 0.5 and 4.9 AU. Embryos are given small initial eccentricities ($e \leq 0.02$) and inclinations ($i \leq 0.1°$). Note that some embryos are therefore initially placed outside the stable regions from Papers I and II. These embryos are quickly removed from the system (usually via dynamical ejection); however, they allow us to populate the stable regions to their very edges. The ejected embryos do not affect the simulation outcome; indeed, it is not likely that embryos could form in the harsh dynamical environment outside the stable zones.

We perform 10–12 early migration simulations for each planetary system to test the likelihood of terrestrial planet formation. In systems that formed terrestrial planets (55 Cnc and HD 38529), we generate lower mass disks of embryos, assuming a late migration scenario, and run two additional simulations. For 55 Cnc, we include 62–64 embryos between 0.5 and 5 AU totaling 1.1 $M_\oplus$, and for HD 38529 we include 63–66 embryos between 0.2 and 2 AU totaling 0.47 $M_\oplus$. For the systems in which planets did not accrete (HD 37124 and HD 74156), we run two additional simulations starting from a disk of smaller bodies to see if any accretion is possible.

2.2. *Numerical Method*

We integrate the systems for 100–200 Myr using the hybrid integrator in Mercury (Chambers 1999). We chose a time step for each system such that the innermost initial orbit is sampled at least 20 times per orbit. Collisions conserve linear momentum and mass, and do not take collisional fragmentation into account, but we discuss the distribution of impact angles and velocities and the likelihood of accretional collisions. Energy is conserved to better than 1 part in 10^4. Each simulation took 3–10 days to run on a desktop PC.

3. RESULTS

We performed 10–12 simulations of terrestrial planet formation in each of the four planetary systems listed in Table 1, assuming an early giant planet migration scenario. For systems in which accretion proceeded, we performed two additional simulations assuming late giant planet migration. For systems in which little accretion occurred, we performed two additional higher resolution simulations to test whether any accretion could happen.

Here we summarize the results for each system. An additional, $\sim$Neptune-mass planet, 55 Cnc e, was discovered in this system in late 2004 (McArthur et al. 2004). It is not included in these simulations. Because of its small mass, its large dynamical separation from the terrestrial zone, and the small mass included in embryos, we do not expect its presence to affect these results.

3.1. *55 Cancri*

3.1.1. *Early Migration*

Paper I revealed a wide stable region in 55 Cnc between 0.7 AU $< a <$ 3.2 AU with $e < 0.2$. We performed 10 "early-migration" terrestrial planet formation simulations, nine of which formed 1–3 terrestrial planets with 1.1 AU $< a <$ 3.6 AU, $e \leq$ 0.36, and masses up to 0.63 $M_\oplus$. Figure 2 shows the final configurations of these nine simulations, with the solar system included for comparison. Six simulations finished with two or three remaining terrestrial bodies, including two systems in which two planets had each accreted at least one embryo. In two of the nine cases, the only embryos that remained had not accreted any other bodies. In one case (simulation 2), the system took 170 Myr to reach a stable configuration with no overlapping orbits.

The impact velocities for our early-migration simulations of 55 Cnc are similar to those seem by Agnor et al. (1999) in accretion simulations including Jupiter and Saturn. By examining the impact angles and velocities, we estimate that 55%–60% of the impacts were accretional (i.e., the final aggregate mass is larger than either impactor), following the results of Agnor & Asphaug (2004). This is comparable to the 55% found by Agnor & Asphaug (2004) for previous terrestrial accretion simulations that formed planets similar to Venus, Earth, and Mars. We therefore consider the final masses of our planets formed in 55 Cancri to be realistic. Despite the fact that we form terrestrial planets of significant mass (>0.5 $M_\oplus$), the fraction of the total embryo mass that remains at the end of the simulations is quite small, ranging from 4% to 20% of the initial terrestrial mass.

Figure 1 shows the initial configurations of a system (simulation 9 from Fig. 2) that formed two terrestrial planets, with masses

