A dynamic search for potential habitable planets amongst the extrasolar planets

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ABSTRACT:

While the detection of habitable terrestrial planets around nearby stars is currently beyond our observational capabilities, dynamical studies can help us locate potential candidates. Following from the work of Menou & Tabachnik (2003), we use a symplectic integrator to search for potential stable terrestrial planetary orbits in the habitable zones of known extrasolar planetary systems. A swarm of massless test particles is initially used to identify stability zones, and then an Earth-mass planet is placed within these zones to investigate their dynamical stability. We investigate 22 new systems discovered since the work of Menou & Tabachnik, as well as simulate some of the previous 85 extrasolar systems whose orbital parameters have been more precisely constrained. In particular, we model three systems that are now confirmed or potential double planetary systems: HD169830, HD160691 and eps Eridani. The results of these dynamical studies can be used as a potential target list for the Terrestrial Planet Finder.

Introduction

To date 122 extrasolar planets have been detected around 107 stars, with 13 of them being multiple planet systems (Schneider, 2004). Observational evidence for the likelihood of the existence of small planets around other stars has been presented by Marcy et al. (2000), suggesting that it is common for rocky worlds to form around young stars. This evidence coupled with the observation by Marcy & Butler (2000) that the mass distribution of planets rises steeply with decreasing mass, leads to the conclusion that up to 50% of all stars may have rocky planets.

For a terrestrial planet to be capable of supporting life as we know it, certain conditions must be met, including the presence of certain heavy elements, surficial liquid water and a range of temperatures that allow the retention of an atmosphere Kasting et al. (1993). The region around a star where such requirements are met is referred to as the habitable zone (HZ). For a terrestrial planet to remain habitable, there is the additional dynamical requirement that other planets in the system don't gravitationally perturb the planet outside of its habitable zone. When these conditions are met a system can be considered to be dynamically habitable.

In this preliminary investigation we use numerical integrations to determine the likelihood of a terrestrial planet existing in the habitable zones of 17 extrasolar systems discovered in the past three year, three of which are known (or suspected) to host two jovian planets.

Planetary Systems

Since the study of Menou & Tabachnik (2003), 22 new extrasolar planets have been detected. Four of these 22 new systems (OGLE-TR-56 b, HD73256 b, HD330075 b and HD76700 b) were rejected from this study because of their short orbital periods (< 5 days), and another four (HD219449 b, HD59586 b, gamma Cephei b and HD47536 b) were rejected due to poorly constrained stellar or planetary parameters. We have investigated the potential stability of an Earth-like planet in the habitable zone of the 14 remaining systems (see table 1). We also included three systems studied by Menou & Tabachnik (HD169830, HD160691 and eps Eridani) which have since been found to contain a second jovian planet.

System	M_{star} (M_{sun})	M_{pl} (M_{Jup})	ecc	a (AU)	HZ_{min} (AU)	HZ_{max} (AU)
HD 70642 b	1.0	2.0	0.1	3.3	0.700	1.550
HD 41004A b	0.7	2.3	0.39	1.31	0.343	0.760
HD 104985 b	1.5	6.3	0.03	0.78	1.575	3.488
HD 216770 b	0.9	0.65	0.37	0.46	0.567	1.256
HD 219542B b	1.06	0.3	0.32	0.46	0.787	1.742
HD 3651 b	0.79	0.2	0.63	0.284	0.437	0.967
HD 192263 b	0.79	0.72	0.0	0.15	0.437	0.967
HD 162020 b	0.7	13.75	0.277	0.072	0.343	0.760
HD 142415 b	1.03	1.62	0.5	1.05	0.743	1.644
HD 65216 b	0.92	1.21	0.41	1.37	0.592	1.312
HD 10647 b	1.07	0.91	0.18	2.1	0.801	1.775
HD 111232 b	0.78	6.8	0.2	1.97	0.426	0.943
HD 2039 b	0.98	4.85	0.68	2.19	0.672	1.489
HD 216435 b	1.25	1.49	0.34	2.7	1.094	2.422
HD 169830 b	1.4	2.88	0.31	0.81	1.372	3.038
HD 169830 c		4.04	0.33	3.6		
HD160691 b	1.08	1.7	0.31	1.5	0.816	1.808
HD160691 c		1.0	0.8	2.3		
eps Erid b	0.8	0.86	0.608	1.5	0.448	0.992
eps Erid c		0.1	0.3	40		

