THE STABILITY AND PROSPECTS OF THE DETECTION OF TERRESTRIAL/HABITABLE PLANETS IN MULTIPLE PLANET AND MULTIPLE STAR SYSTEMS

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Abstract. Given the tendency of planets to form in multiples, and the observational evidence in support of the existence of potential planet-hosting stars in binaries or clusters, it is expected that extrasolar terrestrial planes are more likely to be found in multiple body systems. This paper discusses the prospects of the detection of terrestrial/habitable planets in multibody systems by presenting the results of a study of the long-term stability of these objects in systems with multiple giant planets (particularly those in eccentric and/or in mean-motion resonant orbits), systems with close-in Jupiter-like bodies, and systems of binary stars. The results of simulations show that while short-period terrestrial-class objects that are captured in near mean-motion resonances with migrating giant planets are potentially detectable via transit photometry or the measurement of the variations of the transit-timing due to their close-in Jovian-mass planetary companions, the prospect of the detection of habitable planets with radial velocity technique is higher in systems with multiple giant planets outside the habitable zone and binary systems with moderately separated stellar companions.

1 Introduction

A survey of the currently known extrasolar planetary systems indicates that more than 30 of these systems are hosts to two or more giant planets. Similar to our solar system, where the simulations of planet formation show that terrestrial and giant planets form in multiples, many of these systems may also harbor smaller terrestrial-class objects. A study of the stars of these systems reveals that some of these stars are members of binaries or multi-star systems. In fact, approximately 25% of planet-hosting stars are within dual-star environments implying that planet
formation in multi-star systems is robust and many of these systems may host additional smaller objects.

At present, the detection of terrestrial/habitable planets in systems with multiple giant planets and/or close stellar companions is not a feasible task. However, space-based telescopes such as NASA’s Kepler and SIM are on their ways to pave the road to the discovery of many of these objects in the near future. It, therefore, proves useful to study the characteristics of multibody systems, and to identify the dynamical and orbital properties of those that are capable of hosting habitable planets.

In a multibody system, the perturbation of the giant planets and stellar companions have profound effects on the formation and long-term stability of habitable planets. As shown by the simulations of the formation of terrestrial planets in our solar system, the formation of these objects (especially in the habitable zone) and their water contents are strongly affected by the dynamics of Jupiter (Chambers & Cassen 2002). The perturbative effect of this object will increase the orbital eccentricities of the planetesimals and protoplanetary bodies, which in turn results in their collision and/or ejection from the system. The radial mixing of these objects, induced by the close approach of Jupiter, delivers planet-forming material, including water-carrying protoplanets, from different regions of the asteroid belt to the accretion zone of proto-Earth.

The efficiency of the removal of material and the collisional growth of protoplanetary bodies is a function of the orbital eccentricity of the giant planet. For instance, as shown by Chambers & Cassen (2002) and Raymond (2006), an eccentric Jupiter will cause severe depletion of icy asteroid from the outer part of the asteroid belt, which subsequently results in the formation of a smaller and drier Earth. In an extrasolar planetary system with multiple stars and/or giant planets, such effects are much stronger. In order for such multibody systems to be habitable, not only do Earth-like planets, with substantial amounts of water, have to form in their habitable zones, the orbits of these objects have to be immune to the perturbation of other bodies and maintain their stability for long times.

This paper presents the results of an extensive study in identifying systems in which the interactions among multiple bodies allow long-term stability of terrestrial-class objects and the indirect detection of these bodies. In the next section, the results of a study of the stability of habitable planets in system with multiple giant planets are presented. As examples of such systems, the two systems of 55 Cnc and GJ 876 are discusses. In section 3, habitability of moderately close binary star systems are studied, and in section 4 the results of a study of the implications of the dynamics of terrestrial-class and Super-Earth objects on their detections using the transit timing variation method in the vicinity of hot-Jupiters are presented.

