Dynamical Stability and Habitability of a Terrestrial Planet in HD74156

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ABSTRACT:

The detection of extrasolar terrestrial planets located in the habitable regions of a star system is presently beyond our observational technologies. However, systems with multiple Jupiter-like extrasolar planets may prove to be candidates for supporting terrestrial planets provided that stable regions exist. The advantage of searching for terrestrial planets in such systems is the knowledge that planets have formed in these systems, suggesting that terrestrial planets may have formed as well. The results of numerical integrations for the systems HD74156 and HD12661, each of which have two Jovian-type planets orbiting their parent star, demonstrates that a region exists in HD74156 where a terrestrial planet can remain in orbit on a timescale of 10^5 years, while HD12661 cannot support additional planets. The Swinburne Supercomputer running the SWIFT computer code is used for the simulation of both massless test particles used to identify stability zones, and for Earth-mass planets placed within the identified stability zones to investigate their short-term dynamical stability. The results are extended to explore the effects of changing the inclination of the planetary system and the eccentricity of the terrestrial planet. These results can be used to constrain the search region within HD74156 in which habitable terrestrial planets are most likely to be found.

Introduction

To date (June 2003), 108 extrasolar planets have been detected around 94 stars, with 12 of them being multiple planet systems[1]. While direct observation of these planets is not possible (with the exception of the transiting planet of HD209458) they can be detected indirectly, typically using the radial velocity method. The radial velocity method makes use of the periodic Doppler shifting of the spectral lines to indicate that a companion to a star is present in the system. With high-precision radial velocity observations, the star’s radial velocity, its position on the sky with respect to a fixed star and the Doppler shift of radiation emitted by the star can be measured. These three parameters are perturbed with a period equal to that of the planet’s orbital period with an amplitude that is in proportion to the planet’s mass. The main drawback with this method is that only a lower mass can be determined for the planet, as the inclination of the system is generally unknown. The most limiting factor to this method is that at the present time only planets down to Saturn mass can be detected; a terrestrial planet the mass of Earth would not be detected. However, there is much evidence to support the hypothesis that terrestrial planets populate these systems as well.

Observational evidence for the likelihood of the existence of small planets around other stars has been presented by Marcy et al. (2000), who propose that it is common for rocky worlds to form around young stars. IR and mm studies of protoplanetary disks

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[1] Extrasolar Planets Encyclopedia: http://www.obspm.fr/encycl/encycl.html

have shown that within 10^5 years dust particles accrete to millimeter sized objects; it is natural to assume that these objects can result in rocky planets. The observation that the mass distribution of planets rises steeply with decreasing mass (Marcy and Butler 2000) leads to the conclusion that up to 50% of all stars may have rocky planets.

While these observations have led to the conclusion that terrestrial planets must exist around distant stars in higher number than do Jovian-type planets, they do little to extend our knowledge of whether life exists on these planets. No complete definition for the nature of extraterrestrial life exists to be applied to the extrasolar systems, however, it is possible to identify regions around stars where a terrestrial planet may support the type of habitat that we know supports the type of life we have here. This includes the presence certain heavy elements, liquid water on the surface of the planet, and a range of temperatures that would allow the retention of an atmosphere (see Turnbull and Tarter 2003 and references therein). The temperature, luminosity class and spectral type of the star must be considered, as well as the age of system as a whole. The region around a suitable star where such requirements are met is referred to as the habitability zone.

The dynamical stability of the system must be taken into account as well, particularly in light of the impact that large planets can have on the orbit of the terrestrial planet. For a terrestrial planet to remain habitable, there is a dynamical requirement that other planets in the system don't gravitationally perturb the planet outside of its habitability zone. In a recent study involving 85 of the known extrasolar planetary systems, Menou and Tabachnik (2003) found that more than half of these systems, primarily those with distant eccentric giant planets, are not likely to support terrestrial planets and are therefore dynamically inhabitable. Marcy and Butler (2000) give similar evidence for the likelihood of terrestrial planets to be scattered gravitationally from the high eccentricity of Jupiter-like planets that exist between 2 – 3 AU. Under such circumstances the circular orbits and the long term survival of terrestrial planets is not guaranteed.

These two concepts, dynamical stability and a habitable region, can be combined to provide additional insight into the possibilities of Earth-like planets capable of supporting life as we know it existing around other stars. Many extrasolar planetary systems have been investigated in an effort to determine their dynamical stability (Barnes and Quinn 2001, Gozdziewski 2003, Laughlin et al. 2002) and their ability to hold terrestrial planets (Rivera and Lissauer 2002, Noble et al. 2002, Menou and Tabachnik 2003). The primary system chosen for this investigation is HD74156, a multiple planet system with two massive planets in orbit around a star that is similar to the Sun. The less massive interior planet is positioned in orbit close to the star at 0.276 AU, while the more massive exterior planet is located 3.47 AU from the star. The habitability zone for this star ranges from 1.07 AU to 2.52 AU (Turnbull & Turner 2003), providing a range where a terrestrial planet could reside.

In this paper numerical integrations will be used to investigate the possibilities of a terrestrial planet existing between the known planets in HD74156, and whether such a planet is likely to remain dynamically stable within the habitability zone of the system on short timescales. Should these conditions be met, the system will be considered to be dynamically habitable. In all instances the simulations are confined to examining Earth-mass planets. The computer simulation tool SWIFT was used on the Swinburne

University supercomputer system to investigate whether a region of stability exists between the two planets in HD74156, first using massless test particles (TP'S) and second using an Earth-sized planet. The simulations are used to identify the stability region should one exist, and to explore the effects of changes to the system inclination and eccentricity of the inserted terrestrial planet. The results of such investigations can help give terrestrial planet seekers an idea of which systems are most likely to hold terrestrial planets within the habitable zone, and focus their search in a particular region in the system shown to dynamically support such a planet.

Methodology

The objective of this study is to investigate the planetary systems around HD74156 in order to determine if there is a likelihood that it can support a terrestrial planet in the habitability zone. This was accomplished using computer simulations on the Swinburne supercomputer running the SWIFT code which will be described below.

The first step was to set up two similar astronomical systems, one that was found by Barnes & Raymond (2002) to have a narrow stability zone between the widely spaced planets of the system, and for comparison purposes one that was found not to have additional zones of stability between the two planets of the system. The system capable of supporting a terrestrial planet described above is HD74156 and the system incapable of supporting additional planets is HD12661. Each has two 'jupiters' in orbit around a Sun-like star, though the orbital properties and masses of the planets differ.

Each of the system's suitability for having terrestrial planets was investigated by distributing 100 "massless" test particles (TP's) in the system. These were randomly placed between the two existing planets in HD12661 and HD74156, and numerical integrations run for up to 10^5 years. Stability zones were defined as those areas where the TP's clumped together and remained at a fairly constant semi-major axis for the duration of the simulation.

The second step was to replace the TP's with a simulated Earth-mass planet placed at various semi-major axes within the previously determined stability zone in the system and conduct a series of simulations of 10^5 years to observe the behavior of the simulated planet in particular and the whole system in general.

The third step in the simulation experiment was to vary the system inclination (0°, 2.5°, 5°) and the eccentricity (0.01 and 0.1) of the terrestrial planet in HD74156 to see whether this affected the stability of the planet.

SWIFT Code on the Swinburne Supercluster

The SWIFT Solar System Dynamics software program being run on the Swinburne Supercluster provides a very sophisticated gravitational system evaluation tool that can be most simply thought of as a digital orrery. In its simplest form an orrery provides a model of the time dependent behavior of a group of astronomical bodies, quite commonly our solar system. The most primitive of these systems are models constructed of wire and wood that can be moved to show the evolution of the system.

The SWIFT code provides a powerful celestial mechanics tool to evaluate gravitational dynamical systems that can be changed in terms of the number of planets, their masses, their orbital parameters and their evolution with time. This can be described as an n-body gravitational simulator. The advantage of having a simulator on a supercluster is that complex simulations integrated for many thousands of years can be run and evaluated.