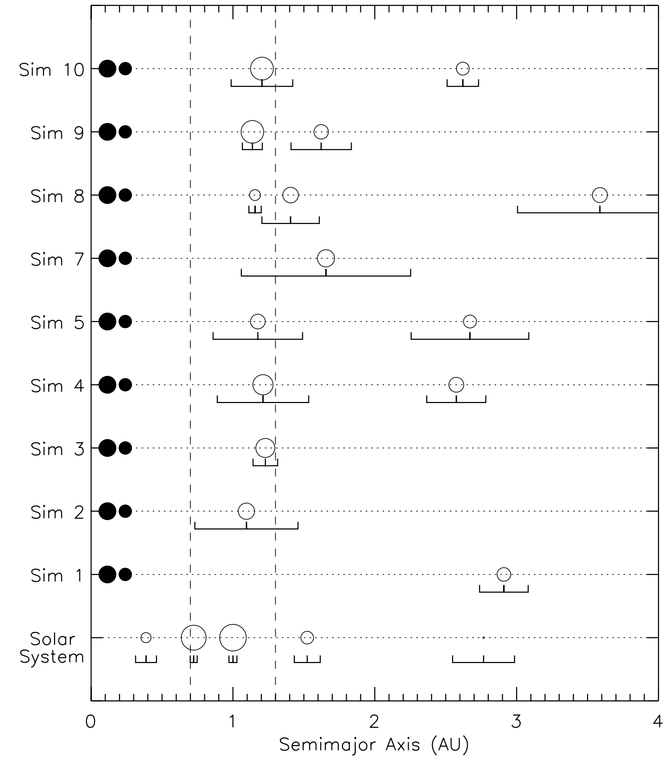

FIG. 2.—Final configurations of all nine simulations in 55 Cnc that formed terrestrial planets. The size of each circle is proportional to its mass$^{(1/3)}$, and the underlying lines are bounded by each body's perihelion and aphelion. The dark filled circles indicate the positions of the two inner known gas giant planets in the system, whose sizes are not on the same scale as the terrestrial bodies (but note that the inner one is more massive). The solar system (including Ceres, the largest asteroid) is included for reference, with 3 Myr averaged orbital values from Quinn et al. (1991). The dashed vertical lines represent the boundaries of the habitable zone in the system, as quoted in Menou & Tabachnik (2003). The terrestrial planets that formed in the habitable zones in simulations 5, 9, and 10 have accreted material from past 2 AU, and have water mass fractions between 2×10^{-4} and 10^{-3}.

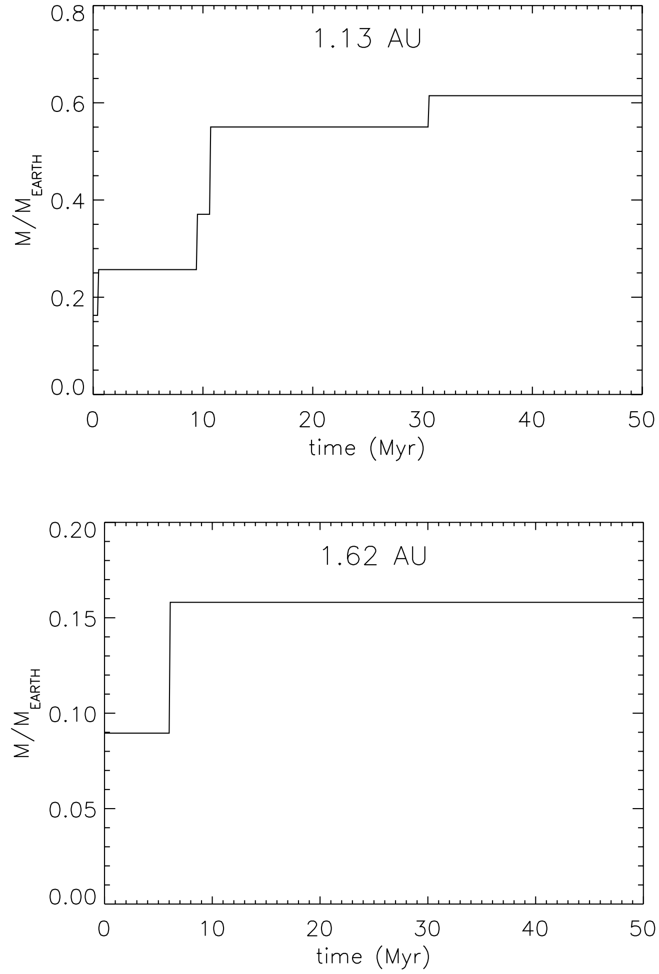

FIG. 3.—Masses of two surviving terrestrial planets in 55 Cnc as a function of time for the two surviving bodies in simulation 9 (see Fig. 2), labeled by their final semimajor axes.

of 0.61 $M_\oplus$ and 0.16 $M_\oplus$. Figure 3 shows the masses of these two planets as a function of time. The larger undergoes four accretion events, reaching its final mass at 30 Myr. The smaller survivor is an aggregation of only two embryos, which formed inside the orbit of the larger survivor. A close encounter at 70 Myr between the two final planets and another embryo caused the two planets to roughly swap positions, and the embryo to be ejected from the system. The planets' final orbital elements are $(a, e) = (1.14$ AU, 0.06) and (1.62 AU, 0.13) for the larger and smaller planet, respectively.