Table 1: System parameters based on data from the Extrasolar Planets Encyclopaedia[2]. Stellar mass is given in solar masses, planetary mass in Jupiter masses, semi-major axis (a), inner and outer habitable zone extent (HZ_{min} and HZ_{max}) in astronomical units.

Determination of Habitable Zones

The location of the habitable zone depends on the mass of the parent star, M_*, and the composition of the atmosphere of the planet (Kasting et al. 1993). In this investigation we use the following formula for determining the HZ of each system:

$$HZ_{inner} = 0.7 \times M_*^2 \quad \text{and} \quad HZ_{outer} = 1.55 \times M_*^2$$

This gives a resulting HZ comparable to those defined by Menou & Tabachnik.

Acknowledgements

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1 - SWIFT integration package http://www.boulder.swri.edu/~hal/swift.htm
2 - Extrasolar Planets Encyclopaedia http://www.obspm.fr/encycl/encycl.html

Numerical Technique

To follow the evolution of the planetary systems, we use the SWIFT integration software package[1]. This allows us to model a planetary system and a swarm of massless test particles in orbit around a central star. We use the Regularized Mixed Variable Simpletic algorithm (Levison & Duncan, 1994) which integrates close encounters between planets and test particles symplectically. The time step is chosen to be 1/20 of the shortest orbital period in the simulation to ensure accuracy.

Each system's suitability for harboring additional planets was investigated by randomly distributing 1000 massless test particles in the systems HZ and integrating for 10^6 or 10^7 years. The initial test particles eccentricities were the range 0.0 to 0.1 with maximum inclinations of 10 degrees. Most systems were modelled three times to ensure that the results were independent of exact initial conditions.

Stability zones are defined as those regions where a significant number of test particles cluster and remain at a constant orbital distance for the duration of the simulation. If stability zones were found, an Earth mass planet was added to the stable zone (with a range of semi-major axis and eccentricity values) and evolved for 10^7 years.

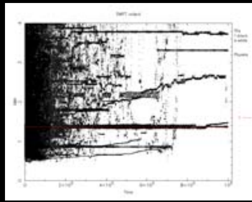

Figure 1: HD65216 – semi-major axis vs time plot shows that all the only TPs remaining in the HZ are in resonance with the planet.

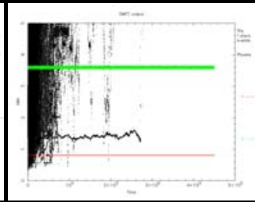

Figure 2: HD169830 – semi-major axis (AU) vs time (years) plot shows that all of the TPs were ejected from the HZ by 5 x 10^5 years.

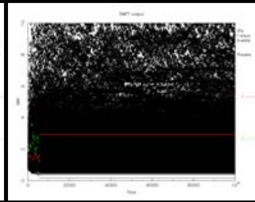

Figure 3: HD160691 – all simulations eject the outer planet very quickly. The orbital elements are currently unconstrained and our simulations indicate that the current values are likely incorrect.

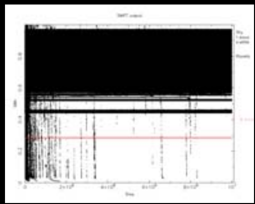

Figure 4: HD3651 – after 10^7 years there is a broad TP stable zone between 0.57-0.96 AU and possible stable zones between 0.43-0.56 AU.

