STABILITY OF ADDITIONAL PLANETS IN AND AROUND THE HABITABLE ZONE OF THE HD 47186 PLANETARY SYSTEM

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ABSTRACT

We study the dynamical stability of an additional, potentially habitable planet in the HD 47186 planetary system. Two planets are currently known in this system: a "hot Neptune" with a period of 4.08 days and a Saturn-mass planet with a period of 3.7 years. Here we consider the possibility that one or more undetected planets exist between the two known planets and possibly within the habitable zone (HZ) in this system. Given the relatively low masses of the known planets, additional planets could have masses $\lesssim 10\,M_\oplus$, and hence be terrestrial-like and further improving potential habitability. We perform N-body simulations to identify the stable zone between planets b and c and find that much of the inner HZ can harbor a $10\,M_\oplus$ planet. With the current radial velocity threshold of ~ 1 m s^{-1}, an additional planet should be detectable if it lies at the inner edge of the habitable zone at 0.8 AU. We also show that the stable zone could contain two additional planets of $10\,M_\oplus$ each if their eccentricities are lower than $\sim$0.3.

Key words: methods: N-body simulations – planetary systems

1. INTRODUCTION

Recent advances have brought the astronomical community to the verge of discovering a terrestrial planet in the habitable zone (HZ) of its parent star. Classically, the HZ is defined as the range of orbits for which a terrestrial mass planet ($0.3 \lesssim M \lesssim 10\,M_\oplus$), with favorable atmospheric conditions, can sustain liquid water on its surface (Kasting et al. 1993; Selsis et al. 2007). Many giant planets have been discovered in the HZ, and low-mass planets have been found very close to the HZ (see Udry et al. 2007; Selsis et al. 2007; von Bloh et al. 2007, for example), but no serious candidates for habitability have been found.

Recently Bouchy et al. (2008) used the HARPS spectrograph (Mayor et al. 2003) to detect two planets around the nearby star HD 47186: a hot Neptune (HD 47186 b; $22.78\,M_\oplus$) with an orbital period of 4.08 days and a Saturn-mass planet (HD 47186 c; $0.35 M_{\rm Jup}$) with a period of 3.7 years. The orbital elements for this system are given in Table 1. A curious characteristic of the host star HD 47186 is that its mass and luminosity are very similar to our own Sun, albeit with higher metallicity (Table 1 of Bouchy et al. (2008)). Therefore, the HZ of this system may be similar to our own solar system's, and hence lies between the two known planets. Bouchy et al. (2008) found that the combined radial velocity (RV) amplitude for this system is 4.30 m s^{-1} with 0.91 m s^{-1} residuals and reduced $\chi^2 = 2.25$. So potentially habitable planets may lie at or below the current RV detection threshold but may be discovered by further observations. Here we perform N-body simulations to assess the stability of additional hypothetical planets within the HZ of HD 47186. The relatively small masses of the two known planets suggest that an additional planet would likely also have low mass. Masses less than $10\,M_\oplus$ are often considered the upper limit for terrestrial-like planets (Pollack et al. 1996; Bodenheimer et al. 2000; Hubickyj et al. 2005), hence an additional planet in the HZ of this system might have a mass conducive to habitability.

As of 2009 February 27, 290 extrasolar planetary systems are known including 37 multiplanet systems.[5] Barnes & Quinn (2004) found that many multiplanet systems tend to be close to the edge of stability such that slight perturbations to the system would result in destabilization (Barnes & Quinn 2001; Goździewski et al. 2001; Goździewski & Maciejewski 2001; Erdi et al. 2004). This observation led to the "Packed Planetary Systems" (PPS) hypothesis (Barnes & Raymond 2004; Raymond & Barnes 2005; Raymond et al. 2006; Barnes & Greenberg 2007; see also Laskar 1996) which postulates that if a region of stability is available in between two known planets, then that region will harbor an unseen planet (in other words, planetary systems tend to be "packed," with no large gaps between planets). To constrain the location of additional planets, a large number of studies have mapped out stable zones in known extrasolar planetary systems, mainly using massless test particles (e.g., Rivera & Lissauer 2000; Jones et al. 2001; Menou & Tabachnik 2003; Dvorak et al. 2003; Barnes & Raymond 2004). Recently, Bean et al. (2008) reported the discovery of a Saturn-mass planet in the narrow, well characterized stable zone of HD 74156 (Barnes & Raymond 2004; Raymond & Barnes 2005). This constituted the first prediction of the orbit and mass of an extrasolar planet (Barnes et al. 2008a).[6]