2 Multiple Giant Planet Systems

The formation and stability of terrestrial planets are strongly affected by the perturbation of giant bodies. Not only do the latter objects remove protoplanetary material that may contribute to the formation of terrestrial planets, they may
Fig. 1. Graphs of the lifetimes of test particles in the planetary systems of GJ 876 and 55 Cnc (Rivera & Haghighipour 2007). The habitable zones of the two systems are also shown. The red arrows in both graphs show the locations of the terrestrial-size planets of the two systems.

also destabilize the regions where these planets can form. Such perturbative effects are stronger in extrasolar planetary systems with several Jovian-type bodies, in particular those in eccentric orbits (e.g., GJ 876, υ Andromedae, 47 UMa, 55 Cnc, Gl 581, HD 40307, HD 37124, HD 74156, HD 160691, and HD 69830).

Prior to the study of habitable planet formation in such systems, it is necessary to determine whether the orbit of an Earth-like planet in the habitable zones of their central stars are stable. For this purpose, the equations of the motion of an Earth-like planet have to be integrated for a long time and for different values of its orbital elements. Given the system’s vast parameter-space, performing such integrations will be a very time-consuming task. However, it is possible to consolidate many of these integrations into one by taking into account that an Earth-like planet is two orders of magnitude smaller than a giant body and its affect on the orbital dynamics of the latter object may be negligible. In other words, to the zeroth order of approximation, Earth-like planets can be replaced by test particles. Given that it is desired for a habitable planet to spend most of its orbital motion in the system’s habitable zone, it would also not be too unrealistic to assume that these test particles have circular orbits. Such test particle approximations are not exact, but produce a rough mapping of the parameter-space which indicates regions where small planets can have stable orbits. Figure 1 shows the results of two of such integrations for GJ 876 and 55 Cnc (Rivera & Haghighipour 2007). GJ 876 is a system of two giant planets with semimajor axes of 0.13 AU and 0.21 AU, and eccentricities of 0.27 and 0.025, respectively. The motion of an Earth-like planet in the habitable zone of this system (0.1-0.25 AU) is disturbed by the gravitational forces of its two giant bodies. Results of the numerical integrations of test particles indicate that the habitable zone of this system is unstable and as expected, stability occurs at distances outside the influence zones of the giant planets. The stable regions of Figure 1a are representatives of orbits in which Earth-size planets
may potentially exist. As an example, the location of the recently discovered 7.5 Earth-mass planet of this system (Rivera et al. 2005), denoted by a red arrow in Figure 1a, is in one of such stable regions.

The planetary system of 55 Cnc shows a different characteristic. Unlike GJ 876, this system has a habitable zone that extends from 0.70 AU to 2.71 AU and is outside the gravitational influence of the system’s three giant planets ($a=0.115$, 0.24, 5.77 AU, and $e=0.014, 0.086, 0.025$). In this system, the habitable zone and a vast area in its vicinity are stable and can host smaller (i.e., terrestrial-class) objects. The two Earth-size planet of this system, with semimajor axes of 0.038 AU and 0.781 AU, are located in this area (Fischer et al. 2008). These integrations indicate that, in a multiplanet system, although small planets may exist at distances outside the orbits of giant bodies, terrestrial-size objects are more likely to be found in systems where giant planets are so far away from the central star that stable regions exist interior to their orbits. For more details, the reader is referred to Rivera & Haghighipour (2007).

### 3 Binary Star Systems

Other interesting and dynamically complicated multibody planetary systems are planets in binary stars. In such systems, (giant) planets revolve around a star of a binary. Approximately 25% of the currently known stars with extrasolar planets are of this kind. The fact that (giant) planets exist in such environments is an indication that planet formation in dual-star systems is robust and many of these systems may also host smaller (e.g., terrestrial-class) objects.

The formation and the prospect of the detection of habitable planets in binary-planetary systems are affected by the perturbations of their giant planets and the gravitational force of their stellar companions. In the majority of the currently known binary-planetary systems, the stellar companion is at distances of 250 AU to 6000 AU from the primary (planet-hosting) star and its perturbative effect is negligible. However, systems with giant planets exist (namely, GJ 86 and γ Cephei) in which the binary separation is smaller than 20 AU. In such systems, terrestrial/habitable planet formation is strongly affected by both the giant planet and the secondary star. Simulations of the orbital evolution of an Earth-like planet in the γ Cephei system have shown that the rate of the survival of a terrestrial planet is much higher at distances close to the parent star. In other words, habitable planets can have stable orbits in such close binaries when the habitable zone is outside the region of the influence of the giant planet and close to the planet-hosting star (Haghighipour 2006).

