Extreme Habitability: Formation of Habitable Planets in Systems with Close-in Giant Planets and/or Stellar Companions

Nader Haghighipour

*Institute for Astronomy and NASA Astrobiology Institute, University of Hawaii-Manoa, Honolulu, Hawaii, USA*

**Abstract.** With more than 260 extrasolar planetary systems discovered to-date, the search for habitable planets has found new grounds. Unlike our solar system, the stars of many of these planets are hosts to eccentric or close-in giant bodies. Several of these stars are also members of moderately close (<40 AU) binary or multi-star systems. The formation of terrestrial objects in these "extreme" environments is strongly affected by the dynamics of their giant planets and/or their stellar companions. These objects have profound effects on the chemical structure of the disk of planetesimals and the radial mixing of these bodies in the terrestrial regions of their host stars. For many years, it was believed that such effects would be so destructive that binary stars and also systems with close-in giant planets would not be able to form and harbor habitable bodies. Recent simulations have, however, proven otherwise. I will review the results of the simulations of the formation and long-term stability of Earth-like objects in the habitable zones of such "extreme" planetary systems, and discuss the possibility of the formation of terrestrial planets, with significant amounts of water, in systems with hot Jupiters, and also around the primaries of moderately eccentric close binary stars.

1. Introduction

An analysis of the orbital properties of the currently known extrasolar planets indicates that many of these objects have dynamical characteristics that are profoundly different from those of the planets in our solar system. While around the Sun, planets keep nearly circular orbits with smaller planets at closer distances and the larger ones farther way, from the 263 exoplanets that were discovered at the time of the writing of this article, 68 were at distances smaller than 0.1 AU from their host stars, and 126 revolve in orbits with eccentricities larger than 0.2 (figure 1). A deeper look at the parent stars of these planets indicates that the differences between their planetary systems and the Solar System are not limited to the semimajor axes and eccentricities of their planetary companions. Several of these stars (approximately 20% of currently known extrasolar planet-hosting stars) are members of binaries or multi-star systems.

Since the masses of the majority of extrasolar planets are within the range of a few Neptune- to several Jupiter-masses, the eccentric and close-in orbits of these bodies, and the fact that several of them exist around the components of binary stars, raise questions on the formation of such extreme planetary systems, and also on the possibility of the existence of smaller planets, such as terrestrial-
class objects, around their host stars, and particularly in their systems’ habitable zones. In this paper, I review the current status of research on the formation of habitable planets in these extreme planetary environments, and discuss the results of the simulations of Earth-like planet formation in systems with close-in giant planets and binary companions.

2. Systems With Close-in Giant Planets

It is widely accepted that the close-in giant planets have formed at larger distances and have migrated to their current positions. During their migrations, these objects perturb the orbits of smaller bodies on their paths and affect the interactions among these objects. In general, the perturbative effect of a migrating giant planet causes the orbital eccentricities and/or inclinations of planetesimals and protoplanets to rise to higher values. Whether these dynamically hot objects can cool down and re-interact to form terrestrial bodies depends on the mass of the migrating planet and its rate of migration. While, as shown in figure 2, simulations by Armitage (2003) indicate that a giant planet migration will disrupt a disk of planetesimals and reduces its surface density to very low values (unless the migration occurs in a very short time), a systematic search of the parameter-space by Lufkin et al (2006) have resulted in identifying the ranges of the mass and rate of the migration of a giant planet for which dynamically excited planetesimals can return to low inclination and low eccentricity orbits (through gas-drag and dynamical friction) and increase the possibility of terrestrial planet formation (figure 2). As shown by the four-panel graph in figure 2, for a low-mass (top left), or a fast migrating (bottom left) giant planet, the majority of planetesimals acquire eccentricities smaller than 0.4, implying that they may survive planetary migration and return to dynamically cool orbits in short times.

Recent numerical integrations by Fogg & Nelson (2005, 2007), Raymond et al. (2006), and Mandell et al. (2007) have shown that it is indeed possible for many planetesimals to survive giant planet migration and form terrestrial bodies (figure 3). As shown by Raymond et al. (2006) and Mandell et al. (2007), under
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Figure 2. Left: the variation of surface density of a disk of planetesimals in terms of the time of the migration of a giant planet (Armitage 2003). As shown here, unless the migration is fast, giant planet migration destabilizes planetesimals resulting in their removal from the disk. Right: eccentricity of planetesimals during giant planet migration. As shown in the two left graphs, for a low mass, or a fast migrating giant planet, the increase in planetesimals’ eccentricity may not be too high implying that they may be able to return to low eccentricity orbits.

certain circumstances, not only do planetesimals survive giant planet migration, they can also form Earth-like objects, with substantial amounts of water, in the habitable zone of their central stars. By integrating the orbits of 1200 planetesimals and 80 Moon- to Mars-sized objects distributed in a protoplanetary disk with a mass of 17 Earth-masses, these authors have shown that an Earth-like planet can form in the habitable zone of a star after 200 Myr, when a Jupiter-size object migrates from 5 AU to 0.25 AU in $10^5$ years (figure 3). The initial distribution of water in the disk of planetesimals is similar to those of our solar system’s primitive asteroids, with a 0.5 water-to-mass ratio for protoplanetary objects beyond the location of the giant planet.

