PREDICTING PLANETS IN KNOWN EXTRA-SOLAR PLANETARY SYSTEMS II: TESTING FOR SATURN-MASS PLANETS

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ABSTRACT

Recent results have shown that many of the known extrasolar planetary systems contain regions which are stable for massless test particles. We examine the possibility that Saturn-mass planets exist in these systems, just below the detection threshold, and attempt to predict likely orbital parameters for such unseen planets. To do this, we insert a Saturn-mass planet into the stable regions of these systems and integrate its orbit for 100 million years. We conduct 200-600 of these experiments to test parameter space in HD37124, HD38529, 55Cnc, and HD74156. In HD37124 the global maximum of the survival rate of Saturns in parameter space is at semimajor axis \(a = 1.03\) AU, eccentricity \(e \sim 0.1\). In HD38529, only 5\% of Saturns are unstable, and the region in which a Saturn could survive is very broad, centered on \(0.5 < a < 0.6\), \(e < 0.2\). In 55Cnc we find three maxima at \((1.0\text{ AU}, 0.02), (2.0\text{ AU}, 0.08),\) and \((3.0\text{ AU}, 0.17)\). In HD74156 we find a broad maximum with \(a = 0.9-1.2\) AU, \(e \leq 0.15\). Several of these maxima are located in the habitable zones of their parent stars and are therefore of astrobiological interest. We suggest the possibility that companions may lie in these locations of parameter space, and encourage further observational investigation of these systems.

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

1. INTRODUCTION

There are currently 110 known extrasolar planets, including ten systems containing two or more planets. These planets are known to be Jovian both from their large masses, which range from 0.11 Jupiter masses (HD49674; Butler et al. 2003) to 17.5 Jupiter masses (HD202206; Udry et al. 2002), and from their sizes, measured in HD209458 to be 1.27 Jupiter radii (Charbonneau et al. 2000). The vast majority of these planets were discovered by the radial velocity technique, which is very efficient at finding massive planets. All planetary systems must be dynamically stable for at least the age of their host star. Recent work by Barnes & Quinn (2004) suggests that a large fraction of systems are on the edge of stability: a small change in semimajor axis \(a\) or eccentricity \(e\) causes the system to become unstable. The “packed planetary systems” (PPS) hypothesis presented in Barnes & Raymond (2004; hereafter Paper 1) predicts that all planetary systems are “on the edge.” This leads to speculation that those systems which appear stable may harbor unseen planets which push them to the edge of stability. The PPS hypothesis suggests that if a region exists in a planetary system in which the orbit of a massive planet is stable, then its presence is likely.

The first paper of this series (Paper 1) used integrations of massless test particles to map the stability of regions in certain extrasolar planetary systems in \((a, e)\) space. Of the five systems examined, three (HD37124, HD38529, and 55Cnc) were found to contain zones between the giant planets in which test particles were dynamically stable for 5-10 Myr. Stable regions have been found in \(a\) space (assuming circular orbits) for \(v\) And (Rivera & Lissauer 2000), GJ876 (Rivera & Lissauer 2001) and 55Cnc (Rivera & Haghhipour 2003).

In this work we test for the presence of unseen Saturn-mass planets in four known extrasolar planetary systems: HD37124 (Butler et al. 2003), HD38539 (Fischer et al. 2003), 55Cnc (Marcy et al. 2002), and HD74156 (Naef et al. 2004). We choose Saturn-mass planets because they lie roughly at the detection threshold for the current radial velocity surveys (Butler et al. 1996). The reflex velocity caused by a Saturn-mass planet at 1 AU on a solar-mass star is 8.5 \(m s^{-1}\), and scales with the planet’s semimajor axis as \(a^{-1/2}\). For comparison, the smallest amplitude reflex velocity of any detected planet is 11 \(m s^{-1}\) (HD1641; Marcy et al. 2000). Although seven sub-Saturn mass planets have been discovered as of November 2003 (e.g. Fischer et al. 2003), none has \(a > 0.35\) AU.\textsuperscript{2}

Paper 1 found that no test particles survived in HD74156 for longer than a few Myr. However, Dvorak et al. (2003) found orbits stable for test particles between 0.9 and 1.4 AU. We therefore include HD74156 in our sample.