The code for solving N-body simulations has two main components: 1) the force calculation (Newton's law of gravitation); and 2) time evolution (equations of motion). These components are described by a mathematical model, a set of mathematical equations which predict the future state of the system based on a given set of initial conditions[2].

The SWIFT Solar System Dynamics software package was designed by Hal Levison and Martin Duncan to solve N-body simulations for a set of mutually gravitationally interacting bodies as well as a group of "massless" test particles which are gravitationally influenced by the massive bodies but do not affect each other or the massive bodies[3]. The algorithms employed in the package are Wisdom-Holman mapping (Wisdom and Holman 1991) which deals with gravitational N-body problems with a dominant central mass; the Regularized Mixed Variable Simpletic model (Levison and Duncan 1994) developed to follow the long-term dynamical evolution of a group of test particles; a fourth order T+U Simpletic method (Gladman et al. 1991) which exhibits good performance for moderately eccentric orbits; and a Bulirsch-Stoer method. The program is written such that the calls to these different algorithms are seamless. SWIFT runs on the Swinburne Supercluster, a network of 160 computers whose combined processing power exceeds 1080 Gflops[4]. Detailed descriptions of the simulator and the SWIFT code are contained in the aforementioned references.

One feature of these simulation systems that requires a brief discussion is the idea of using "massless" test particles. If the test particles were truly massless then they would do nothing in a system that is controlled under a collection of gravitational central fields. Thus these particles must have mass to sense the field, however, their mass is not used to perturb the fields felt by the main bodies of the simulation. The idea of such massless particles permeates the jargon of this type of computational program and will be adopted here as well.

Integration Parameters

In all of the integrations, the observational data published by the Extrasolar Planet Encyclopedia (see footnote 1) were used for the orbital parameters of the parent star and known planets in the systems. However, orbital data obtained via the radial velocity method is not necessarily accurate (Tabachnik and Tremaine 2002). As such, it is important to keep in mind that while the data that this investigation is based upon is the most accurate that is available at this time, the data is constantly being updated and refined and may not necessarily remain entirely accurate. Case in point, the orbital data used by Barnes and Raymond (2002) for HD74156 less than one year ago differs from the current data obtained from the Extrasolar Planet Encyclopedia as well as the

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[2] Swinburne Online Computational Astrophysics Mod. 1, Act. 3
[3] SWIFT website: www.boulder.swri.edu/~hal/swift.html
[4] Swinburne website: http://supercomputing.swin.edu.au

California and Carnegie Planet Search Catalog[5]. As such, although both the Barnes and Raymond investigation as well as this investigation found HD74156 to have a stability zone, the location of this zone differs between our two investigations (~0.55 – 0.6 AU vs. ~1 – 1.07 AU, respectively).

As the radial velocity method of detection does not allow the inclination of the system to be determined, the majority of the simulations were run with the system coplanar at 0°. In a number of cases with a test planet placed at 1 AU in HD74156 the inclination of the whole system was simulated at 2.5° and 5.0° as well as 0°. In both of these cases the change of inclination resulted in the planet remaining bound through the duration of the simulation 2 out of 3 times, as opposed to 3 out of 3 times when the system inclination was set to 0°.

In all cases with a test planet, an Earth-sized planet (0.003 M_{jup}) was used. The test planet was placed at a variety of locations within the target stability zone identified by the test particle simulations, with some of them being stable and others not. In the stable orbits, the eccentricity of the test planet was varied between 0.1 and 0.01, resulting in a small effect on the ultimate stability. Both of these issues will be discussed later in the paper. The criterion for a planet to be considered to be ejected from the system was when the eccentricity equaled or exceeded 1.

The typical integration timescale involving a test planet was 10^5 years with an integration timestep of 0.01 years. These values were chosen primarily to adhere to the constraints placed upon the computational resources made available for this investigation. For HD74156 the integration timescale corresponds to 707,227 orbits for the interior planet,1,565 orbits for the exterior planet, and approximately 100,000 orbits for the test planet, depending upon its exact placement. For HD12661 the integration timescale corresponds to 138,467 orbits for the interior planet and 25,268 orbits for the exterior planet.

For HD74156, the integration timestep of 0.01, chosen to favor accurate modeling for the innermost planet, resulted in 14.14 steps per orbit for the interior planet, 630 steps per orbit for the exterior planet, and approximately 100 steps per orbit for the test planet, dependent upon its exact placement in the system. Unfortunately, the ability to use different timesteps most appropriate for all of the planets in the system at the same time, as is commonly done in similar investigations (Menou and Tabachnik 2003, Barnes and Quinn 2002), was not an option with the software used in this investigation. The value of 14.14 steps per orbit is close to the optimal value of 20 steps per orbit commonly used in dynamical investigations (Menou and Tabachnik 2003, Barnes and Quinn 2002, Rivera and Lissauer 2000), and as such was considered to be accurate enough for the purposes of this investigation.

Each particular instance of a simulation setup was run a minimum of three times, with the initial starting positions recalculated at the beginning of each simulation. Both the starting positions of the planets and test particles were randomly generated by the simulator. In most instances, the initial location of planets in the system appeared to have no large impact on the final results of the simulations.

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[5] California and Carnegie Planet Search Catalog: http://exoplanets.org/planet_table.shtml

HD74156

Distance:	64.56 pc	
Spectral type:	G0	
Apparent magnitude:	B = 8.16, V = 7.62	
Coordinates :	RA = 08 42 25.1222 DEC = +04 34 41.151	
Metallicity:	Fe/H]= 0.13	
Mass (M sun):	M= 1.05 *Jupiter Masses: 1099.35*	
Habitability Zone:	1.07 – 2.52 AU	
Planets:	**HD 74156 b**	**HD 74156 c**
M sin i:	1.56 Mj	7.5 Mj
Semi-Major Axis:	0.276 AU	3.47 AU
Orbital Period:	51.61 ± 0.053 d.	2300.0 d.
Eccentricity:	0.649 ± 0.022	0.395 ± 0.074
Omega (deg):	183.7 ± 3.3	240 ± 12
T Peri (JD-2450000):	1981.4 ± 0.57	849
Inclination:	*unknown*	*unknown*

Table 1: The planets in HD74156 were detected using the radial velocity method by the Geneva search team. All parameters are based upon observational data, which is periodically refined and updated.

HD12661

Distance:	37.16 pc	
Spectral type:	G6 V	
Apparent magnitude:	V = 7.44	
Coordinates :	RA = 02 04 34.29 DEC = +25 24 51.5	
Metallicity:	[Fe/H] = 0.293	
Mass (M sun):	M = 1.07 *Jupiter Masses: 1120.29*	
Habitability Zone:	0.93 – 1.87 AU	
Planets:	**HD 12661 b**	**HD 12661 c**
M sin i:	2.30 Mj	1.57 Mj
Semi-Major Axis:	0.83 AU	2.56 AU
Orbital Period:	263.6 ± 1.2d.	1444.5 ± 12.5d.
Eccentricity:	0.35 ± 0.03	0.20 ± 0.04
Omega (deg):	291.73 ± 5.0	162.4 ± 18.5
T Peri:	2449941.9 ± 6.2	2449733.6 ± 49.0
Inclination:	*unknown*	*unknown*

Table 2: The planets in HD12661 were detected using the radial velocity method by the California Carnegie search team. All parameters are based upon observational data, which is periodically refined and updated.

