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HABITABLE PLANET FORMATION IN BINARY PLANETARY SYSTEMS

Nader Haghighipour
Institute for Astronomy and NASA Astrobiology Institute, University of Hawaii-Manoa, Honolulu, HI 96822; nader@ifa.hawaii.edu

and

Sean N. Raymond
Center for Astrophysics and Space Astronomy, and Center for Astrobiology, University of Colorado, Boulder, CO 80309;
raymond@lasp.colorado.edu
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ABSTRACT

Recent radial velocity observations have indicated that Jovian-type planets can exist in moderately close binary star systems. Numerical simulations of the dynamical stability of terrestrial-class planets in such environments have shown that, in addition to their giant planets, these systems can also harbor Earth-like objects. In this paper we study the late stage of terrestrial planet formation in such binary planetary systems, and present the results of the simulations of the formation of Earth-like bodies in their habitable zones. We consider a circumprimary disk of Moon- to Mars-sized objects and numerically integrate the orbits of these bodies at the presence of the Jovian-type planet of the system and for different values of the mass, semimajor axis, and orbital eccentricity of the secondary star. Results indicate that Earth-like objects, with substantial amounts of water, can form in the habitable zone of the primary star. Simulations also indicate that by transferring angular momentum from the secondary star to protoplanetary objects, the giant planet of the system plays a key role in the radial mixing of these bodies and the water contents of the final terrestrial planets. We will discuss the results of our simulation and show that the formation of habitable planets in binary planetary systems is more probable in binaries with moderate to large perihelia.

Subject headings: binaries: close — celestial mechanics — planetary systems — planets and satellites: formation — solar system: formation

1. INTRODUCTION

For the past several years, the formation of terrestrial planets in binary star systems has been the subject of research by many authors. Quintana et al. (2002, 2003) and Lissauer et al. (2004) studied the interactions of planetesimals and protoplanetary objects around the stars of α Centauri, and showed that terrestrial-type planets can form around these stars when dynamical friction is included in numerical simulations. Barbieri et al. (2002) and Turrini et al. (2005, 2006) also studied terrestrial planet formation in this system and, by considering gas drag as the primary force for reducing planetesimals relative velocities, showed that it is indeed possible to form terrestrial-class objects around the primary of α Centauri stars. In a recent article, Quintana et al. (2007) have extended their simulations to wider binary systems and have identified regions of the parameter space for which terrestrial planets can form around the stars of the binary.

The studies of terrestrial planet formation in dual-star systems, as presented in the literature, share one common ground: the systems considered in these studies do not contain giant planets, and the formation of terrestrial planets has been simulated only at the presence of the two stars of the system. In this paper we extend these studied to more complex environments and simulate the formation of terrestrial planets in binary star systems in which the primary star is host to a Jupiter-like planet. The purpose of our study is to understand how, in such binary planetary systems, the dynamics of the stellar companion will affect the formation and the water contents of Earth-like objects in the habitable zone[1] of the primary star.

The systems of our interest are moderately close ($\leq$40 AU) binaries. Recent detections of Jovian-type planets in such environments (e.g., GJ 86 and [see Els et al. 2001] and γ Cephei [see Hatzes et al. 2003]) have raised questions about the formation of these objects and the possibility of the existence of smaller bodies in these systems. In regard to the latter, simulations of the orbital dynamics of terrestrial planets in the γ Cephei planetary system have indicated that small objects can have long-term stable orbits in binary planetary systems provided their orbits lie outside the influence zone[2] of the system's giant planet and are limited to the region between this object and its host star (Haghighipour 2006). In this study we choose systems in which the primary star has a Jovian-type body in an orbit outside its habitable zone.

Unlike the majority of the binary planetary systems that have so far been discovered,[3] the relatively smaller separations of the binary components in our systems imply that the effect of the farther companion on the formation and dynamical evolution of planets around the primary star is not negligible. For instance, the perturbative effect of the secondary star can change the structure of the circumprimary disk and truncate it to a smaller size (Artymowicz & Lubow 1994). The latter removes material that may be used in the formation of planets. For this reason, it was believed that circumstellar disks around the components of a close

[1] The region around a star where a terrestrial-class planet can maintain liquid water on its surface.