In our solar system, chondritic material is seen to contain hydrated minerals past 2–2.5 AU, with water mass fractions of up to >10% for some carbonaceous chondrites (Abe et al. 2000; see Fig. 2 from Raymond et al. 2004). The mass of the star ρ Cnc is 0.95 $M_\odot$, so the temperature distribution in its circumstellar disk should be similar to the solar nebula. The temperature during the formation of the postmigration generation of planetesimals would imprint a corresponding distribution of water content. If we apply the initial water distribution of Raymond et al. (2004) such that embryos inside 2 AU are dry, embryos between 2–2.5 AU contain 0.1% water, and those outside 2.5 AU contain 5% water, then we can calculate the water content of the terrestrial planets we have formed in 55 Cnc. Of the seven terrestrial planets whose semimajor axes lie in the habitable zone (see Fig. 3), three (simulations 5, 9, and 10) have accreted material from past 2 AU and have water mass fractions between 2×10^{-4} and 10^{-3} (the Earth's is roughly 10^{-3}). In particular, note that the inner planet in simulation 9, shown in Figures 2 and 3, accreted two embryos from outside 2 AU and has a water mass fraction of 7×10^{-4}. This is the best candidate habitable planet formed in our 10 early-migration simulations, as its mass is significant (0.6 $M_\oplus$), its eccentricity is small enough that its orbit stays inside the habitable zone, and its water content is substantial.

3.1.2. *Late Migration*

We performed two additional late-migration simulations in 55 Cnc, starting from a depleted disk. Each simulation finished with 5–9 remaining bodies in the stable zone from Paper II. The largest surviving planet in either simulation accreted nine other embryos, but reached only 0.13 $M_\oplus$. If the disk were depleted by another order of magnitude, then the most massive terrestrial bodies would only be roughly a lunar mass. Such planets are too small to have long-lasting plate tectonics (Williams et al. 1997), and are unlikely to be habitable.[6] In addition, this planet did not accrete any water-rich bodies from outside 2 AU and was dry. Low-mass disks do tend to form drier planets than more massive disks, because the dynamical self-stirring of the disk is not efficient (Raymond et al. 2004, 2006b). However, an additional source of gravitational stirring is present in the form of three

[6] The mass cutoff for a planet to have tectonic activity for 4–5 Gyr is thought to lie ~0.3 $M_\oplus$, depending on the planetary density (Williams et al. 1997; Raymond et al. 2006b).

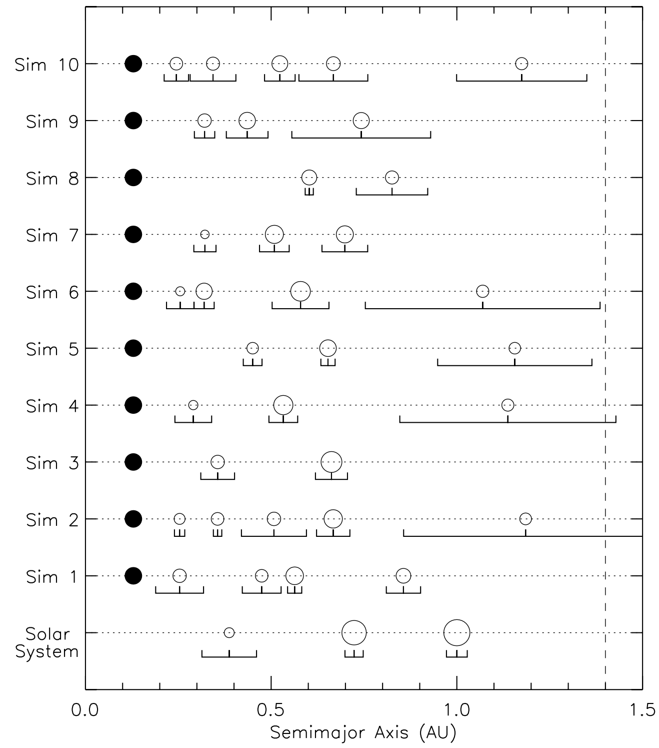

Fig. 4.—Final configurations of all 10 simulations of HD 38529, formatted as in Fig. 2. The filled circles represent the position of the inner known giant planet. The dashed vertical line at 1.4 AU represents the inner edge of the habitable zone in this system, whose host star's mass is 1.39 $M_{\odot}$.

giant planets, but (free) eccentricities induced by the giant planets are only ~0.05–0.1 in the stable zones (Fig. 3 from Paper II), enough to cause radial mixing on only a small scale. The fact that several "early migration" planets did accrete water-rich embryos leads us to the conclusion that, even in this complicated dynamical environment, the self-gravity of the disk of embryos is important. Embryos in low-mass disks do not self-scatter enough to cause significant radial mixing and water delivery.