Table 1 shows the orbital parameters for the four extrasolar planetary systems we investigate. Note that the best fit orbital elements for some systems, especially HD74156c, have changed many times. We therefore adopt elements as of a given date, with the knowledge that they may fluctuate. In \$2\textsuperscript{e} we describe our initial conditions and numerical method. We present the results for each planetary system in \$3, and compare these with other work in \$4. We present our conclusions in \$5.

2. NUMERICAL METHOD

For each planetary system in Table 1, 200 to 600 values of \(a\) and \(e\) are selected at random from within the regions which are stable for test particles, shown in Table 2. In the case of HD74156, which has no stable region, we drew values from the following region: \(\Delta a = 0.5-1.5\text{ AU}, \Delta e = 0.0-0.2\). For each of these \((a, e)\) points we assign the new planet one Saturn mass, an inclination of 0.1\(^\circ\), and a randomly chosen mean anomaly. The longitude of periastron is aligned with the most massive giant planet in the system. This assumption helps find more stable systems, as most of the known planetary systems with ratios of orbital periods less than 5:1 are found to be librating about a common longitude of periastron (Ji et al. 2003, and references

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2Data from http://www.exoplanets.org
3. RESULTS

We present the results for three systems which were shown in Paper 1 to contain zones which are stable for massless test particles for at least 5-10 Myr. In addition, we examine the system HD37124 which did not contain such a stable zone. In Table 2, we present the initial conditions for the simulations of each system, including the parameter space sampled and the number of Saturn-mass planet experiments. Table 3 summarizes our results.

3.1. HD37124

This system has an interesting resonant structure. The ratio of the periods of the two known giant planets is 12.7, making it by far the most compact of our candidate systems. Three mean-motion resonances with the inner planet lie near the sampled region of parameter space – the 2:1 (0.86 AU), 3:1 (1.12 AU), and 5:2 (0.995 AU). The 5:2 resonance bisects the sampled region and has important consequences for the survival rate of test planets, as shown below.

Paper 1 showed that test particles are stable in HD37124 for semimajor axes between 0.9 and 1.1 AU, with eccentricities between 0 and 0.25. We integrated the orbits of 472 Saturn-mass planets in this system, 290 (61%) of which survived for 100 Myr. Figure 1 shows the distribution in \((a, e)\) space of the Satums, in which solid dots represent planets which survived and crosses represent unstable configurations.

Figure 2 shows the survival rate of Saturn-mass planets as a function of semimajor axis including Poisson error bars. Note the strong decline in survival rate at the 2:5 mean motion resonance with the inner planet (located at 0.995 AU), and the peaks in survival rate immediately interior and exterior. There is a smaller peak at \(a \approx 0.90\) AU. We saw no strong dependence of the survival rate on mean anomaly in the resonance. The peaks on either side of the resonance are reminiscent of Jupiter and Saturn in our solar system, which lie slightly out of perfect 5:2 resonance, and whose orbits are stable.

Figure 3 shows the data averaged into bins in both \(a\) and \(e\) such that each bin contains roughly 25 points. The shade of each square represents the fraction of planets in that bin which survived, and has a Poisson error of 20%. Over-plotted are contours of constant survival rate, also spaced by 20%, to show the underlying distribution and the location of maxima. The outer edge of the system’s habitable zone is marked by the black dashed line. Three local maxima are evident in the Figure: 1) \(a \approx 0.92\) AU, \(e \approx 0.12\), 2) \(a \approx 1.02\) AU, \(e \approx 0.1\), and 3) the absolute maximum at \(a \approx 0.98\) AU, \(e \approx 0.07\). Each of these maxima is located in the habitable zone of the system, although maximum 2 is at the outer edge.