The above-mentioned stability condition categorizes the type of the close binary-planetary systems that may be habitable, and raises the question of the possibility of the formation of Earth-like objects in the habitable zones of such systems. A recent study by Haghighipour & Raymond (2007) has addressed this issue by simulating the late stage of terrestrial planet formation around the primary of a moderately close binary-planetary system. The left graph of Figure 2 shows snap shots of the formation and evolution of one of such simulations. The system in
this figure consists of two Sun-like stars with a separation of 30 AU. The binary eccentricity is 0.2 and the primary is host to a Jupiter-size planet in a circular orbit at 5.2 AU. The system also includes a disk of protoplanetary bodies with 120 Moon- to Mars-sized objects distributed randomly between 0.5 AU and 4 AU. The orbit of the giant planet was chosen to be circular to minimize its initial perturbative effect on the collision and evolution of protoplanetary objects. To simulate the delivery of water to the region of the accretion of a terrestrial planet around the primary star, a water gradient was assumed for the protoplanetary bodies. Similar to the water distribution among the primitive asteroids in the asteroid belt, inside 2 AU, protoplanets were taken to be dry, between 2 AU and 2.5 AU, they were given 1% water, and beyond 2.5 AU, their water content was set to 5%. Simulations show that after 100 Myr, an Earth-size object (1.17 Earth-mass) was formed inside the habitable zone at 1.16 AU, with an eccentricity of 0.02 and water content of 0.164%. As a point of comparison, the orbital eccentricity of Earth is 0.017 and its water content is approximately 0.1%.

Simulations were also carried out for different values of the binary’s mass-ratio, semimajor axis, and orbital eccentricity. The right graph of Figure 2 shows some of the final results for a binary mass-ratio of unity. As shown here, the sizes and water contents of the final terrestrial planets vary with the semimajor axis and eccentricity of the stellar companion. In fact, it is the periastron distance of the secondary star that dictates the evolution of the system and the final assembly of the terrestrial planets. In binaries with small periastra, the interaction between the secondary star and the giant planet increases the orbital eccentricity of the latter body and causes close approaches between this object and the planetary embryos. By transferring angular momentum from the secondary star to the protoplanetary disk, the giant planet causes many of these object, including those that carry water,
to be ejected from the system. As a result, in closer and eccentric binaries, the final products of the simulations are smaller terrestrial planets that contain less or no water. The left graph of Figure 3 shows the relation between the periastron of the binary ($q_b$) and the semimajor axis of the outermost terrestrial planet ($a_{\text{out}}$). As shown in this graph, similar to Quintana et al. (2007), simulations with no giant planets favor regions interior to $0.19q_b$ for the formation of terrestrial objects. This implies that, for the simulation of Figure 2, where the primary is a Sun-like star, and the inner edge of the habitable zone is at $\sim 0.9$ AU, habitable planets would not form if the perihelion distance of the secondary star is smaller than $0.9/0.19 = 4.7$. In simulations with giant planets, on the other hand, Figure 3 shows that terrestrial planets form closer-in. The ratio $a_{\text{out}}/q_b$ in these systems is between 0.06 and 0.13.

A detailed analysis of the simulations of the systems in which habitable planets formed indicates that binaries in these systems have large periastra. The right graph of Figure 3 shows this for the simulations of Figure 2. The circles in this figure represent systems with habitable planets. The numbers on the top of the circles show the mean eccentricity of the giant planet at the end of each simulation. As a comparison, systems with unstable giant planets have also been marked. Since at the beginning of each simulation, the orbit of the giant planet was considered to be circular, a non-zero eccentricity for the orbit of this object is the result of the interaction between this body and the secondary star. As shown in this graph, Earth-like objects are formed in systems where the orbital eccentricity of the giant planet is small. In other words, systems in which the interaction between this object and the secondary star is weak. Figure 3 indicates that habitable planet formation favors binary-planetary systems with moderate to large perihelia, and with giant planets on low eccentricity orbits.
4 Transiting Systems

Detecting more than 50 extrasolar planets during the past decade, transit photometry has proven to be a successful technique in identifying planetary bodies around other stars. This technique that measures the decrease in the brightness of a star when occulted by a transiting planet, is more sensitive to close-in and larger objects; the currently known transiting planets are of Neptune- to Jupiter-size and majority of them have orbital periods between 2 to 4 days.