Results and Discussion

The initial computer simulations focused on populating the two systems with test particles. The relevant parameters such as stellar mass and planet orbital elements for these systems are shown in Tables 1 and 2, and are based on observational data supplied by the Extrasolar Planet Encyclopedia (see footnote 1). The most straightforward parameters for using the SWIFT simulator are the Keplerian orbital parameters of a, e and i, which with the exception of i are supplied by the observational data. With these parameters entered into the system, the software program is able to calculate a set of corresponding Cartesian coordinates which consist of the three dimensional position and velocity information about particles or planets. Both of these sets of units are specified in Table 5, which shows a common instance of setup parameters used in the simulations. These two coordinate systems are easily translated between and the transformations are shown in the Swinburne materials [6]. Of particular importance in this problem are the orbital semi-major axes and eccentricity for the test particles and the planets. For the purposes of this investigation, the key indicators that an object is no longer in a stable orbit in the system is that the eccentricity equals or exceeds 1 and/or the semi-major axis extends beyond the exterior planet or falls within that of the interior planet.

The location of the stable region between the two planets will also depend upon the Hill radius of the planets in orbit around the star. The Hill radius is defined as the zone of influence around a planet within which the planetary tidal forces on a small body are greater than those of the central massive body. Moreover, it is common practice in dynamical studies to consider the true zone of influence as being three times the Hill radius (Turnbull & Tarter 2003, Menou & Tabachnik 2003). Should a test particle or test planet come within the zone of influence of the planets its orbital path will be disrupted and in some cases the planet's orbit destabilized to the point of ejection.

HD74156

System Inc.	TP SMA Range (AU)	TP Ecc. Range	TP Max Inc.	Total Int. Time (yr)	Output Timestep (yr)	Int. Timestep (yr)	TP Cluster SMA Range (AU)
0.0	0.27 – 3.4	0.01 – 0.5	0.2	10000	10	0.01	0.7 – 1.2
0.0	0.27 – 3.4	0.01 – 0.5	0.2	10000	10	0.01	0.6 – 1.1
0.0	0.27 – 3.4	0.01 – 0.5	0.2	10000	10	0.01	0.8 – 1.1
0.0	0.27 – 3.4	0.01 – 0.2	0.2	10000	10	0.01	0.6 – 1.3
0.0	0.27 – 3.4	0.01 – 0.2	0.2	10000	10	0.01	0.8 – 1.4
0.0	0.27 – 3.4	0.01 – 0.2	0.2	10000	10	0.01	0.6 – 1.2
2.5	0.27 – 3.4	0.01 – 0.2	0.2	10000	10	0.01	0.7 – 1.2
2.5	0.27 – 3.4	0.01 – 0.2	0.2	10000	10	0.01	0.7 – 1.3
2.5	0.27 – 3.4	0.01 – 0.2	0.2	10000	10	0.01	0.7 – 1.3
2.5	0.27 – 3.4	0.01 – 0.5	0.2	10000	10	0.01	0.6 – 1.0
2.5	0.27 – 3.4	0.01 – 0.5	0.2	10000	10	0.01	0.7 – 1.1
2.5	0.27 – 3.4	0.01 – 0.5	0.2	10000	10	0.01	0.6 – 1.2
5.0	0.27 – 3.4	0.01 – 0.5	0.2	10000	10	0.01	0.8 – 1.0
5.0	0.27 – 3.4	0.01 – 0.5	0.2	10000	10	0.01	0.4, 0.7 – 1.0
5.0	0.27 – 3.4	0.01 – 0.5	0.2	10000	10	0.01	0.9
5.0	0.27 – 3.4	0.01 – 0.2	0.2	10000	10	0.01	0.7 – 1.1
5.0	0.27 – 3.4	0.01 – 0.2	0.2	10000	10	0.01	0.7 – 1.2
5.0	0.27 – 3.4	0.01 – 0.2	0.2	10000	10	0.01	0.6 – 1.2

Table 3: Test Particle simulation runs for HD74156 give strong evidence for a stability zone to exist somewhere between 0.6 AU and 1.4 AU.

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[6] Swinburne Online Computational Astrophysics Mod. 5, Act. 1

HD12661

System Inc.	TP SMA Range (AU)	TP Ecc. Range	TP Max Inc.	Total Int. Time (yr)	Output Timestep (yr)	Int. Timestep (yr)	TP Cluster SMA Range (AU)
0.0	0.83 – 2.5	0.01 – 0.2	0.2	10000	10	0.01	0.4
0.0	0.83 – 2.5	0.01 – 0.2	0.2	10000	10	0.01	0.5, 0.6
0.0	0.83 – 2.5	0.01 – 0.2	0.01	10000	10	0.01	0.4
0.0	0.83 – 2.5	0.01 – 0.2	0.01	10000	10	0.01	0.4
0.0	0.83 – 2.5	0.01 – 0.2	0.2	10000	10	0.01	none
0.0	0.83 – 2.5	0.01 – 0.2	0.2	10000	10	0.01	none
0.0	0.83 – 2.5	0.01 – 0.2	0.2	10000	10	0.01	0.4

Table 4: Test Particle simulation runs for HD12661 give no evidence of a stability zone between the planets in the system.

Tables 3 and 4 show the list of the most pertinent simulations that were performed to identify stability zones in the two extrasolar planetary systems. The average duration of any one simulation for this initial test was 10^4 years and took approximately 20 minutes to run. A number of longer duration simulations of 10^5 years were run as well and returned similar results. These simulations, which took on average 2 hours each, are not reflected in this table.

The results of the integrations for these systems populated with 100 test particles are shown in Figures 1 and 2, which are representative of the simulations run for each instance. Figure 3 shows the same simulation as Figure 2 with 1000 test particles rather than just 100. This demonstrates that similar results are obtained when using the maximum number of test particles as with 100. The important consideration in this case is that the 100 test particle case could be run in considerably less time, and was therefore both prudent and necessary to use in light of the limited computer processing time available.