The PPS model was further developed by the identification of an analytic stability boundary in two-planet systems (Barnes & Greenberg 2006, 2007). The boundary lies where the ratio of two quantities, $\beta/\beta_{\rm crit}$, approximately equals unity. Here β depends on the total angular momentum and energy of the system and $\beta_{\rm crit}$ depends only on the masses (Marchal & Bozis 1982; Gladman 1993). If $\beta/\beta_{\rm crit} \gtrsim 1$ (and no resonances are present), then the system is stable. Moreover, Barnes et al. (2008a) found that systems tend to be packed if $\beta/\beta_{\rm crit} \lesssim 1.5$ and not packed when $\beta/\beta_{\rm crit} \gtrsim 2$. Barnes & Greenberg (2007) pointed out that the vast

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[6] It should be noted that HD 74156 d remains a controversial detection; Wittenmyer et al. (2009) in a reanalysis of the Bean et al. (2008) spectra see no evidence for a third planet orbiting HD 74156.

Table 1
Orbital Parameters of Planets Around HD 47186 (Bouchy et al. 2008)

Parameters	HD 47186b	HD 47186c
P [days]	4.0845 ± 0.0002	1353.6 ± 57.1
e	0.038 ± 0.020	0.249 ± 0.073
$m \sin i$ (M_{Jup})	0.07167	0.35061
a (AU)	0.050	2.395

majority of two-planet systems are observed with $\beta/\beta_{\mathrm{crit}} < 1.5$ and hence are packed.

Our investigation into possible habitable planets in HD 47186 is further motivated by the large separation between the two known planets: the $\beta/\beta_{\mathrm{crit}}$ value for this system is 6.13, the largest value among known, noncontroversial systems that have not been affected by tides.[7] This value is much higher than the packing limit, giving further support to the argument that at least one additional companion might exist between the two known planets. Moreover, the success of N-body investigations in predicting the mass and orbit of additional planetary companions suggests that a similar analysis on HD 47186 could yield similar results. But this time, the yet-to-be-detected planet could be habitable. In Section 2 we describe our numerical methods and map out stable regions for a hypothetical $10\,M_\oplus$ planet d between the two known planets. Following Raymond et al. (2008), we then investigate the perturbations of this hypothetical planet on the orbits of the known planets b and c. This approach allows us to exclude a portion of parameter space that is dynamically stable but offers a low probability of detection. Finally, in Section 3, we discuss our results.

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[7] See http://www.astro.washington.edu/users/rory/research/xsp/dynamics/ for an up to date list of $\beta/\beta_{\mathrm{crit}}$ values for the known extrasolar multiple planet systems.

2. DYNAMICAL STABLE ZONES IN HD 47186

2.1. Numerical Simulations

We started our simulations by assigning the two known planets from HD 47186 their best-fit orbits and masses from Table 1 (Bouchy et al. 2008), and assuming mutual inclinations of 1 deg. We also included a hypothetical planet d in between the orbits of planets b and c. From simulation to simulation, we varied planet d's semimajor axis in the range $0.06 \leqslant a_d \leqslant 2.32$ AU in steps of 0.02 AU and eccentricity in the range $0 \leqslant e_d \leqslant 0.6$ in steps of 0.05, for a total of 1483 simulations. We assigned planet d a mass of $10\,M_\oplus$, which would induce in the star a RV amplitude of 3.5–0.6 m s^{-1} in the range that we considered (0.06–2.3 AU). We evolved each system with the Mercury (Chambers 1999) integrator, using the symplectic Wisdom–Holman mapping (Wisdom & Holman 1991), with no general relativity. Each system was integrated with a timestep of 1.0 day and conserved energy to better than 1 part in 10^5. Simulations were stopped after 10 Myr or if there was a close encounter between any two planets of less than 3 Hill radii. Previous work has shown that most unstable planetary systems undergo instabilities on a timescale of 1 Myr or less (e.g., Barnes & Quinn 2004). Thus, our 10 Myr integrations should be sufficient to give a realistic depiction of the stable zone.