3.2. *HD 38529*

3.2.1. *Early Migration*

Papers I and II found a large region in HD 38529 that was stable for both massless and Saturn-mass particles. This region contains two dynamically distinct zones: from 0.3 to 0.5 AU, planets are stable for $e < 0.15$, and from 0.5 to 0.8 AU, they are stable for $e < 0.3$. Figure 4 summarizes the results of the 10 early migration simulations of HD 38529. In each of the 10 simulations, 2–5 terrestrial bodies remain after 200 Myr, averaging 3.4 surviving bodies per simulation, with $0.04\ M_{\oplus} \leq M \leq 0.5\ M_{\oplus}$, $0.24\ \mathrm{AU} < a < 1.2$ AU, and $e \leq 0.3$. Most of the survivors have accreted other bodies, and roughly one planet per system was massive enough to be tectonically active (>0.2–0.3 $M_{\oplus}$; Williams et al. 1997, Raymond et al. 2006b). However, the final systems look more like asteroid belts than planetary systems. As discussed below, this may be due to the development of chains of apsidal libration, which prevent bodies from undergoing close encounters.

In order for a relatively massive terrestrial planet to grow, it needs a substantial feeding zone from which to accrete embryos. A planet with a higher eccentricity encounters embryos at a range of heliocentric distances, and has the chance to accrete more embryos than a lower eccentricity planet (e.g., Levison & Agnor 2003). However, the stable zones in HD 38529 extend only to moderate eccentricities ($e < 0.15$). So, planets with higher eccentricities and wider feeding zones are actually unstable. Only planets at relatively low eccentricities with smaller feeding zones can form in the system.

The impact velocities in HD 38529 are higher than for 55 Cnc. This is simply because the stable zone in HD 38529 extends to higher eccentricities than in 55 Cnc. Thus, embryos may interact and collide with higher eccentricities and therefore at higher impact speeds. Indeed, we estimate that only ~30% of collisions in HD 38529 are accretional, following the results of Agnor & Asphaug (2004). We have not accounted for the expected debris and smaller bodies, which may reduce the eccentricities of larger bodies via dynamical friction (e.g., Goldreich et al. 2004). We consider the masses of the bodies we form in HD 38529 to be upper limits. The total number of surviving bodies may be a lower limit, reinforcing the possibility that it is more likely for an asteroid belt to exist in HD 38529 than terrestrial planets of significant size.

Simulation 10 from Figure 4 is an interesting case, in which five terrestrial bodies remain, three of which have accreted at least one other embryo. The surviving bodies have semimajor axes of 0.24, 0.34, 0.52, 0.67, and 1.17 AU, and the known giant planets have final semimajor axes of 0.13 and 3.65 AU. At first glance, this appears to be a chain of mean-motion resonances among the inner planet and four innermost survivors with period ratios of 5:2, 5:3, 2:1, and 10:7, respectively. However, an inspection of the resonance angles (see, e.g., Murray & Dermott 1999, § 8.2) shows that the relevant resonance angles are circulating, not librating. This configuration is therefore either a coincidence (note that the ratios are not exactly in resonance), or these bodies are in a more complicated multibody resonance, such as the three-body resonance between Jupiter, Saturn, and Uranus in our solar system (Murray & Holman 1999).

Apsidal libration, which occurs when two consecutive bodies' longitudes of periastron oscillate about each other, pervades the system. We search for these librations using the distribution function of the relative orientation of planetary orbits. Figure 5 demonstrates libration among the surviving bodies in simulation 10. Each panel of Figure 5 shows the distribution function $P(\Lambda)$, where Λ is the normalized difference between the longitude of pericenter of a terrestrial body and that of a giant planet, as defined in Barnes & Quinn (2004). Each row of the figure corresponds to a given surviving terrestrial body in simulation 10, labeled by the body's semimajor axis. The left column represents the relative alignment of that body's orbit with respect to the inner giant planet, and the right column with respect to the outer giant planet. A flat $P(\Lambda)$ curve indicates that the longitudes are circulating, while a sharp peak indicates that a body's longitude of pericenter is librating about that of the giant planet, and is therefore in apsidal libration. It is clear from Figure 5 that the inner two terrestrial bodies are in apsidal libration with the inner giant planet, whose precession period is about 8000 yr. The amplitude of libration of the innermost one is smaller, but both are locked in this libration. Similarly, the outermost terrestrial body is in apsidal libration with the outer giant planet with a precession period of 22,000 yr. The two intermediate terrestrial bodies are separated enough from both gas giants that their secular dynamics are not dominated by either, and their longitudes of periastron circulate (as in, e.g., the bottom panel of Fig. 5 from Paper II).