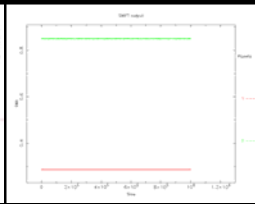

Figure 5: HD3651 with an Earth mass planet initially at a=0.85AU & e=0.0. Appears stable for 10^6 years.

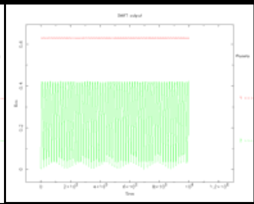

Figure 6: HD3651 with an Earth mass planet initially at a=0.85AU & e=0.0. The terrestrial's eccentricity (green) is pumped up to uninhabitable values .

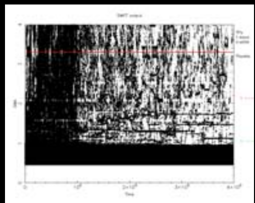

Figure 7: eps Eridani – shows a wide zone of stability at 0.43AU< a <1AU, closely corresponding with the HZ 0.448 – 0.992 AU

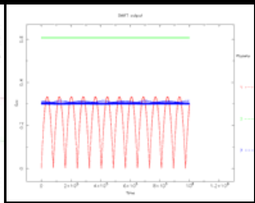

Figure 8: eps Eridani with an Earth mass planet initially at 0.46AU &and e=0.0. The eccentricity of the test planet (red) is pumped to uninhabitable values.

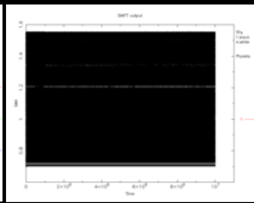

Figure 9: JD70642 – shows a broad zone of stability between 0.7 – 1.55 AU which a few thin cleared regions. Potential habitability.

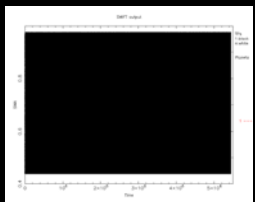

Figure 10: HD192263 – the HZ stays very stable within0.43 – 0.96 AU for 10^7 years.

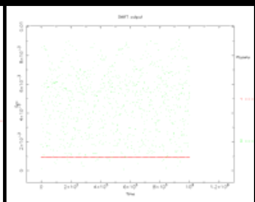

Figure 11: HD192263 with an Earth mass planet initially at a=0.7AU and e=0.0. Stable for at least 10^6 years.

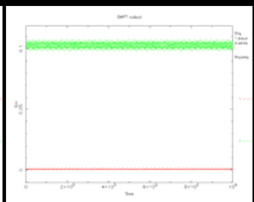

Figure 12: HD192263 with an Earth mass planet initially at a=0.7AU and e=0.1. Eccentricity remains constant.

Results & Discussion

The systems we have investigated broadly fall in four categories: (1) unstable systems which eject all 1000 test particles within 10^6 years; (2) uninhabitable systems which may contain stable test particle zones but which result in high eccentricity pumping of Earth mass planets placed in those regions; (3) potentially habitable systems which have broad stable test particle zones and stable Earth mass planets for some initial planetary orbits; and (4) highly likely habitable systems which resulted in stability for all test particles and all Earth mass planets configurations tested. Our results are summarised in table 2.