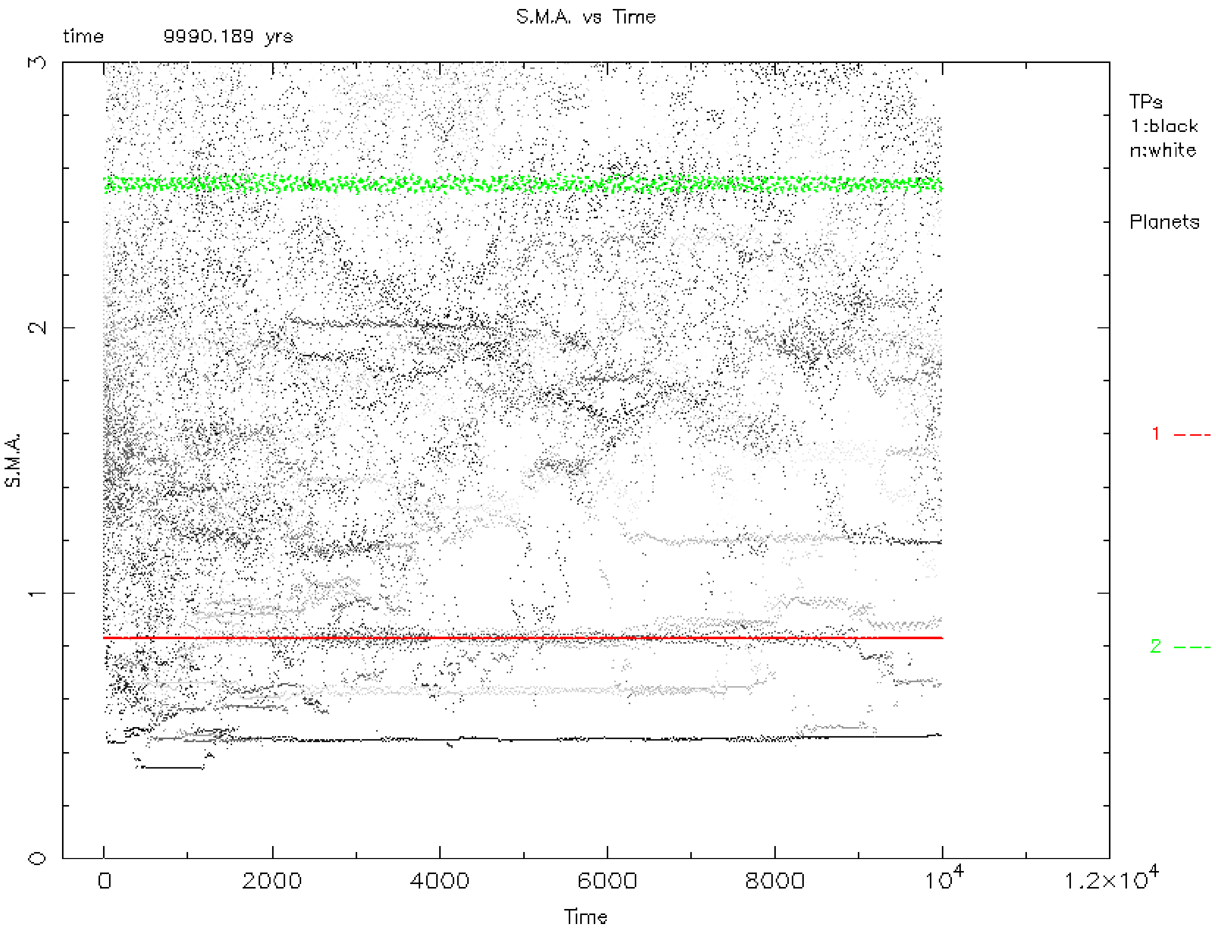

Figure 1:
HD12661 with 100 “massless” TP’s placed between the planets in the system (shown in red and green) integrated for 10^4 years. A small number of particles cluster at 0.4 AU and remain for the duration of the simulation, but the rest of the region between the planets (shown in red and green) shows no clustering of TP’s.

Figure 1 shows that in the case of HD12661 the zone between the planets is unstable as no test particles in this region cluster together and last for the duration of the integration. In contrast to this HD74156 shows that the majority of the test particles are retained and remain in the region of approximately 0.6 AU through 1.4 AU for the duration of the simulation. It should be noted that those few test particles that remain in the HD12661 system are located at approximately 0.4 AU.

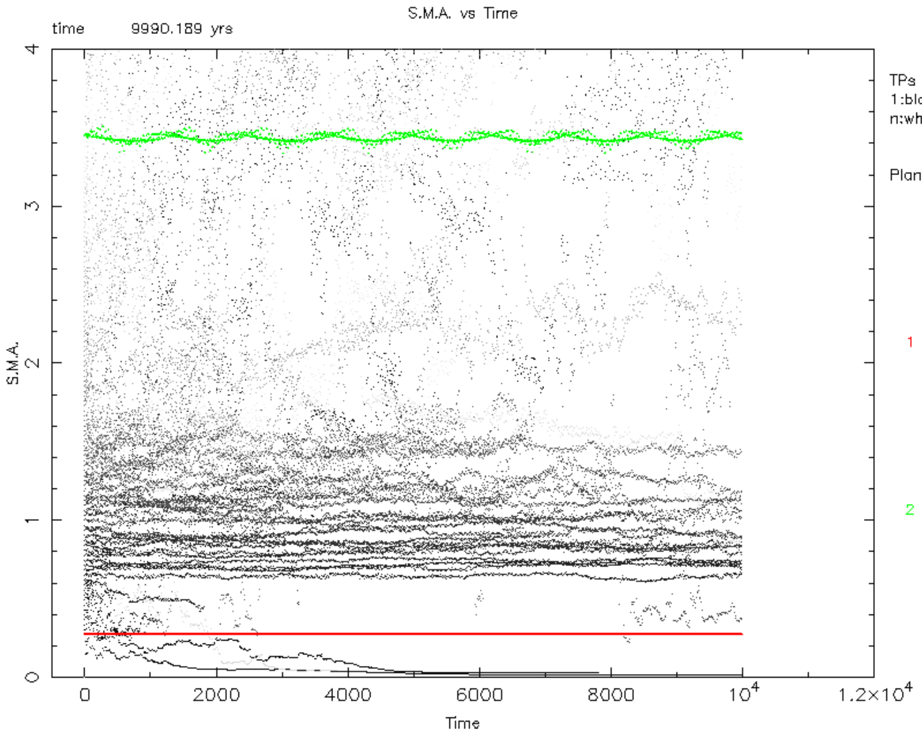

Figure 2: HD74156 with 100 "massless" TP's inserted between planets in the system and integrated for 10^4 years. Particles cluster between 0.6 – 1.4 AU and remain for duration.

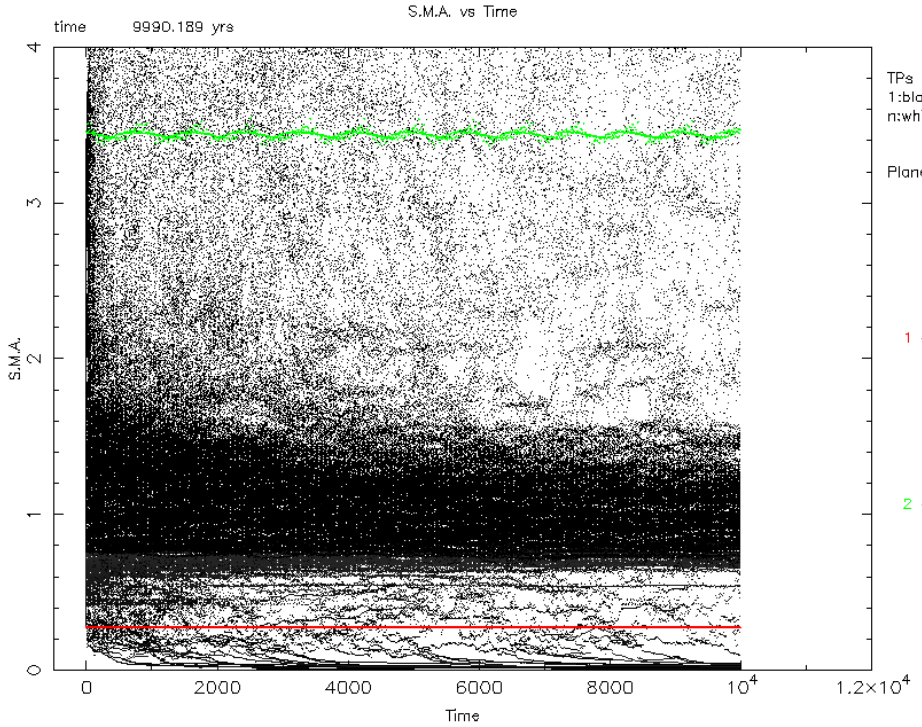

Figure 3: HD74156 with 1000 "massless" TP's inserted between the planets in the system and integrated for 10^4 years. On this timescale, the particles cluster between 0.6 – 1.4 AU and remain for the duration of the simulation, as in the simulations with 100 TP's.

The test particle simulations show that in HD 74156 there should be a stability region that begins about 0.6 AU and extends to approximately 1.4 AU. Figure 4 shows the HD74156 case with the test particles replaced by a terrestrial planet (shown in green) placed at 1.07 AU with e=0.01 in a coplanar system of i=0º. The choice of this location coincides with the edge of the habitable zone for the system, shown in Figure 5. The simulation in Figure 4 shows that this is a stable region for a terrestrial planet.