In the absence of a test planet, the longitudes of periastron of the inner and outer giant planet librate about each other with an amplitude of roughly 31° and a precession period of 171 kyr. With the insertion of a Saturn-mass test planet, we find evidence for secular resonances in various configurations of test planets. Fig. 4 shows the time evolution of the longitudes of periastron of each planet in two cases. The initial orbital elements for the test planet in these systems were \((a, e) = (0.90\ AU, 0.11)\) (top panel) and \((1.01\ AU, 0.08)\) (bottom panel). The top panel shows a system in which the Saturn-mass test planet is in a strong secular resonance with the inner giant planet, as the orientation of the two planets’ orbits are tracking each other with time. The bottom panel shows a case in which the test planet’s longitude of periastron is librating about that of the outer giant planet. At the same time, the test planet’s orbit tracks that of the inner giant planet for over half of its precession cycle of \(\sim 7.5\ kyr\) (e.g. 231 to 237 kyr). An additional, 1.5 kyr oscillation is superimposed on the evolution of the test planet. The secular dynamics of the test planet in this case are affected by both giant planets in a complex way, yet the system is stable. We expect simple systems in secular resonance to be stable because of the avoidance of close approaches between planets. The presence of the Saturn-mass test planets makes an analytical treatment of the secular resonance structure of the system beyond the scope of this paper. Note in Fig. 4 that the precession rates of both the inner and outer giant planets are different in the top and bottom panels, due to the different locations of the test planet.

3.2. HD38529

The resonant structure of HD38529 is quite different from that of HD37124, as the separation between the two known planets is much larger. The stable region for test particles lies between 0.27 and 0.82 AU, with eccentricities up to 0.3. The inner edge is cut off by the 1:3 resonance with the inner planet. We see no evidence of secular resonances playing a significant role in the dynamics.

We integrated the orbits of 200 Satums in this system, of which 191 (95.5%) survived for 100 Myr. Figure 5 shows the data binned and over-plotted with contours as in Fig. 3. The only unstable regions in this system lie at small semimajor axes and high eccentricities. The vast majority of the zone which is stable for massless test particles is also stable for Saturn-mass planets. It is therefore difficult to dynamically constrain the location of such a planet beyond the results of Paper 1, although its orbit would likely be stable in the given region.

3.3. 55 Cnc

This system is interesting dynamically, as it is composed of an interior pair of planets in 3:1 mean motion resonance with a distant, separated companion. Paper 1 showed that there exists a large region between the inner pair and the outer planet which is stable for test particles, at 0.7 AU < \(a\) < 3.4 AU, with eccentricities up to 0.2. This stable region is bounded at its inner edge by the 1:5 resonance with the inner planet at 0.72 AU, and at its outer edge by the 5:2 resonance with the outer planet at 3.2 AU. Several mean motion resonances with the outer planet are located in the stable region, notably the 3:1 resonance at 2.84 AU, the 4:1 resonance at 2.34 AU, and the 5:1 resonance at 2.02 AU.

We integrated the orbits of Satums in 512 locations within this zone, and 384 (75%) of these survived for 100 Myr. Figure 6 shows the distribution in \((a, e)\) space of our experiments, in the same format as Figs. 3 and 5, with Poisson errors of \(\sim\)
We see three local maxima: 1) a relatively narrow maximum at \( a \approx 1.0 \) AU, \( e \approx 0.03 \), 2) a broad maximum centered roughly at \( a \approx 2.0 \) AU, \( e \approx 0.08 \) but which extends to higher values of \( a \), and 3) \( a \approx 3 \) AU, \( e \approx 0.17 \). Region 1 is of great astrobiological interest, as it lies in the habitable zone of its parent star, which is bounded by the black dashed lines. Region 3 is bordered by the 3:1 (2.84 AU) and 5:2 (3.2 AU) mean motion resonances with the outer planet. We see no clear trend of survival rate with mean anomaly near these resonances.

### 3.4. HD74156

Paper I found that no test particles survived in this system for longer than 1 Myr. The region in which they survived the longest was for \( a \) between 0.5 and 1.5 AU at relatively low eccentricities. The 1:5 mean motion resonance (with the inner planet) is at 0.82 AU and the 5:1 resonance (with the outer planet) at 1.3 AU are located at the outskirts of the region we investigate. Therefore, only very high order mean motion resonances are found in the center. We find no evidence of secular resonances in the region.

We performed 600 integrations of Saturn-mass planets in this system with \( a \) in the above mentioned region, and \( e \) between 0 and 0.2. Of these 600 Satums, 296 (49%) survived for 100 Myr. Figure 7 shows the distribution of the surviving planets in these simulations. We see three small islands of stability at \((a,e) \approx \): 1) \((1.0 \text{ AU}, 0.02)\), 2) \((1.0 \text{ AU}, 0.1)\), and 3) \((1.2 \text{ AU}, 0.13)\). These three islands lie at a slightly higher survival rate than the surrounding, larger region of stability between 0.9 - 1.2 AU with \( e \leq 0.15 \), in which the survival rate is 75%.