These librating configurations may be an additional factor in explaining the low accretion rate in this system. Orbits in apsidal libration tend to avoid close encounters because the orientation

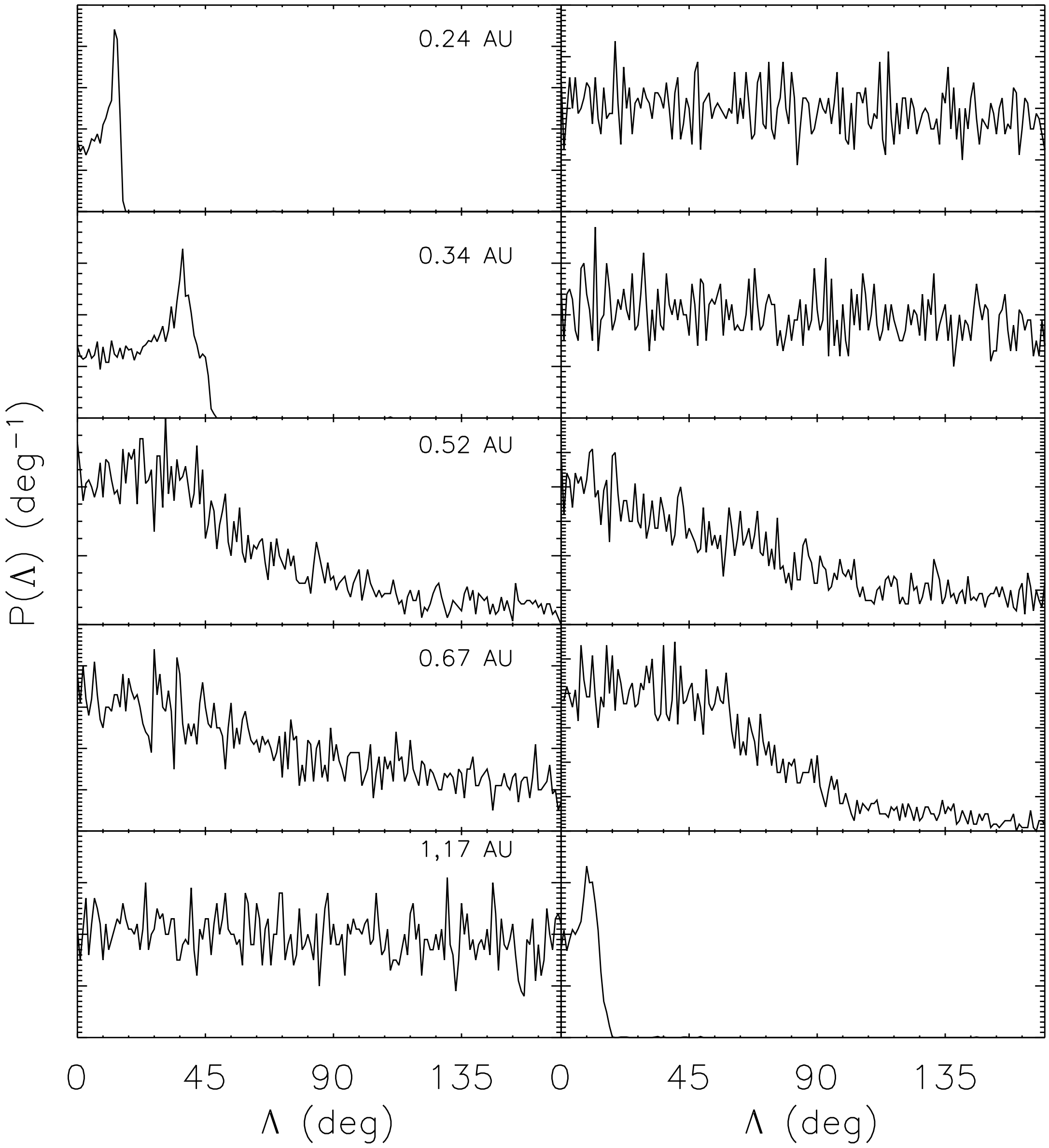

Fig. 5.—Distribution function of the alignment of the longitudes of pericenter for all surviving terrestrial bodies from simulation 10 of HD 38529, formatted as in Fig. 6*b*. Each row corresponds to a given object: the left column shows the alignment with respect to the inner giant planet at 0.12 AU, and the right column with respect to the outer giant planet at 3.65 AU. The inner bodies are in apsidal libration with the inner giant planet, and the outer body with the outer giant.