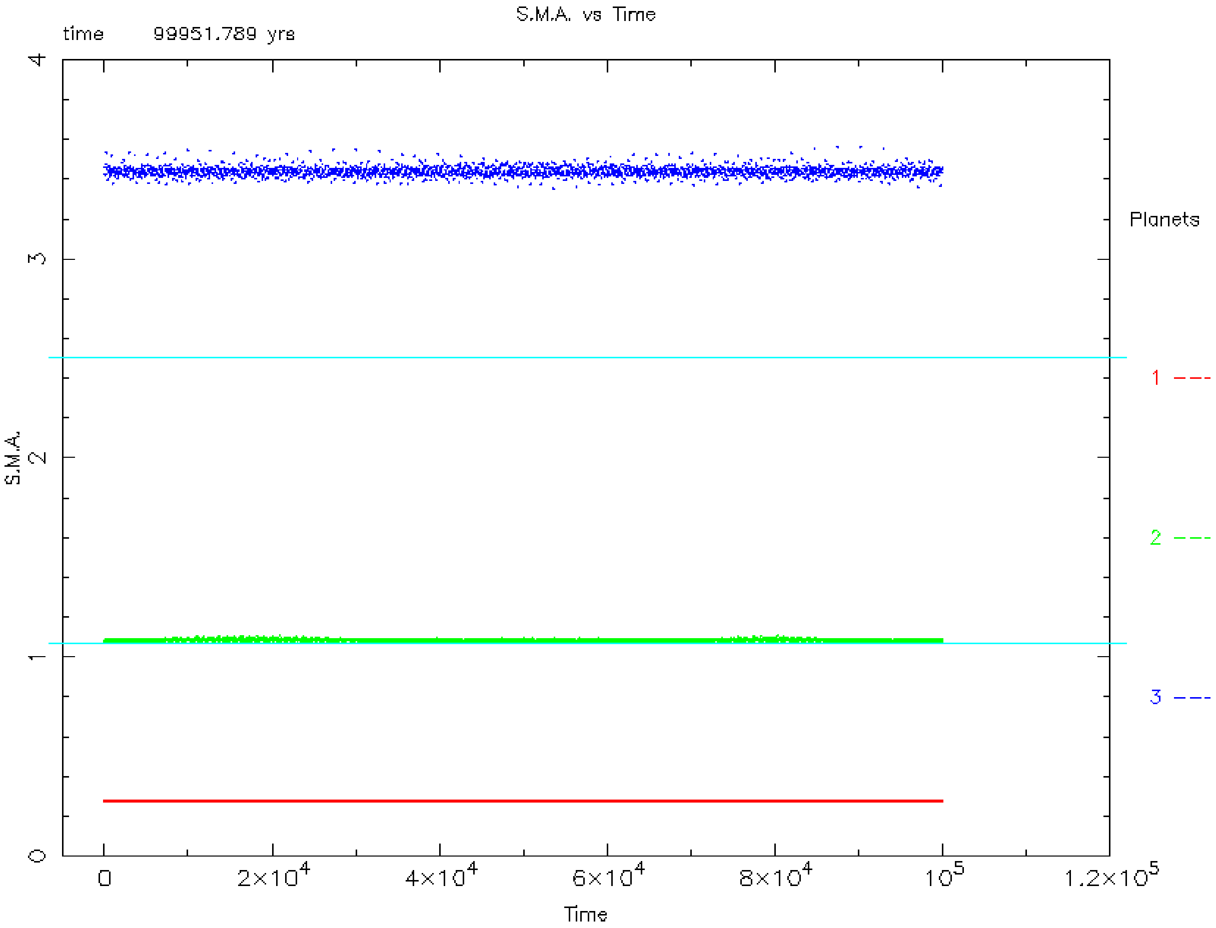

Figure 4: HD74156 with Earth-sized planet placed at 1.07 AU and integrated for 10^5 years (see Table 4 for simulation parameters). The planet remains bound to the system for the duration of the simulation. The habitability zone of the system is defined by the turquoise lines at 1.07 AU and 2.52 AU.

Table 5 below shows the setup parameters for the simulation illustrated in Figures 4 through 6. This is an example of the typical setup used for all of the simulations in this investigation.

Planet Setup:

Number of Planets	3
Central Body Mass $_{j}$	1099.35

1) HD74156 b (shown in red)

Ecc	**S.M.A.**	**Inc.**	**Mass**
0.64900	0.27600	0.00000	1.56

x	**y**	**z**
0.099763741471389	-0.00085984581230429	0
v_x	**v_y**	**v_z**
4.1586494156008	25.75201324974	0

Rclose
0.021504608297144362

2) Terrestrial Planet (shown in green)

Ecc	**S.M.A.**	**Inc.**	**Mass**
0.010000	1.07000	0.00000	0.003

x	**y**	**z**
-0.84839858736898	0.65845034628922	0
v_x	**v_y**	**v_z**
-3.7555299853875	-4.9329495201402	0

Rclose
0.010367446050886202

3) HD74156 c (shown in blue)

Ecc	**S.M.A.**	**Inc.**	**Mass**
0.39500	3.47000	0.00000	7.5

x	**y**	**z**
0.47475990170385	-4.5936911668705	0
v_x	**v_y**	**v_z**
2.3150088234125	0.80237143707898	0

Rclose
0.456314375479865

Test Particles Setup:

Number of TP's	10	**Randomized?**	yes

Test Particle Setup		
Ecc Range	0.01	0.2
SMA Range	0.27	3.4
Max Inc	0.2	

Simulation Parameters:

Simulation Timing	
Total Integration Time	100000
Output Timestep	50
Integration Timestep	0.01

Table 5: Simulation parameters for simulation shown in Figures 4 and 5. This is typical of the simulations run with a test planet, and took approximately 20 minutes to run.

Based on Figure 4 alone, one could assume that not only does the terrestrial planet remain dynamically stable for the duration of the simulation, but that it remains within the habitability zone of the system as well. Figure 5 illustrates that this is not the case. In this figure the habitability zone as determined by Turnbull and Tartar (2003) is superimposed on the y vs. x plot of the system. In this instance the terrestrial test planet was placed at 1.07 AU (the inner edge of the habitability zone) with an initial eccentricity of 0.01 with the intention of keeping the orbit close to circular and the planet within the habitability zone. Although the initial eccentricity was 0.01, as the system evolves the eccentricity ranges from 0.01 to over 0.3, as shown in Figure 6, resulting in the test planet moving in and out of the habitability zone over time. It remains uncertain whether a planet would remain habitable under these conditions, although there is some evidence to support the theory that a planet can remain habitable in spite of the eccentricity of its orbit taking it periodically out of the habitability zone (Williams and Pollard 2002). To err on the side of safety, however, this particular configuration is considered not to be dynamically habitable, which is in agreement with Menou and Tabachnik (2003) and Turnbull and Tarter (2003).