2.2. Mapping Stable Zones

In Figure 1, we show the results of our simulations plotted in a–e space. The green and red filled circles represent stable and unstable simulations, respectively. The two known planets in HD 47186 are shown as blue filled circles, and the vertical bars represent the observational uncertainties in their eccentricities. The two curves overlaying the stable/unstable points are the crossing orbits for planets b and c. The blue shaded background
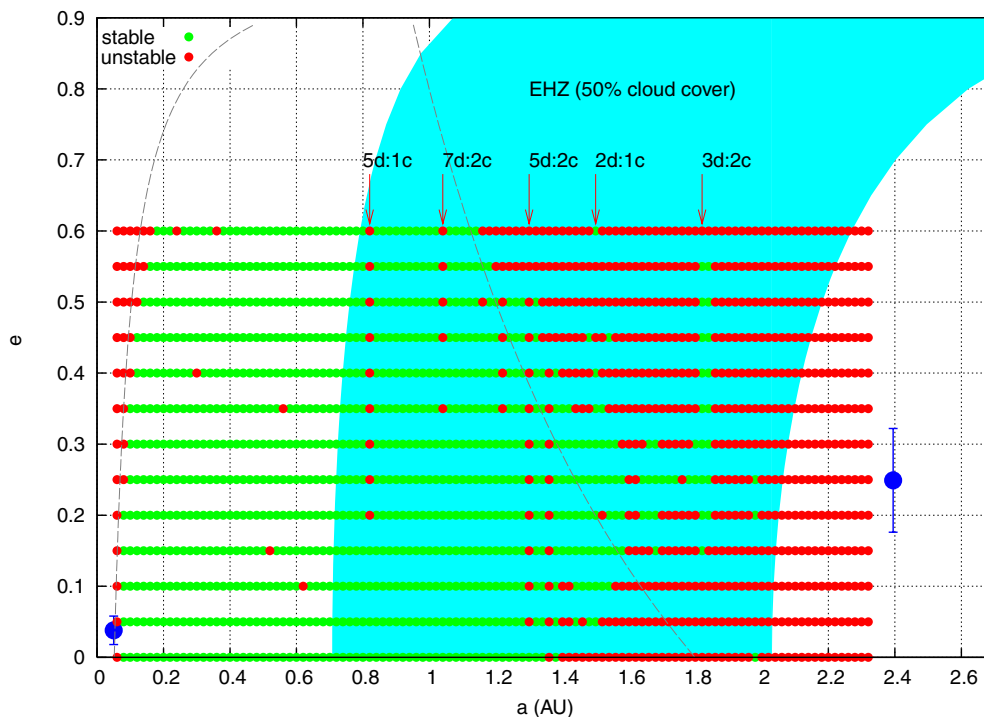

Figure 1. Stable zone for a hypothetical $10\,M_\oplus$ in between the two known planets of HD 47186. The red and green circles represent stable and unstable simulations, respectively. The known planets HD 47186 b and c are indicated by blue filled circles: the error bars represent the observational uncertainties in the best-fit eccentricities. The curves on top of the stable/unstable zones represent crossing orbits for planets b and c. The blue background shows the eccentric HZ (Barnes et al. 2008b) for this system. Also shown are the several MMRs between planet d and c.