We see a strong trend in the survival rate of planets as a function of semimajor axis, as shown in Fig. 8. The fraction of systems which are stable for 100 Myr increases sharply between 0.8 and 1.0 AU, then flattens off and decreases slightly past 1.2 AU. The stable zones found in Fig. 7 lie at the peak of the curve.

### 4. DISCUSSION

Menou & Tabachnik (2003; hereafter MT) investigated the possibility of Earth-sized planets residing in the habitable zones (HZs) of known extrasolar planetary systems. The location of the HZ is a function of the luminosity (and therefore mass) of the host star, as well as the atmospheric composition of the planet (Kasting et al. 1993). For each system MT integrated the orbits of 100 massless test particles in the HZ for 10^6 years. They considered all four of our systems. The HZs for each system are as follows – HD37124: 0.6-1.2 AU, HD38529: 1.4-3 AU, HD74156: 0.6-1.2 AU, and 55Cnc: 0.7-1.3 AU. MT found no surviving planets in the HZ of HD37124. Their stability criterion requires a particle to remain in the HZ at all times, limiting its eccentricity such that the particle’s aphelion and perihelion remain in the HZ. Paper I used over 500 test particles to systematically map out the region in HD37124 which is stable for test particles, finding it to be centered at 1 AU. The eccentricities in this stable region are small enough to keep test particles in the HZ of the system throughout their orbits. In addition, we find three local maxima of the survival rate Saturn-mass planets in this system, all of whose orbits remain in the HZ.

For HD38529 our results are consistent with MT, as the stable region from Paper I lies well outside the HZ, and the region we investigated with Saturns does not overlap with the HZ. In the case of 55Cnc our results are again consistent with MT, who find that a significant fraction of low-inclination test particles survive at 1.0 AU, with eccentricities centered on 0.09. The stable region for 55Cnc from Paper I encompasses the HZ entirely for eccentricities below 0.25. In addition, Table 3 shows a maximum in the survival rate of Saturns at \((a,e) = (1.0 \text{ AU}, 0.03)\), very close to the value from MT. MT’s results for HD74156 are consistent with Paper I, but we have found two regions in the HZ which are stable for Saturn-mass planets in 83% of cases. However, this may be due to the fact that the orbital elements used by MT are different than those we have used here. In particular, the semimajor axis of the outer planet used here is 0.35 AU larger (3.82 AU vs 3.47 AU), increasing the separation of the two giant planets and therefore possibly causing the region in between to become more stable for an additional companion. Note that the current value for HD74156c is 3.40 AU (Naef et al. 2004).

Dvorak et al. (2003) investigated the possibility of an unseen planet in HD74156, using both test particles and massive ones. They find a broad, relatively stable region for test particles between 0.9 and 1.4 AU, with the most stable location being at \( a = 1.25 \text{ AU} \) and \( e < 0.2 \). This is a region in which Paper I found no stable test particle orbits. Fig. 8 shows a plateau in survivability between 1.0 and 1.25 AU. Dvorak et al. (2003) found no trend in the results of their simulations of massive planets, and concluded that the presence of an unseen companion in the system was unlikely. Further observations will shed light on this issue, although the 75% survival rate of Saturns for the entire region with 0.9 AU < \( a < 1.2 \) AU, \( e \leq 0.15 \) suggests that this is a real possibility. Note again that the best-fit orbit of the outer planet in this system has recently been revised to \( a = 3.40 \text{ AU}, e = 0.58 \) (Naef et al. 2004). The closer proximity and higher eccentricity of this planet strongly affects the dynamics between the two known planets. Both Dvorak et al. (2003) and Paper I assume the orbital elements from Table 1 in their calculations.

### 5. CONCLUSIONS

We have found specific locations in four known extrasolar planetary systems in which Saturn-mass planets could exist on stable orbits. Such a planet would lie just below the detection threshold of current radial velocity surveys, and may be detected in the near future. Table 3 summarizes our results, detailing the location in \((a,e)\) space of each maximum in the survival rate for each of our four candidate systems. If an additional planet is discovered in the stable region of one of these systems, it would mark the first successful prediction of a planet since John Couch Adams predicted the existence of Neptune in 1845 based on perturbations to Uranus’ orbit.