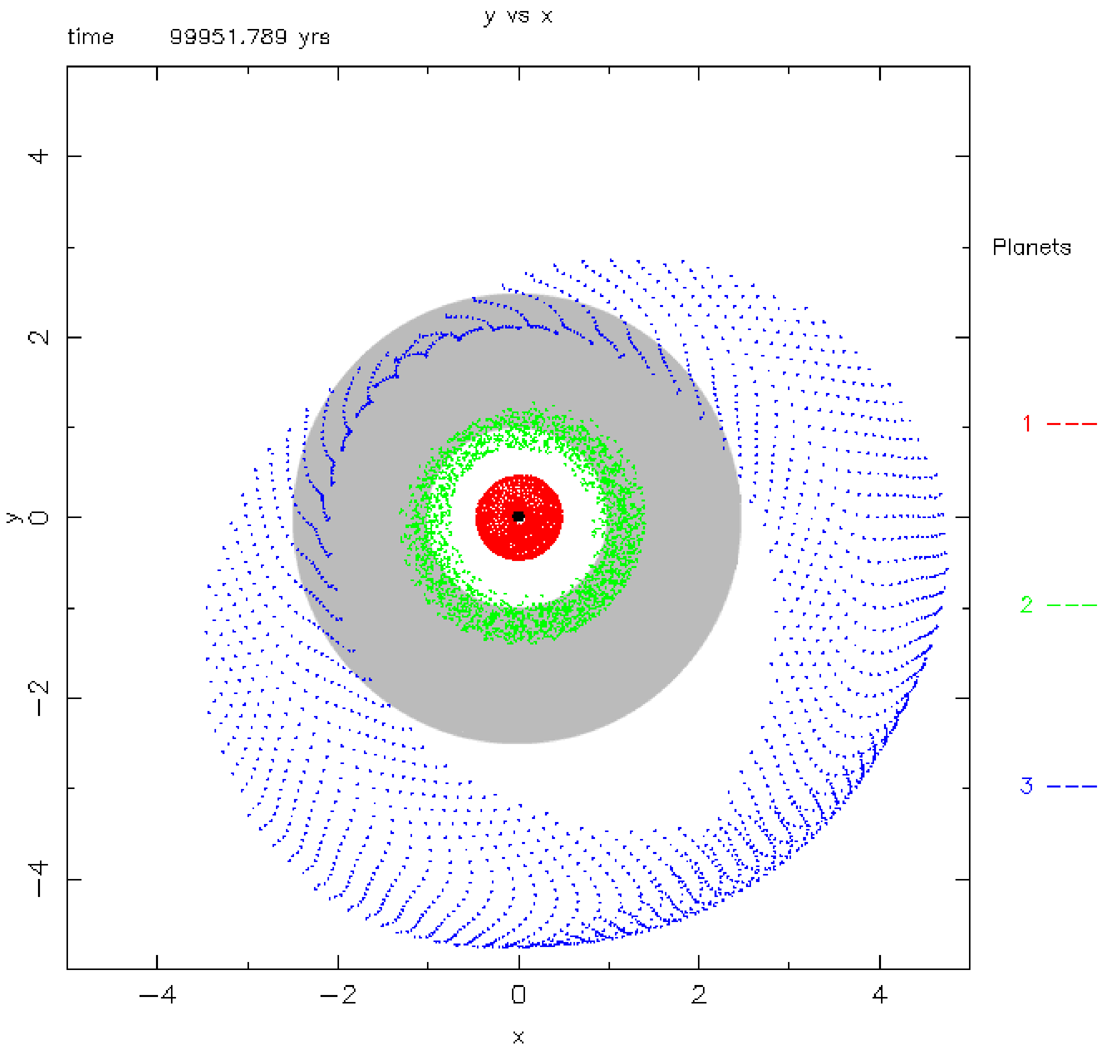

Figure 5: The habitability zone of HD 74156 is shown in gray. While an terrestrial planet placed at the inner edge of the habitability zone at a=1.07 with e=0.01 remains bound to the system for the duration of a 10^5 year simulation, it remains only partially in the habitable zone due to the cyclical variations in eccentricity.

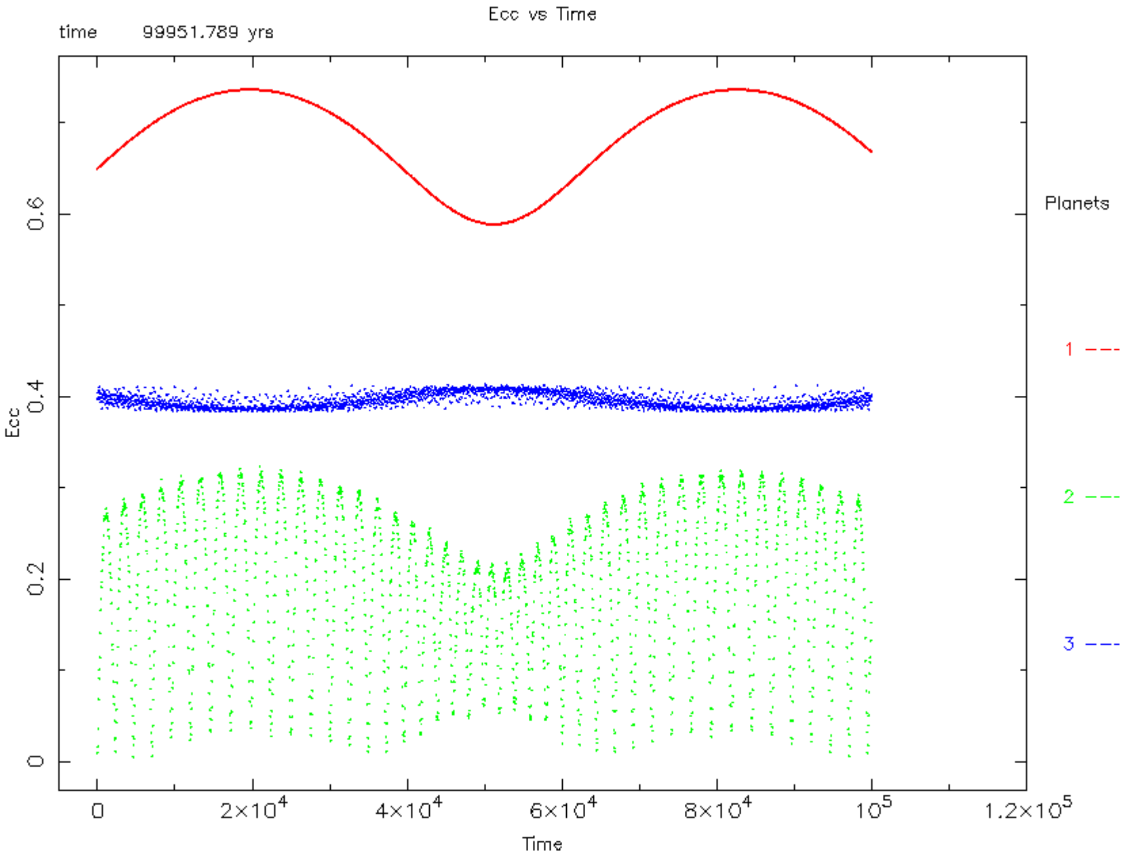

Figure 6: The eccentricity of the test planet (green) given an initial e=0.01 varies over time in step with the system's innermost planet (red) which has a high eccentricity.

Two other parameters that were varied in the simulations were the inclination of the system and the eccentricity of the orbit of the terrestrial planet. Tables 6 and 7 show the list and results of the simulations. For a planet placed at 1 AU in the system HD74156 the optimal values from these simulations were i=0° and e=0.1. For a planet placed at 1.07 AU, the inner edge of the habitability zone, the optimal values were i=0° and both e=0.01 and e=0.1. It should be noted that with an eccentricity of 0.01 for a planet placed at 1.07 AU, the planet does not consistently remain within the habitability zone as illustrated in Figure 5, and therefore cannot be considered dynamically habitable. When assigned an eccentricity of 0.1 however, the planet does remain in the habitability zone as evidenced by Figure 7, and can therefore be considered dynamically habitable. This result is in disagreement with those of Menou and Tabachnik (2000), who ran simulations using massless test particles in lieu of planets to test the dynamical stability and therefore habitability of the 85 systems in their investigation, and who did not find HD74156 to be dynamically habitable under any circumstances.

HD74156 with 0.003 M_{jup} test planet.

Planet S.M.A.	Planet Eccentricity	Planet Inclination	System Inc.	Total Int. Time in Years	Planet Survival in Years
0.8	0.10	0.0	0.0	100,000	70,000
0.8	0.10	0.0	0.0	100,000	100,000
0.8	0.10	0.0	0.0	100,000	14,000
0.8	0.01	0.0	0.0	100,000	70,000
0.8	0.01	0.0	0.0	100,000	55,000
0.8	0.01	0.0	0.0	100,000	90,000
1.0	0.01	0.0	0.0	100,000	100,000
1.0	0.01	0.0	0.0	100,000	41,000
1.0	0.01	0.0	0.0	100,000	100,000
1.0	*0.10*	*0.0*	*0.0*	*100,000*	*100,000*
1.0	*0.10*	*0.0*	*0.0*	*100,000*	*100,000*
1.0	*0.10*	*0.0*	*0.0*	*100,000*	*100,000*
1.0	0.10	2.5	2.5	100,000	100,000
1.0	0.10	2.5	2.5	100,000	100,000
1.0	0.10	2.5	2.5	100,000	20,000
1.0	0.10	5.0	5.0	100,000	100,000
1.0	0.10	5.0	5.0	100,000	55,000
1.0	0.10	5.0	5.0	100,000	100,000
1.07	*0.01*	*0.0*	*0.0*	*100,000*	*100,000*
1.07	*0.01*	*0.0*	*0.0*	*100,000*	*100,000*
1.07	*0.01*	*0.0*	*0.0*	*100,000*	*100,000*
1.07	*0.10*	*0.0*	*0.0*	*100,000*	*100,000*
1.07	*0.10*	*0.0*	*0.0*	*100,000*	*100,000*
1.07	*0.10*	*0.0*	*0.0*	*100,000*	*100,000*
1.2	0.01	0.0	0.0	100,000	18,000
1.2	0.01	0.0	0.0	100,000	33,000
1.2	0.01	0.0	0.0	100,000	4,000
1.2	0.10	0.0	0.0	100,000	5,000
1.2	0.10	0.0	0.0	100,000	100,000
1.2	0.10	0.0	0.0	100,000	3,000
1.5	0.01	0.0	0.0	100,000	3,000
1.5	0.01	0.0	0.0	100,000	3,000
1.5	0.01	0.0	0.0	100,000	3,000
1.5	0.30	0.0	0.0	100,000	1,000
1.5	0.30	0.0	0.0	100,000	3,000
1.5	0.30	0.0	0.0	100,000	3,000