is the "eccentric habitable zone" (EHZ) for this system (Barnes et al. 2008b). The EHZ is defined as the HZ from Selsis et al (2007), assuming 50% cloud cover, and modified to take into account variations in the orbit-averaged flux with eccentricity, which appears to be the key factor in determining surface temperature (Williams & Pollard 2002). Also labeled are some of the mean-motion resonances (MMRs) between the hypothetical planet d and outer massive planet c. Out of the 1483 simulations, 856 (57%) simulations were stable for 10 Myr, and the stable zone includes the inner half of the EHZ. Within this stable zone, several MMRs produce "islands" of instability associated with specific MMRs, notably $5d{:}1c$, $7d{:}2c$, and $5d{:}2c$. Conversely, beyond the crossing orbit of planet c (black dashed curve overlapping the EHZ), there are several MMRs, such as $2d{:}1c$, $7d{:}3c$ (not shown, but lies in between $5d{:}2c$ and $2d{:}1c$) and $3d{:}2c$ that provide stability. This result is similar to that of Raymond et al (2008), who found regions of stability/ instability associated with mean motion resonances in the 55 Cancri planetary system.

Using just dynamical stability as a metric, all of the stable (green) points in Figure 1 should be equally likely to support a $10\,M_\oplus$ planet. To narrow down the possible orbit of planet d, we calculate a quantity called "Fraction of Time spent on Detected orbits" (FTD; Raymond et al. 2008), which takes into account the back-reaction of planet d on the orbits of planets b and c. The FTD provides a measure of the probability of finding planets b and c on their current best-fit orbits, including observational uncertainties (see Table 1), taking into account perturbations from planet d. In practice, the FTD simply evaluates the time spent by each observed planet (b and c) on its best-fit orbit, to within the uncertainties. A stable hypothetical planet can cause oscillations in the known planets' orbits that may be larger than the uncertainties. If the FTD value is small, then the oscillation amplitudes are large and the chance of observing the system in its current configuration is small. Hence, it is less likely for a hypothetical planet d to have those orbital parameters. If the FTD value is close to 1, then it is more probable for planet d to be in that orbit. Note, however, that some systems may be observed in unlikely configurations (Veras & Ford 2009).

Figure 2 shows the FTD for the stable region mapped out in Figure 1: yellow is the most likely region for planet d to exist (high FTD), and black is the least likely (low FTD; see color bar). Comparing Figures 1 and 2, the region $a < 0.2$ AU is an unlikely location for planet d to exist. On the other hand, beyond $a \approx 0.3$ AU, the FTD value is uniformly close to 1. Therefore, planet d does not significantly perturb planet c (otherwise there would have been low FTD values), and acts effectively as a massless particle. This leaves a large contiguous stable region with high FTD values from 0.3 to 1.3 AU. We see that planet d might exist in the habitable zone of HD 47186. 52.5% of the stable simulations are within the EHZ, but it is not clear how likely it is that planet d should exist there.

We also performed 30 simulations to see if two additional planets could exist in the stable zone. We placed two planets of $10\,M_\oplus$ each in the range $0.3 \leqslant a_{\rm d} \leqslant 1.3$ AU and $0 \leqslant e_{\rm d} \leqslant 0.6$. We found that 16 cases resulted in unstable simulations and 14 stable. Most of the stable simulations (13, ∼93%) had low eccentricity ($e < 0.3$). In some stable cases, both hypothetical planets were in the EHZ.

Additional simulations assuming that the masses of the known planets b and c are twice their minimum mass, equivalent to an inclination angle of 30 deg, did not show any significant change in the stability boundaries. We found that the inner stability boundary near planet b is not at all affected, whereas the region between 1.5 AU and 1.8 AU is slightly modified. Specifically, regions stabilized by 2:1 mean-motion resonance near 1.5 AU, are now smaller with some of the stable points turning into unstable. Overall, there is no significant change in the stability of the HZ.