3. Habitable Planets in Binary Star Systems

Given that a large fraction of main and pre-main sequence stars are formed in binaries or clusters (Abt 1979; Duquennoy & Mayor 1991; Mathieu et al. 2000), it is not surprising that approximately 20% of the currently known extrasolar planet-hosting stars are members of binary systems. When the separation of these binaries are larger than 100 AU, the perturbative effect of the gravitational force of one stellar component on the formation and dynamics of planets around the other star is negligible. However, when the separation of a binary is smaller than 100 AU, the perturbative effect of the farther companion becomes more pronounced, and strongly affects the long-term stability and the possibility of the formation of planets in binary systems.

Planet formation in binaries has been the subject of debate for a long time. Artymowicz & Lubow (1994) have shown that a circumstellar disk around the
primary of a binary system may lose a large portion of its planet-forming material due to the interaction with an eccentric secondary star. Thébault et al. (2004) have shown that such an interaction may also increase the orbital eccentricities of smaller objects inhibiting giant/terrestrial planet formation by destabilizing the orbits of their building blocks. However, the detection of circumstellar disks in systems such as L1551, in which the binary separation is ∼45 AU, and the stars of the system maintain circumstellar materials with masses of approximately 0.05 solar-masses (comparable to the minimum mass of our solar system’s nebula) in disks with radii of 10 AU (Rodriguez et al. 1998), and the recent detection of Jovian-type planets in three moderately close (<40AU) binaries of γ Cephei (Hatzes et al. 2003), GL 86 (Els et al. 2001), and HD 41004 (Zucker et al. 2004; Raghavan et al. 2006), with separation smaller than 20 AU, have shown that it is possible for binary systems to maintain enough material in their circumstellar disks to trigger planet formation in the same fashion as around single stars. These binary-planetary systems, with their small separations, and with hosting Jupiter-like planets, present another case of extreme planetary systems. Whether such systems can harbor habitable planets depends on the degree of the interactions between their secondary stars, their giant planets, and their disks of embryos. As shown by Haghighipour (2006), terrestrial-class objects in binary-planetary systems can maintain long-term stability in orbits close to their host stars and outside the influence zones of their systems’ giant planets. That means, in order for habitable planets to have stable orbits in such systems, the habitable zones of their central stars have to be much closer to them than the orbits of their giant planets. In a recent article, we studied this topic by integrating the orbits of 120 Moon- to Mars-sized planetary embryos, with water contents similar to those of our solar system’s primitive asteroids, in a system consisting of the Sun, Jupiter, and a farther stellar companion (Haghighipour & Raymond 2007). Figure 4 shows the results for different values of the mass of the secondary star and its orbital parameters. As shown on the right graph, it is possible to form terrestrial-class objects, with substantial amounts of water, in the habitable zone of the primary star. The left graph of figure 4 shows a case in which a 1.17 Earth-masses object is formed at 1.16 AU from the primary star, with an orbital eccentricity of 0.02, and water to mass ratio of 0.00164 (Earth’s water to mass ratio is approximately 0.001).

Figure 3. Habitable planet formation during giant planet migration. Graphs from Raymond et al. (2006) left, and Fogg & Nelson (2007) right.
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Figure 4. Habitable planet formation in a binary star system with Sun-like stars. Graph from Haghighipour & Raymond (2007).

The results of our simulations also indicate a relation between the perihelion of the binary ($q_b$) and the semimajor axis of the outermost terrestrial planet ($a_{out}$). As shown in the left graph of figure 5, similar to Quintana et al. (2007), simulations with no giant planets favor regions interior to $0.19q_b$ for the formation of terrestrial objects. That means, around a Sun-like star, where the inner edge of the habitable zone is at $\sim 0.9$ AU, a stellar companion with a perihelion distance smaller than $0.9/0.19 = 4.7$ AU would not allow habitable planet formation. In simulations with giant planets, on the other hand, figure 5 shows that terrestrial planets form closer-in. The ratio $a_{out}/q_b$ in these systems is between 0.06 and 0.13. A detailed analysis of our simulations also indicate that the systems, in which habitable planets were formed, have large perihelia. The right graph of figure 5 shows this for simulations in a binary with equal-mass Sun-like stars. 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. For 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 is indicative of the interaction of this body with the secondary star. As shown here, Earth-like objects are formed in systems where the interaction between the giant planet and the secondary star is weak and the average eccentricity of the giant planet is small. That implies, habitable planet formation is more favorable in binaries with moderate to large perihelia, and with giant planets on low eccentricity orbits.

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Figure 5. The graph on the left shows the relation between the perihelion of an equal-mass binary and the location of its outermost terrestrial planet. The graph on the right shows the region of the $(e_b, a_b)$ space for a habitable binary-planetary system. Figures from Haghighipour & Raymond (2007).

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