[2] The influence zone of a planetary-sized object with a mass m_p is defined as the region between $a_p(1 - e_p) - 3R_{\rm H}$ and $a_p(1 + e_p) + 3R_{\rm H}$, where a_p is the planet's semimajor axis, e_p is its orbital eccentricity, and $R_{\rm H} = a_p(m_p/3M)^{1/3}$ represents its Hill radius. The quantity M denotes the mass of the central star.

[3] See Haghighipour et al. (2007) for a complete and up-to-date list of binary planetary systems.

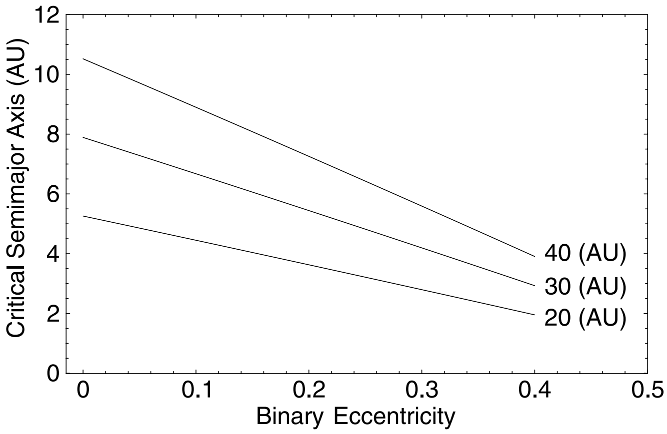

Fig. 1.—Graph of the critical semimajor axis of a planet in an equal-mass binary star system for three different values of the separation of the binary.

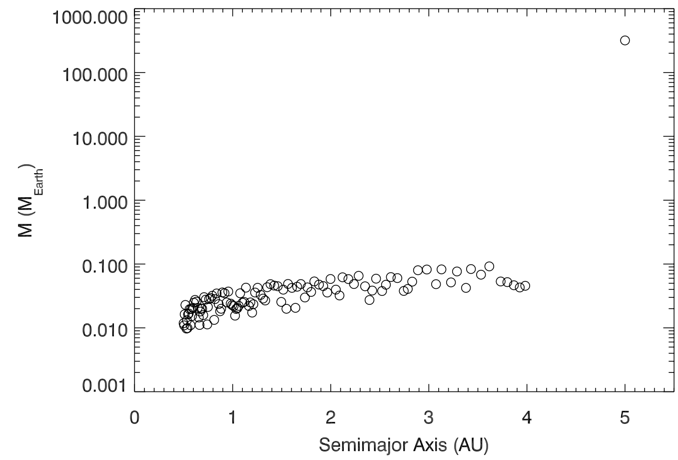

Fig. 2.—Radial distribution of original protoplanetary objects.

binary may not be large and massive enough to begin planet formation. However, observations by Mathieu (1994), Akeson et al. (1998), Rodriguez et al. (1998), and Mathieu et al. (2000) have shown otherwise. These observations confirm the presence of potentially planet-forming environments around the components of binary stars and imply that planet formation around a star of a binary may be as common as around a single star. In fact, the observations of two well-separated disks in the binary system of L1551 by Rodriguez et al. (1998) indicate that, despite of disk truncation, it is still possible for the both components of a binary to retain a relatively significant amount of their original circumstellar materials (0.03–0.06 $M_{\odot}$) in disks with considerable radii ($\sim$10 AU). The masses of these disks are comparable to the minimum solar-mass model of the primordial nebula of our solar system (Weidenschilling 1977; Hayashi 1981), implying that planet formation in dual-star systems can begin and continue in the same fashion as around our Sun.

In this paper we base our study on the latter consideration. We assume that in a binary system, planetesimal formation follows a process similar to that around a single star, and giant and terrestrial planets are formed through the interactions of these objects. It is important to emphasize that in such systems, the stellar companion has a strong effect on the accretion of planetesimals and the formation of larger bodies. In general, the perturbations due to the secondary star increase the relative velocities of planetesimals (Heppenheimer 1978; Whitmire et al. 1998), which may cause their collisions to result in breakage and fragmentation. This object can also inhibit the formation of protoplanets by destabilizing the regions where the building blocks of these bodies exist (Whitmire et al. 1998). It has, however, been shown that the effect of the binary companion on increasing the relative velocities of planetesimals may be counterbalanced by dissipative forces such as gas drag and dynamical friction (Marzari et al. 1997; Marzari & Scholl 2000). As shown by these authors, the combined effect of gas drag and gravitational force of the stellar companion results in a strong alignment of the periastra of planetesimals, which increases the efficiency of their accretion by reducing their relative velocities. It is also important to mention that this process is more effective when the sizes of the two colliding planetesimals are comparable. As shown by Thébault et al. (2006), depending on the size distribution of small bodies and the radius of each individual planetesimal, the periastron alignment process may in fact increase their mutual velocities and cause their collisions to become eroding. In this paper we assume that a Jupiter-like planet has already formed around the primary of our binary star system,[4] and the interactions of planetesimals have been efficient and have resulted in the formation of a disk of planetary embryos (e.g., via oligarchic growth; see Kokubo & Ida 1998) around this object.