Does the presence of a stable region imply the presence of a planet? Must all systems contain as many planets as they can? Laskar (1996) speculated that “a planetary system will always be in this state of marginal stability, as a result of its gravitational interactions.” The “packed planetary systems” (PPS) hypothesis, presented in Paper I (see also Barnes & Quinn, 2004), extends this idea by suggesting that all systems contain as many planets as they can dynamically support without self-disrupting. All systems may be on the edge of stability, but observational constraints prevent the detection of smaller or more distant bodies which push apparently stable systems to this edge.

The formation scenario of a planet of any size in between two gas giant planets is of great interest. In the Solar System no stable regions exist between the orbits of the gas giants. The detailed formation scenario of a smaller giant planet between two others is unclear, be it through gravitational instability (e.g. Mayer et al. 2002) or core-accretion (Pollack et al. 1996). Gas giant planets at small orbital radii may have formed farther out.
in the protoplanetary disk and migrated inward, which further complicates this formation scenario.

Certain stable regions in HD37124, 55Cnc and HD74156 are located in the habitable zones of their parent stars (see Table 3). Clearly, the discovery of a planet of any size in these regions is of great astrobiological importance, as any giant planet would likely have one or more large moons. Understanding the formation of terrestrial planets in these systems is vital. In the upcoming third paper of the “predicting planets” series (Raymond & Barnes 2004) we present results of simulations of terrestrial planet formation in between the known giant planets in the same four systems examined here.

6. ACKNOWLEDGMENTS

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Rivera & Haghighipour 2003, Scientific Frontiers in Research on Extrasolar Planets, ASP Conference Series, 294, 205

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

Fig. 1.— The distribution in (a, e) space of 472 Saturn-mass planets in HD37124. Solid dots represent systems which were stable for 100 Myr, and crosses represent unstable configurations.
Fig. 2.— The survival rate of Saturn-mass planets in HD37124 as a function of semimajor axis, with Poisson error bars. Note the strong instability at the 2:5 mean motion resonance, and the stable regions immediately interior and exterior.

Fig. 3.— The data for HD37124 from Fig. 1, binned on the $a$ and $e$ axes. The shade of each bin represents the fraction of planets in that bin which survived for 100 Myr, with Poisson error of roughly 20%. Contours of constant survival rate are over-plotted to bring out structure, spaced by 20%. The black dashed line is the outer edge of the system’s habitable zone. Note the three local maxima, including one on either side of the 2:5 resonance at 0.995 AU.
FIG. 4.— Evolution of the orientation of orbits (measured by the longitude of periastron) for two test systems of HD37124. The orbital elements of the Saturn-mass test planets are \((a, e) = (0.90\ \text{AU}, 0.11)\) (top) and \((1.01\ \text{AU}, 0.08)\) (bottom). Both systems were stable for 100 Myr.

<table>
<thead>
<tr>
<th>System</th>
<th>Planet</th>
<th>(M (M_J))</th>
<th>(a) (AU)</th>
<th>(e)</th>
<th>(\omega)</th>
<th>(T) (JD)</th>
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<tr>
<td>HD37124</td>
<td>b</td>
<td>0.86</td>
<td>0.54</td>
<td>0.1</td>
<td>97.0</td>
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<td></td>
<td>c</td>
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<td>2.95</td>
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<td>b</td>
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<td></td>
<td>c</td>
<td>12.8</td>
<td>3.68</td>
<td>0.36</td>
<td>14.7</td>
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<td>55Cnc</td>
<td>b</td>
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<td>0.115</td>
<td>0.02</td>
<td>99.0</td>
<td>2450001.479</td>
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<tr>
<td></td>
<td>c</td>
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<td>0.339</td>
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<tr>
<td></td>
<td>d</td>
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<td>5.9</td>
<td>0.16</td>
<td>201.0</td>
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<tr>
<td>HD74156(^1)</td>
<td>b</td>
<td>1.61</td>
<td>0.28</td>
<td>0.647</td>
<td>185.0</td>
<td>2451981.38</td>
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<tr>
<td></td>
<td>c</td>
<td>8.21</td>
<td>3.82</td>
<td>0.354</td>
<td>272.0</td>
<td>2451012.0</td>
</tr>
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</table>

\(^1\)Best fit values as of August 22, 2002. The current best fit for planet \(c\) is \(a = 3.40\ \text{AU}, e = 0.58\) (Naef et al. 2003).
FIG. 5.—Binned data from 200 simulations of Saturns in HD38529 with contours of constant survival rate over-plotted, as in Fig. 3. Contours of constant survival rate are spaced by 25%. The only unstable systems lie at low $a$ and high $e$.