of perihelion is the same for both orbits. In simulation 10 we have three such bodies in the inner system (giant planet plus two terrestrial planets) and two in the outer system (outer giant and terrestrial planets). The place where collisions are most likely to occur is at the juncture between these two regimes. The two terrestrial bodies in this juncture are indeed the most massive in the simulation. In almost every simulation, the most massive terrestrial planet lies in this middle region, between about 0.5 and 0.7 AU. Inside this astrocentric distance, bodies are likely to be in apsidal with the inner planet (and each other), and outside with the outer giant planet. Of course, these librating configurations are only induced after most accretion has happened in the system, and objects are no longer on crossing orbits.

3.2.2. *Late Migration*

We performed two additional late-migration simulations in HD 38529, starting from a low-mass disk. As in the early migration simulations, 3–4 bodies remained in each case. The most massive of these accreted 11 other embryos but reached only 0.12 $M_\oplus$, below the likely cutoff for habitability (Williams et al. 1997). If the disk were depleted by another order of magnitude, planets larger than the Moon ($\sim$0.013 $M_\oplus$) could not form.

3.3. *HD 37124*

Paper I showed that the region in HD 37124 that is stable for massless test particles lies roughly between 0.9 and 1.1 AU, with eccentricities between 0 and 0.2. Paper II showed that the likelihood of a Saturn-mass planet surviving in this region of parameter space for 100 Myr is roughly 50%, with a maximum in survival rate between 0.9 and 1.2 AU at $e \sim 0.1$.

In 12 early-migration simulations in HD 37124, almost all embryos were ejected, and no terrestrial planets formed. However, in seven cases, a solitary embryo survived to the end of the simulation. All such embryos had final semimajor axes 0.9 AU < a < 1.1 AU and eccentricities $0.1 < e < 0.22$. In addition, in each case the surviving embryo appears to be in apsidal libration

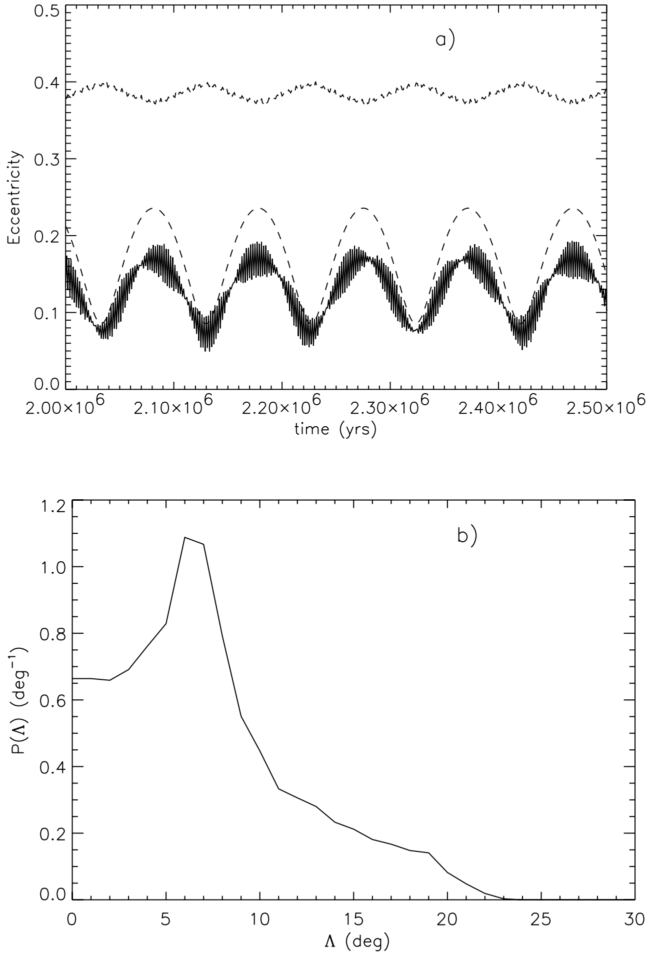

FIG. 6.—*a*: Eccentricity evolution of the two giant planets (*dashed lines*) and one remaining planetary embryo (*solid line*) with a semimajor axis of 0.95 AU in a simulation of HD 37124. The period of the giant planets' eccentricity variations is 96 kyr. *b*: Distribution function, $P(\Lambda)$, of the same embryo as a function of Λ, the normalized difference between their longitude of pericenter and that of the inner planet, as in Fig. 5. The embryo is in apsidal libration with the inner giant planet. The shape of the $P(\Lambda)$ curve, similar to that of a harmonic oscillator, indicates that the longitude of pericenter of the embryo's orbit is librating with respect to the giant planet's orbit.