Table 6: Simulation results for HD74156. The most stable configurations (planet remained for duration of simulation 3 out of 3 times) were with the planet placed at 1 AU with an ecc=0.1 and 1.07 AU with both an ecc=0.01 and e=0.1. The most unstable positions for a planet were at 1.2 AU and 1.5 AU, with 0.8 AU being slightly more stable.

HD12661 with 0.003 M_{jup} test planet.

Planet S.M.A.	Planet Eccentricity	Planet Inclination	System Inclination	Total Int. Time in Years	Planet Survival in Years
0.4	0.01	0.0	0.0	100,000	12,000
0.4	0.01	0.0	0.0	100,000	18,000
1.5	0.01	0.0	0.0	100,000	1,000
1.5	0.01	0.0	0.0	100,000	3,000
1.5	0.01	0.0	0.0	100,000	3,000

Table 7: Simulation results for HD12661. Both the planet placed at 0.4 AU, where there had been evidence of the possibility of stability, and the planet placed at 1.5 AU, within the planet's habitability zone, were ejected from the system early in the simulation.

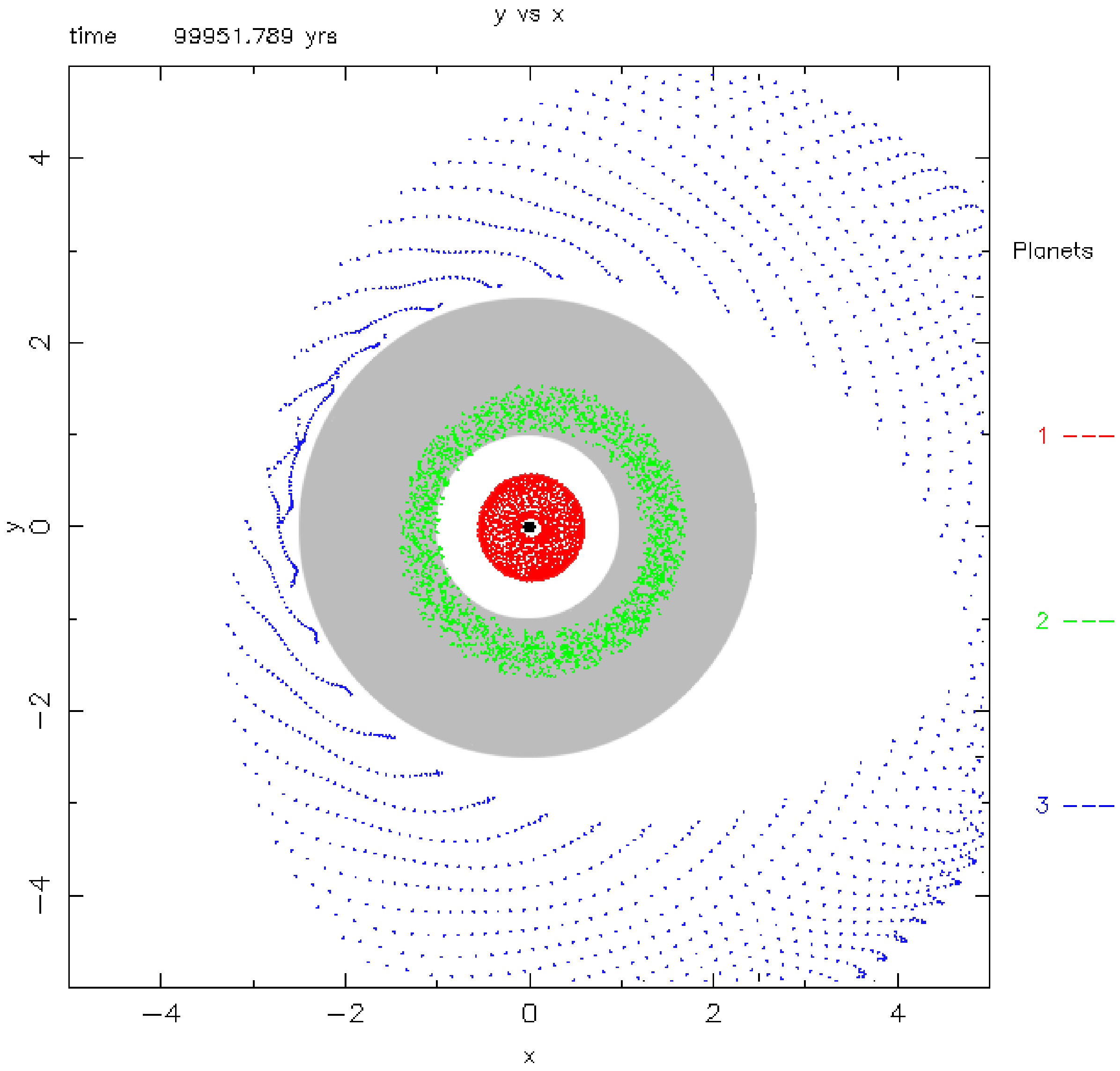

Figure 7: A planet placed at the edge of the habitability zone at 1.07 AU with e=0.1 not only remained stable for the duration of the10^{5} year simulation, but remains completely in the habitable zone in spite of its cyclical variations in eccentricity. As such, this system can be considered to be dynamically habitable.

The first comparison that can be made between the two systems HD74156 and HD12661 are the physical makeup of the two systems which is shown in Tables 1 and 2. This shows that the masses of their stars are very similar, though the M sin i for the planets orbiting around the stars do differ significantly. HD12661 has a heavier inner planet and lighter outer planet compared to HD74156, while the spacing between the planets and their eccentricities are greater in the later case. The integrations of the test particles and terrestrial planets in these systems have shown that HD74156 can support such astronomical objects while HD12661 is unable to keep an additional planet.

In the case of HD12661, the planetary system can be considered to be fully populated, at least for the region inside the orbits of the two existing planets where the habitability zone exists. These results confirm those found by Barnes and Raymond (2000).
The HD74156 system is not fully populated and can take at least an additional planet within the orbits of the two original planets. As well, there is some freedom in the choice of the eccentricity of this planet. Figure 6 shows that the eccentricity of the test planet with an initial e=0.01 varies over time in step with the system's innermost planet with its high eccentricity. This is likely due to the combination of the outer planet's higher mass and its distance from the star compared to the inner planet.