As mentioned earlier, we focus our attention on the formation of habitable planets, that is, Earth-like objects in the habitable zone of the primary star. Since all life on Earth requires the presence of liquid water, we consider water-rich planets to be the best candidates for habitability, and pay close attention to the acquisition of water during the formation of these objects. Similar to the current models of the formation of habitable planets in our solar system, we assume that cometary material, if it existed around the stars of a binary system, would provide little to no water to the terrestrial planets that might form in the habitable zone of the primary star. We adopt the model of Morbidelli et al. (2000), who argued that water-rich bodies originating in the solar system's asteroid belt were the primary source of Earth's water, and simulate the late stage of terrestrial planet formation (Wetherill 1996) by numerically integrating the orbits of a few hundred protoplanetary objects, for different values of the mass, semimajor axis, and orbital eccentricity of the secondary star. It is important to emphasize that the delivery of water to the inner part of the solar system may not be entirely due to the radial mixing of planetary embryos. Smaller objects such as planetesimals, in the outer region of the asteroid belt, may also contribute (Raymond et al. 2007). As shown by Charnoz et al. (2001), the perturbative effect of the secondary star may raise the eccentricities of these objects and increase their radial excursions. The latter may, in turn, result in their radial mixing when these objects collide. In this study, however, merely for the sake of simplicity, we only consider protoplanetary objects and assume an initial gradient in the water contents of these bodies such that radial mixing is required to "deliver" water to planets in the habitable zone (Morbidelli et al. 2000; Raymond et al. 2004; Raymond

[4] The formation of gas-giant planets in a dual-star system is still a subject of research. While simulations by Nelson (2000) indicate that gas-giant planet formation may not proceed through the disk instability mechanism around the primary of a binary star system with separation of $\sim$50 AU, recent simulations by Boss (2006) show that Jupiter-like planets can form in such environments via the gravitational instability of a marginally unstable circumprimary disk. On the other hand, as shown by Thébault et al. (2004), the core accretion mechanism may also be able to form giant planets around the primary of a binary star system. However, as the results of their simulations for planet formation in the γ Cephei system indicate, the semimajor axis of the final gas-giant planet may be smaller than its observed value.