It is widely accepted that such close-in giant planets were formed at large distances and arrived at their current orbits after undergoing radial migration through interaction with the circumstellar disks of their parent stars. Numerical simulations have indicated that, despite the scattering of planet-forming material and fully formed planets to large distances during the inward migration of a giant body, Earth-like planets can still form in such systems and possibly close to the transiting object (Raymond et al. 2006, Mandell et al. 2007). In the case of the latter, the gravitational force of the smaller planet perturbs the orbit of the giant body and causes variations in the time of its transits. As shown by Agol et al. (2005) and Steffen & Agol (2005), such transit timing variations (TTV) can be used to identify the orbital and physical characteristics of the perturbing terrestrial planet.

The variations in the transit timing of a giant planet are functions of the mass and orbital elements (i.e., semimajor axis and eccentricity) of the perturbing body. Agol et al. (2005) have shown that these variations become considerably large when the perturbing and transiting planets are in a mean-motion resonance. Given the small size of a perturbing object (i.e., terrestrial-size) and its proximity to the transiting body, it would not be surprising if for some values of the orbital elements of the two planets, the orbit of the former object became unstable. Since large TTV signals require strong interactions between the transiting and perturbing planets (i.e., close approaches which are results of larger orbital eccentricity), and they are larger when the two bodies are in a mean-motion resonance, it is therefore necessary to identify regions of the parameter-space for which an Earth-like planet can maintain its orbit for long times and produce large TTV signals.

Recently Haghighipour et al. (2008) have addressed this issue by integrating the motion of an Earth-size planet in a transiting system. The planetary model considered by these authors consists of a Sun-like star, a transiting Jupiter-size planet in a 3-day circular orbit, and an Earth-size object. Using the N-body integration package MERCURY (Chambers 1999), these authors simulated the dynamics of this system for different values of the semimajor axis (0.01 AU to 0.075 AU), orbital eccentricity (0, 0.05, 0.1, 0.3), and orbital inclination (0, 5 deg.) of the small body for 1 Myr. Results for a co-planar system are shown in Figure 4. The circles in this figure represent the values of the semimajor axis and eccentricity of the Earth-size planet at the beginning of each simulation. Black circles correspond to stable orbit whereas green indicates instability. The widths of the major resonances are also shown. Note that no Earth-like planet was placed in the region between $a - 3R_H$ and $a + 3R_H$ where $a$ and $R_H$ are the semimajor
Fig. 4. Graph of stability for an Earth-size planets in a transiting system. The central star is Sun-like. The transiting planet (not shown here) is Jupiter-like in a 3-day circular orbit at 0.0407 AU. The circles correspond to the values of the semimajor axis and eccentricity of the Earth-like planet at the beginning of each simulation. The orange dotted lines show the boundaries of the unstable region for an Earth-size planet. The red circles present conservative regions of the stability of a terrestrial-class object.

axis and Hill radius of the Jupiter-like planet. As shown in this figure, regions exist where the orbit of the Earth-size planet becomes unstable. For outer orbits, this region extends to the outer edge of 2:1 MMR and is limited to eccentricities below 0.2. For the inner orbits, stability seems to exist interior to 2:3 MMR and for the values of eccentricity equal to and smaller than 0.3. Integrations for longer times (beyond 1 Myr) and for a massive perturber (up to 15 Earth-mass) have, however, indicated that, except for 1:2 and 1:3 MMRs, where the orbit of the Earth-like planet stays stable for values of its orbital eccentricity up to 0.5 (Haghighipour 2008b), as the mass of the Earth-like planet increases, the boundaries of the unstable region expand and tend toward lower values of eccentricity. In a conservative approach, the red circles in Figure 4 show the most stable regions of the eccentricity-semimajor axis space. As shown here, a terrestrial-class object in the vicinity of a transiting giant planet, will be stable if its orbit has an eccentricity lower than 0.2 and is in a low-order MMR with the giant body. As shown in Figure 5, the TTV signal produced by such a perturber is quite large and falls within the sensitivity of the current detection techniques.
Fig. 5. Graphs of TTV signals for an Earth-size planet in an interior 1:2 (Left) and exterior 5:2 (right) MMR with a transiting giant planet. Graphs from Haghighipour et al. (2008c).

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