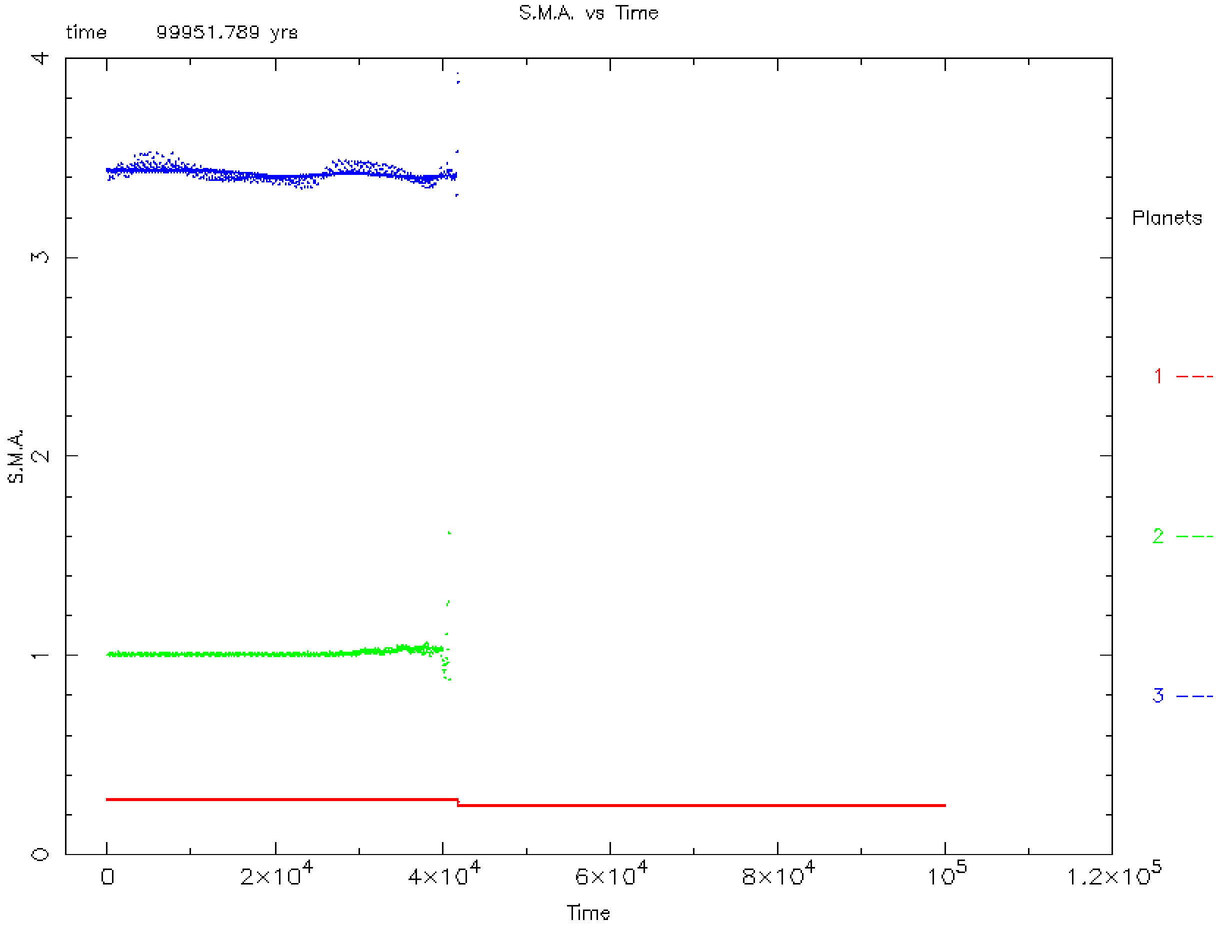

Figure 8: In this instance, a planet placed at 1AU with e=0.01 in a coplanar system of i=0 was ejected early in the simulation. This caused the outer planet to be ejected as well, and altered the orbit of the inner planet.

Figure 8 shows an interesting example of an occurrence seen occasionally in the integrations where the terrestrial planet was ejected from the system. In most such cases the orbits of both the interior and exterior planet were somewhat perturbed when the terrestrial planet was ejected, resulting in a change of SMA or eccentricity. In the case illustrated in Figure 8 the outer planet was also ejected, most likely due to a close encounter with the terrestrial planet and such events happening at times in the orbital relationships where even small perturbations cannot be tolerated. This would be an interesting area for future exploration.

Summary

It has been demonstrated that some systems with multiple Jupiter-like extrasolar planets may be able to support additional planets under certain conditions. In the systems investigated in this paper HD12661 showed that a system with a 2.3 M_{jup} planet with e=0.35 at 0.83 AU and a 1.57 M_{jup} planet with e=0.2 at 2.56 AU in orbit around a 1120.29 M_{jup} central star was unable to support addition planets between its larger bodies; however, HD74156 with a 1.56 M_{jup} planet with e=0.64 at 0.27 AU and a 7.5 M_{jup} planet with e=0.39 at 3.47 AU in orbit around a 1099.35 M_{jup} central star, was able to support at least one additional terrestrial planet. In the later case, this system was found to be stable for at least 10^5 years from a variety of initial conditions. The breadth of the stability region, as determined by TP's was found to be approximately 0.8 AU. However, among the test planets inserted at 0.8 AU, 1 AU, 1.07 AU, 1.2 AU and 1.5 AU, only the planets placed at 1 AU and 1.07 AU consistently remained stable for the duration of the integrations. This suggests that the breadth of the stability zone capable of holding a terrestrial planet may be less than 0.1 AU.

The results of computer simulations for the system HD74156 which has two Jupiter-like planets in orbit demonstrates that a region exists where a terrestrial planet can remain in orbit on a timescale of 10^5 years and with some variation in eccentricity of its orbit (0.01 – 0.1) and the system inclination ($\sim 5^o$). This is as expected for a system that would have a stable orbit. If only a very narrow range of orbital parameters could be tolerated the system would be susceptible to destabilization in orbit from relatively small perturbations in the system. Moreover, conditions were found which allowed an Earth-mass planet remain within the habitability zone for the duration of the 10^5 year integration, giving evidence that under the right conditions HD74156 can be considered a dynamically habitable system capable of hosting an Earth-like planet.

References

Barnes, R.; Quinn, T., 2001, *The Astronomical Journal*, Vol. 550, p.884-889.
Barnes, R. K.; Raymond, S. N., 2002, American Astronomical Society Meeting 201, #46.15.
Gladman, B.; Duncan, M.; Candy, J., 1991, *Celestial Mechanics and Dynamical Astronomy*, vol. 52, no. 3, p. 221-240.
Gozdziewski, K., 2003, *Astronomy and Astrophysics*, v.398, p.315-325.
Gozdziewski, K., 2003, *Astronomy and Astrophysics*, v.398, p.1151-1161.
Levison, H.; Duncan, M., 1994, *Icarus*, vol. 108, no. 1, p. 18-36.
Laughlin, G.; Chambers, J.; Fischer, D., 2002, *The Astrophysical Journal*, Vol. 579, p. 455- 467.
Marcy, G.; Butler, R.P.; Vogt, S.S.; Fischer, D.A.; 2000*, American Astronomical Society Meeting 197,* #70.01.
Marcy, G.; Butler, R.P, 2000, *The Publications of the Astronomical Society of the Pacific*, Volume 112, Issue 768, pp. 137-140.
Menou, K.; Tabachnik, S., 2003, *The Astrophysical Journal*, Volume 583, Issue 1, pp. 473-488.
Noble, M.; Musielak, Z.E.; Cunz, M., 2002, *The Astrophysical Journal*, Vol. 572, Issue 2, pp. 1024-1030.
Rivera, E.J.; Lissauer, J.J.; 2000, AAS, SPS Meeting #32, #31.07
Tabachnik, S.; Tremaine, S., 2002, *Monthly Notices of the Royal Astronomical Society*, Vol. 335, Issue 1, pp. 151-158.
Turnbull, M.C.; Tarter, J.C., 2003, *The Astrophysical Journal Supplement Series*, Vol. 145, Issue 1, pp. 181-198.
Williams, D. M.; Pollard, D., 2002, *Int. Journal of Astrobiology*, 1, 61.
Wisdom, J.; Holman, M., 1991, *Astronomical Journal*, vol. 102, p. 1528-1538.