FIG. 6.—Binned data from 512 simulations of Saturns in 55Cnc, with contours of constant survival rate spaced by 20%. The black dashed lines indicate the boundaries of the system’s habitable zone. Note the maxima at $(a, e) \approx (1.03 \text{ AU}, 0.03), (2.0 \text{ AU}, 0.08)$, and $(3.0 \text{ AU}, 0.17)$. 
Fig. 7.— Binned data from 600 simulations of Saturns in HD74156, formatted as in Fig. 3, with contours of constant survival rate spaced by 20%. The dashed lines indicate the boundaries of the system’s habitable zone. The absolute maximum is located at \((a, e) ≃ (1.0 \text{ AU}, 0.02)\) and two local maximum are at \((1.0 \text{ AU}, 0.10)\) and \((1.2 \text{ AU}, 0.13)\).

Fig. 8.— Survival rate of Saturns in HD74156 as a function of semimajor axis, with statistical error bars. Note the strong increase toward 1 AU and the plateau between 1.0 and 1.3 AU.
Table 2
Initial Conditions for Simulations

<table>
<thead>
<tr>
<th>System</th>
<th>$\Delta a$ (AU)</th>
<th>$\Delta e$</th>
<th>N (Saturns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD37124</td>
<td>0.9 – 1.1</td>
<td>0.0 – 0.2</td>
<td>472</td>
</tr>
<tr>
<td>HD38529</td>
<td>0.27 – 0.82</td>
<td>0.0 – 0.3</td>
<td>200</td>
</tr>
<tr>
<td>55Cnc</td>
<td>0.7 – 3.2</td>
<td>0.0 – 0.2</td>
<td>512</td>
</tr>
<tr>
<td>HD74156</td>
<td>1.0</td>
<td>0.5 – 1.5</td>
<td>600</td>
</tr>
</tbody>
</table>

1 Paper 1 found that no test particles in HD74156 survived for longer than 1 Myr. In our simulations, however, we sample the given region of parameter space.

Table 3
Simulation Results

<table>
<thead>
<tr>
<th>System</th>
<th>Stable Region ($a,e$)</th>
<th>Survival Rate$^2$</th>
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<tr>
<td>HD37124</td>
<td>(0.92 AU, 0.12)$^*$</td>
<td>81%</td>
</tr>
<tr>
<td></td>
<td>(0.98 AU, 0.07)$^*$</td>
<td>87%</td>
</tr>
<tr>
<td></td>
<td>(1.02 AU, 0.13)$^*$</td>
<td>84%</td>
</tr>
<tr>
<td>HD38529</td>
<td>(0.3 – 0.8 AU, 0.0 – 0.15)</td>
<td>100%</td>
</tr>
<tr>
<td>55Cnc</td>
<td>(1.0 AU, 0.03)$^*$</td>
<td>93%</td>
</tr>
<tr>
<td></td>
<td>(2.0 AU, 0.08)</td>
<td>89%</td>
</tr>
<tr>
<td></td>
<td>(3.0 AU, 0.17)</td>
<td>96%</td>
</tr>
<tr>
<td>HD74156</td>
<td>(1.0 AU, 0.02)$^*$</td>
<td>83%</td>
</tr>
<tr>
<td></td>
<td>(1.0 AU, 0.10)$^*$</td>
<td>83%</td>
</tr>
<tr>
<td></td>
<td>(1.2 AU, 0.13)</td>
<td>86%</td>
</tr>
</tbody>
</table>

1 Local maxima of the survival rate, i.e. the center of each bin from Figs 3, 5, 6, and 7 in which the survival rate is a maximum. The exact location of the stable region is uncertain on the order of the bin size.

2 Survival Rate for all simulations in the binned region in which the stable region is located. See Figs 3, 5, 6, and 7.

$^*$ Stable regions which lie in the habitable zone of their parent stars, as defined by Kasting et al. (1993).