3. DISCUSSION

We have shown that a hypothetical $10\,M_\oplus$ planet can exist between planets HD 47186 b and c for orbital distances of roughly 0.1–1.3 AU (Figure 1). Our FTD analysis shows that this planet is more likely to be found between ∼ 0.3 and 1.3 AU (Figure 2). We also find that two $10\,M_\oplus$ planets with low eccentricities can exist between planets b and c. A
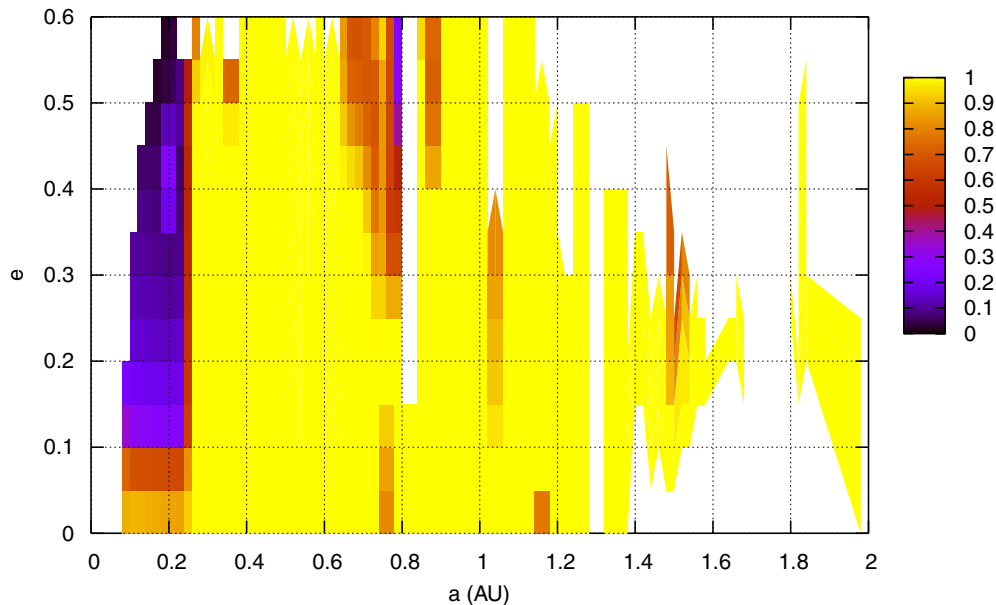

Figure 2. FTD ("Fraction of Time spent on Detected orbits"; Raymond et al. 2008) for the stable zone of HD 47186. The FTD value is shown in the color bar: yellow indicates a high likelihood of detecting planet d with those orbital parameters. The long gaps correspond to unstable zones arising from MMRs.

10 $M_\oplus$ planet between 0.3 and 0.7 AU (the high FTD region in Figure 2) produces an RV amplitude of 1–2 m s^{-1}, and should be detectable in the near future. It is possible that the two known planets in HD 47186 may have migrated to their present location. Previous studies (Raymond et al. 2006; Mandell et al. 2007) have shown that migrating giant planets do not preclude the existence of terrestrial planets. In fact, if the outer planet migrated inward then the most likely place for an extra planet would be just interior to the 2:1 MMR, which lies in the middle of the EHZ. Planets of $\sim 10\,M_\oplus$ or less are thought to be the largest potentially terrestrial planets with rocky surfaces and thin atmospheres. This provides an effective upper limit for habitability as we know it. Therefore, HD 47186 offers the chance to detect a terrestrial planet in the HZ of a nearby, solar-type star. Roughly 30% of systems are thought to harbor super-Earth sized planets ($M_p \lesssim 10\,M_\oplus$; Mayor et al. 2009). If this frequency increases for lower-mass planets, the (non-)detection of HD 47186 d could shed light on the fraction of stars with terrestrial-like planets in the habitable zone, sometimes called $\eta_\oplus$. If, in a complex system such as this one, a terrestrial-scale planet can form and survive, then perhaps $\eta_\oplus$ is relatively large, increasing the likelihood the spacraft such as *Kepler* and *Terrestrial Planet Finder* will find habitable planets. We encourage observers to use our results for assistance in the search for HD 47186 d.

The HD 47186 system is also another critical test of PPS hypothesis, which asserts that planetary systems should not contain large empty gaps. The PPS hypothesis follows naturally from the planet–planet scattering model (Raymond et al. 2009) and clearly predicts that there exists an additional planet in the gap between planets *b* and *c*. In fact, two 10 $M_\oplus$ planets could exist in the stable zone if they are at low eccentricity. The connection between the simple, easily calculated value $\beta/\beta_{\rm crit}$ might provide some insight into the number of planets that can exist between two known planets. It would be interesting, then, to see if this one parameter can be used to test or not whether a system is packed.