System	HZ (AU)	T_{sim} (yrs)	N_{tp}	TP SZ (AU)	habitable planet in HZ	type
HD 70642	0.700 - 1.550	1.0e7	1000	0.74 - 1.55	possible	3
HD 41004A	0.343 - 0.760	4.3e6	0	…	…	1
HD 104985	1.575 - 3.488	1.0e7	990	1.55 - 3.6	probable	4
HD 216770	0.567 - 1.256	1.0e7	594	0.8 - 1.28	e > 0.3	2
HD 219542B	0.786 - 1.742	1.0e7	982	0.8 - 1.7	e > 0.3	2
HD 3651	0.436 - 0.967	1.0e7	641	0.57 - 0.98	e > 0.4	2
HD 192263	0.436 - 0.967	5.5e6	1000	0.44 - 0.98	probably	4
HD 162020	0.343 - 0.760	2.2e6	1000	0.32 - 0.9	e > 0.3	2
HD 142415	0.742 - 1.644	7.7e5	0	…	…	1
HD 65216	0.592 - 1.321	1.0e6	6	…	…	1
HD 10647	0.801 - 1.775	1.0e6	596	0.8 - 1.7	e > 0.2 if a > 1.2	2-3
HD 111232	0.425 - 0.943	6.0e5	576	0.4 - 1.2	e > 0.3	2
HD 2039	0.672 - 1.489	2.0e5	0	…	…	1
HD 216435	1.093 - 2.422	5.5e6	21	0.1 - 1.5	unstable	2
HD 169830	1.372 - 3.038	5e5	0	…	…	1
HD160691	0.816 - 1.808	5e4	0	…	…	1
eps Erid	0.448 - 0.992	1e7	629		e > 0.5	2

Table 2: In all cases 1000 TPs were randomly distributed within the HZ and the simulation run for up to 10^7 years. The second column lists the habitable zone of each system and N_{TP} shows the number of test particles remaining at the end of the simulation, whose duration is reflected by T_{sim}. In the cases where 0 TPs remain, the time that the last particle was ejected from the system is reflected in T_{sim}. The TP SZ indicates the stable zone for a significant number of TPs at the end of the simulation. Planets were then placed in various locations within the TP SZ. Type 1 are unstable for TPs, type 2 have some SZ for TPs but uninhabitable planets, type 3 have SZ for TPs and planets may be habitable, and type 4 are most likely to host habitable planets.

Five of the systems were found to eject all 1000 test particles within a few million years (HD41004A, HD142415, HD2039, HD169830 and HD160691) and one system (HD65216) traps a few particles in resonance with the planet (see Fig. 1). Menou & Tabachnik modelled HD169830 which has since been found to host two jovain planets. We find the HZ of HD169830 to be unstable (Fig. 2) in agreement with Erdi et al. (2004) who found the HZ chaotic and incapable of hosting an Earth mass planet due to the overlapping of the resonances and large masses of the existing planets. Double planet system HD160691 (Fig. 3) was found to be dynamically unstable (as suggested by Bois et al. 2003), likely because the orbital elements for the outer planet remain unconstrained.

Six systems (HD216770, HD219542B, HD3651, HD111232, HD216435 and eps Eridani) were considered to be 'uninhabitable'. These systems contained regions of TP stability, but Earth mass planets placed in these stable zones (with initial e < 0.15) were pumped to high eccentricities (e > 0.3) in just 10^6 years. This is not uncommon when the jovian planet has a reasonably high eccentricity and is quite close to the HZ. See e.g. HD3651 (Figs. 4) with an Earth mass planet with initial a=0.85A & e=0.0 (Figs. 5 & 6). While the double jovian system eps Eridani had a broad TP SZ (see Fig. 7) the eccentricity pumping of eps Eridani b would leave any terrestrial uninhabitable (see Fig. 6).

Two systems were found to have the potential to host habitable planets (HD70642, HD10647) depending on the initial position and eccentricity of the terrestrial planet. Only two systems were found to host stable habitable planets for a wide variety of planetary orbits (HD104985 and HD192263).Both systems had very stable TP zones (see Fig. 10) and due to the low eccentricities of the jovians the Earth mass planets were also stable over a range of initial conditions (see Fig. 11 & 12).

Simple investigations such as this can determine potential stability within the habitable zones using test particle swarms. Investigating the habitability of Earth mass planets within the stable zones required a very large parameter space to be searched. We are continuing this search using methods similar to Asghari et al. (2004).

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