with the inner giant planet. Figure 6*a* shows the eccentricity evolution of a remaining embryo with $a = 0.95$ AU, which is following the eccentricity of the inner planet closely, with superposed higher order fluctuations. The periods of the eccentricity variations of the giant planets are both 96 kyr. The apsidal nodes of the giant planets are librating with an amplitude of 31°. The remaining embryo is in apsidal libration with both giant planets, but more strongly with the inner planet. Figure 6*b* shows the distribution function of Λ, the difference between the longitude of pericenter of the embryo and that of the inner planet, as in Figure 5. The sharp peak at $\Lambda \simeq 6°$ indicates that the embryo's longitude of pericenter is librating about that of the inner giant planet. This is not unexpected, given the results of Paper II, in which we showed that apsidal libration in HD 37124 plays an important role in the stability of Saturn-mass planets.

We performed two additional higher resolution simulations in this system to verify these results. We placed 100 embryos of mass 0.005 $M_\oplus$ between 0.9 and 1.1 AU and integrated the system for 100 Myr. In one case, no embryos survived to the end of the integration. In the other, one embryo survived, again in apsidal libration with the inner giant planet. This embryo accreted one other embryo and had a final mass of 0.01 $M_\oplus$, roughly that of the Moon. This indicates that in situ formation of terrestrial planets in this system is unlikely.

3.4. *HD 74156*

Paper I found a very limited stable region for massless test particles in HD 74156. In Paper II, we showed that roughly 40% of Saturn-mass planets are stable for 0.5 AU $< a <$ 1.5 AU, with a broad peak in survival rate at 0.9 AU $< a <$ 1.4 AU.

As in HD 37124, no terrestrial planets formed in any of the 10 simulations of this system, as the vast majority of embryos were ejected. In six cases, one embryo survived until the end of the simulation, with final orbital elements 0.8 AU $< a <$ 1.5 AU and $0.09 < e < 0.17$, consistent with Paper II.

We again performed two additional simulations with 100 embryos of 0.02 $M_\oplus$ each, spaced randomly between 0.5 and 1.5 AU. In one case one embryo remained after 100 Myr, and in the other, two were left. In neither case had any surviving terrestrial body accreted another embryo. In each case, the final orbital parameters were similar to the survivors in the early-migration simulations, indicating that in situ formation of terrestrial planets in HD 74156 is unlikely.

4. DISCUSSION AND CONCLUSIONS

Our simulations show that certain systems of giant planets are conducive to the formation of terrestrial planets, while others are likely to contain belts of debris or asteroids, and some are not likely to contain any rocky bodies. Our systems of giant planets are drawn from observations, although we have made the important assumption that these systems are complete and have well-determined orbits. We have used slightly outdated orbital parameters in order to remain consistent with previous work (specifically Papers I and II). If, for example, new values of sin *i* were determined for 55 Cnc and HD 38529, it would narrow the stable zones for additional planets and affect the region in which terrestrial planets could form.

Our "early-migration" simulations follow the reasoning of Raymond et al. (2005a), who argue that if giant planets form and migrate in less than ~1 Myr, then terrestrial planets may form via accretion in the standard way from a second generation of planetesimals (Armitage 2003). Our simulations therefore start with the gas giant planets already present, although their formation mechanism is unknown, be it core accretion (e.g., Rice & Armitage 2003) or gravitational collapse (e.g., Mayer et al. 2002). In either scenario, it is likely that the giant planets formed farther out in the disk and migrated inward via interactions with the gaseous disk (e.g., Lin et al. 1996).

If giant planet migration occurred late in the evolution of protoplanetary disks, then the planetesimal disk would be severely depleted (Armitage 2003), and it is unlikely that habitable planets could form in any of the systems studied here. The largest mass of planets that form in our "late-migration" simulations is below the predicted lower limits of 0.2–0.3 $M_\oplus$ for a "tectonic" habitable planet (Williams et al. 1997; Raymond et al. 2006b). Late or slow migration could potentially deplete the disk by an order of magnitude more than we have simulated. Since planet mass scales roughly linearly with surface density (Wetherill 1996; Kokubo et al. 2006), these very low mass disks are not capable of forming planets much more massive than the Moon.