REFERENCES

Barnes, R., Goździewski, K., & Raymond, S. 2008a, ApJ, 680, L57
Barnes, R., & Greenberg, R. 2006, ApJ, 665, L163
Barnes, R., & Greenberg, R. 2007, ApJ, 665, L67
Barnes, R., & Quinn, T. 2001, ApJ, 550, 884
Barnes, R., & Quinn, T. 2004, ApJ, 611, 494
Barnes, R., & Raymond, S. 2004, ApJ, 617, 569
Barnes, R., Raymond, S., Jackson, B., & Greenberg, R. 2008b, AsBio, 8, 557
Bean, J. L., McArthur, B. E., Benedict, G. F., & Armstrong, A. 2008, ApJ, 672, 1202
Bodenheimer, P., Hubickyj, O., & Lissuaer, J. J. 2000, Icarus, 143, 2
Bouchy, F., et al. 2008, A&A, 496, 527
Chambers, J. E. 1999, MNRAS, 304, 793
Dvorak, R., Pilat-Lohinger, E., Funk, B., & Freistetter, F. 2003, A&A, 410, L13
Érdi, B., Dvorak, R., Sándor, Zs., Pilat-Lohinger, E., & Funk, B. 2004, MNRAS, 351, 1043
Gladman, B. 1993, Icarus, 106, 247
Goździewski, K., Bois, E., Maciejewski, A. J., & Kiseleva-Eggleton, L. 2001, A&A, 78, 569
Goździewski, K., & Maciejewski, A. 2001, ApJ, 563, L81
Hubickyj, O., Bodenheimer, P., & Lissauer, J. J. 2005, Icarus, 179, 415
Jones, B. W., Sleep, P. N., & Chambers, J. E. 2001, A&A, 366, 254
Kasting, J. F., Whitmore, D. P., & Reynolds, R. T. 1993, Icarus, 101, 108
Laskar, J. 1996, Celest. Mech. Dyn. Astron., 64, 115
Mandell, A. M., Raymond, S. N., & Sigurdsson, S. 2007, ApJ, 660, 823
Marchal, C., & Bozis, G. 1982, Celest. Mech. Dyn. Astron., 26, 311
Mayor, M., et al. 2003, The Messenger, 114, 20
Mayor, M., et al. 2009, A&A, 493, 639
Menou, K., & Tabachnik, S. 2003, ApJ, 583, 473
Pollack, J. B., Hubickyj, O., Bodenheimer, P., Lissauer, J. J., & Podolak, M. 1996, Icarus, 194, 62
Raymond, S. N., & Barnes, R. 2005, ApJ, 619, 549
Raymond, S. N., Mandell, A. M., & Sigurdsson, S. 2006, Science, 313, 1413
Raymond, S. N., Barnes, R., & Gorelick, N. 2008, ApJ, 689, 478
Raymond, S. N., Barnes, R., Veras, D., Armitage, P., Gorelick, N., & Greenberg, R. 2009, ApJL, in press (arXiv:0903.4700)
Rivera, E. J., & Lissauer, J. J. 2000, ApJ, 530, 454
Selsis, F., Kasting, F., Levrard, B., Paillet, J., Ribas, I., & Delfosse, X. 2007, A&A, 476, 137
Udry, S., et al. 2007, A&A, 469, L43
Veras, D., & Ford, E. B. 2009, ApJ, 690, L1
von Bloh, W., Bounama, C., Cuntz, M., & Franck, S. 2007, A&A, 476, 1365
Williams, D. M., & Pollard, D. 2002, IJAsB, 1, 61
Wisdom, J., & Holman, M. 1991, AJ, 102, 1528
Wittenmyer, R. A., Endl, M., Cochran, W. D., Levison, H. F., & Henry, G. W. 2009, ApJS, in press (arXiv:0903.0652)