Our simulations of 55 Cnc suggest that a potentially habitable planet could form in situ. Such a planet would have a small enough eccentricity to remain in the habitable zone throughout its orbit, and substantial mass and water content. However, as shown in Paper II, a Saturn-mass planet could exist on a stable orbit in the habitable zone of 55 Cnc. Such a planet may preclude the existence of habitable planet, although there remains the possibility of a habitable satellite of the giant planet (Williams et al. 1997).

The systems of terrestrial planets formed in 55 Cnc (and to a lesser extent in HD 38529) do not resemble planets formed in previous dynamical simulations (e.g., Agnor et al. 1999; Chambers 2001; Raymond et al. 2004, 2005a, 2005b, 2006a). Indeed, previous simulations tended to include systems of giant planets similar to Jupiter and Saturn, with relatively low eccentricities. The large masses and higher eccentricities of planets in 55 Cnc and HD 38529 increase the perturbations felt by embryos, causing a much higher rate of dynamical ejection than in previous simulations. The zones in which accretion can occur correspond roughly to the stable zones from Papers I and II, and are much narrower than for systems with only an inside or an outside giant planet. Thus, planets that form in 55 Cnc and HD 38529 are significantly smaller than in previous simulations for the same mass disk. In addition, the distribution of planet masses tends to peak near the center of the stable regions from Papers I and II . Strong perturbations mark the boundaries of the stable regions, so embryos that stray from the edges are quickly ejected.

The case of HD 38529 is an interesting one. Several terrestrial bodies survive in our simulations of HD 38529, but do not accrete into large planets. Despite strong giant planet perturbations, growing terrestrial planets do not reach high enough eccentricities to widen their feeding zones sufficiently to form Earth-sized planets. This is most likely because the stable region from Papers I and II extends only to eccentricities of 0.15 (0.3 in some areas). Thus, planets that reach these high eccentricities are ejected rather than accreting into large terrestrial planets. We therefore speculate that a well-populated asteroid belt may exist in HD 38529, potentially including several Mars-sized planets, but no Earth-sized planets.

Paper II found a wide zone ($0.3 < a < 0.8$, $e < 0.15$) in HD 38529 that is stable for Saturn- or even Jupiter-mass planets. Observations have ruled out the existence of such a massive planet, but not of a ~Neptune-mass planet. However, it appears unlikely that accretion could form a large planet in situ. How do we reconcile this with the PPS hypothesis? There certainly exists the possibility that a massive planet co-migrated with the inner giant planet, settling into the stable region (e.g., Thommes 2005). Indeed, PPS predicts that such a large contiguous stable region *must* contain a planet with significant mass.

This is the third paper of the Predicting Planets series. We have conducted tests of dynamical stability and accretion in four systems of known extrasolar giant planets, HD 37124, HD 38529, HD 74156, and 55 Cnc. We have searched for regions in which the orbits of massless test particles are stable for millions of years (Paper I), which may correspond to stable Earth-mass planets. We have self-consistently tested for regions that are stable for Saturn-mass test particles (Paper II). In this paper, we have demonstrated that terrestrial planets may be able to form by accretion in one of these systems, 55 Cnc.

This series of papers has laid the foundation, along with Barnes & Quinn (2004), for the PPS hypothesis. These papers have clarified the conditions necessary for this hypothesis to be (dis)proven. We have also seen that some systems that initially appeared to contain stable regions, such as HD 168443, which was shown in Barnes & Quinn (2004) to lie far from instability, are in fact packed (Paper I; to be packed to the point that test particles cannot survive for even 10^6 yr). We have also shown that two formation avenues exist for a PPS system, simultaneous or episodic. Comparing Paper II to this work, we see that the only possibility for HD 37124 and HD 74156 to satisfy the PPS hypothesis is for an undetected giant planet to form coevally with the known planets. However, in 55 Cnc and HD 38529, additional planets could have formed and evolved together with the known planets, or possibly formed *after* a quick migratory epoch. In its current nascent state, the PPS hypothesis cannot distinguish between these two formation events. If planets are found where we predict them to be in the 55 Cnc or HD 38529 systems, then nothing can be said about their formation. Should they be found in HD 37124 or HD 74156, then only coeval formation is possible.

It remains to be seen whether the predicted planets exist. We do not predict that stable regions will contain so much mass as to be borderline unstable. Rather, we suggest that any region in a planetary system that can support a massive planet will contain a planet. Future observations of these well-studied planetary systems will test the credence of the PPS hypothesis.

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[7] CONDOR is publicly available at http://www.cs.wisc.edu/condor.

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