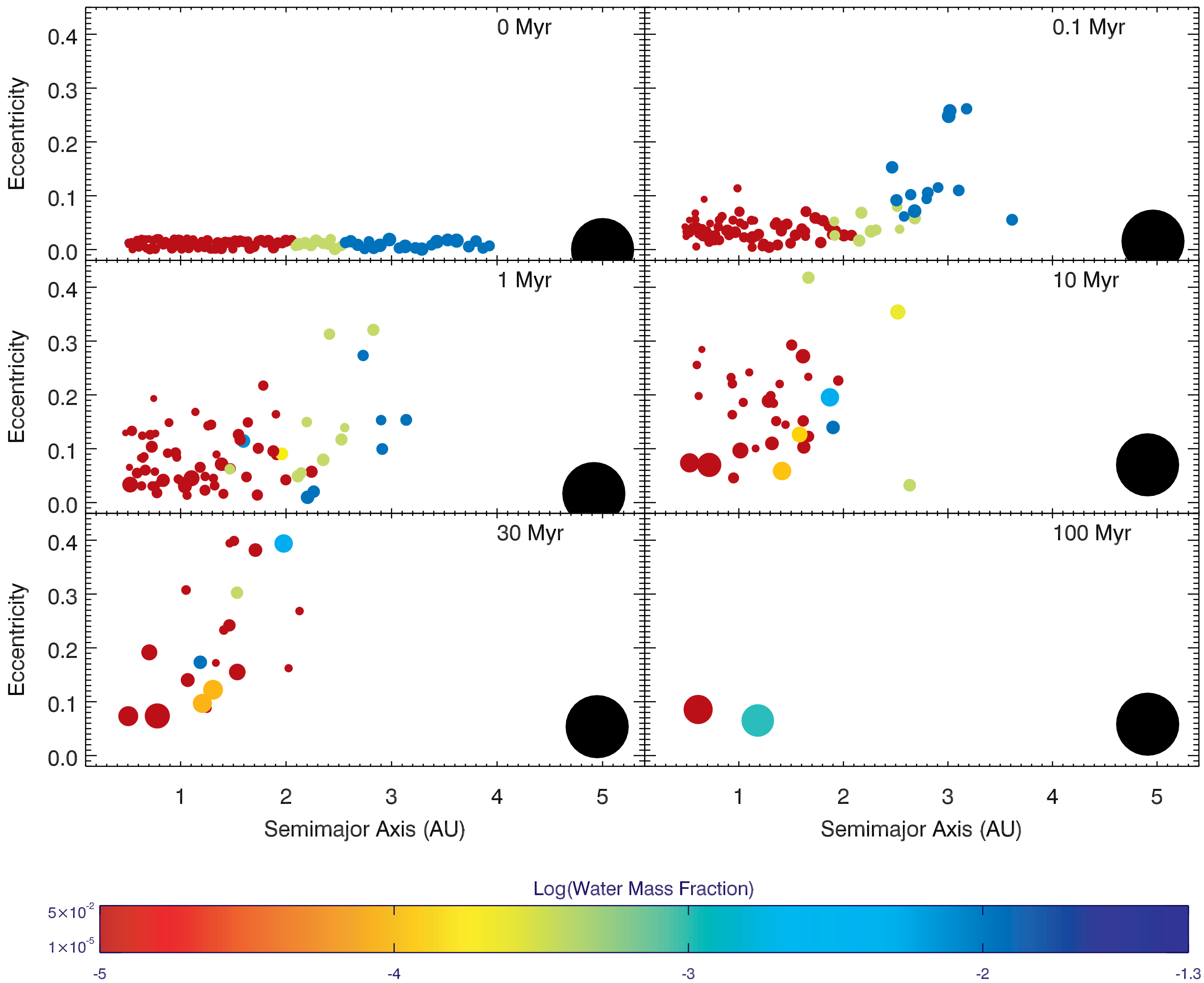

Fig. 3.—Snapshots of the interaction of protoplanetary objects and the formation of terrestrial planets. The mass of the secondary star is 0.5 $M_{\odot}$ and its semimajor axis and eccentricity are 30 AU and 0.2, respectively. The results show a terrestrial-sized planet, with a substantial amount of water, at a semimajor axis of 1.2 AU and with an eccentricity of approximately 0.07. The Jupiter-sized planet of the system is shown by the black circle.

2006). We identify the regions of the parameter space of a binary planetary system for which an Earth-like planet can form in the habitable region of the primary star.

The outline of this paper is as follows. In § 2 we discuss the details of our model. Section 3 has to do with the numerical integrations of the system and the analysis of the results. In § 4 we study the formation of habitable planets, and in § 5 we conclude our study by reviewing the results and discussing their applications.

2. THE MODEL

As mentioned in the introduction, we would like to study the formation of terrestrial planets in the habitable zone of the primary of a moderately close binary planetary system. We are primarily interested in understanding how the motion of the secondary star affects the dynamics of a disk of protoplanetary objects and the final assembly and water contents of the resulting terrestrial-sized bodies. In other words, we would like to study how the process of habitable planet formation in a system consisting of a star, a disk of planetary embryos, and a giant planet will be altered if a stellar companion is introduced to the system.

The statement above portrays a general picture of our model. To ensure the habitability of such a system, Earth-like objects have to form in the habitable zone of its primary star and maintain long-term stable orbits in that region. On the other hand, as shown by Haghighipour (2006), terrestrial planets can have stable orbits only at distances close to the primary star and outside the influence zone of its giant planet. This requires that the habitable zone of the primary to be considerably closer to it than the orbit of its planetary companion. To satisfy this requirement, and also for the purpose of comparing habitable planet formation in binary planetary systems with that around single stars, we make the following assumptions:

1. We assume that the primary of our system is a Sun-like star. As indicated by Kasting et al. (1993), the habitable zone of such a star will extend from 0.95 to 1.37 AU. This is a conservative estimate that places the outer boundary of the habitable zone at a distance where CO_2 clouds start to form (Mischna et al. 2000).

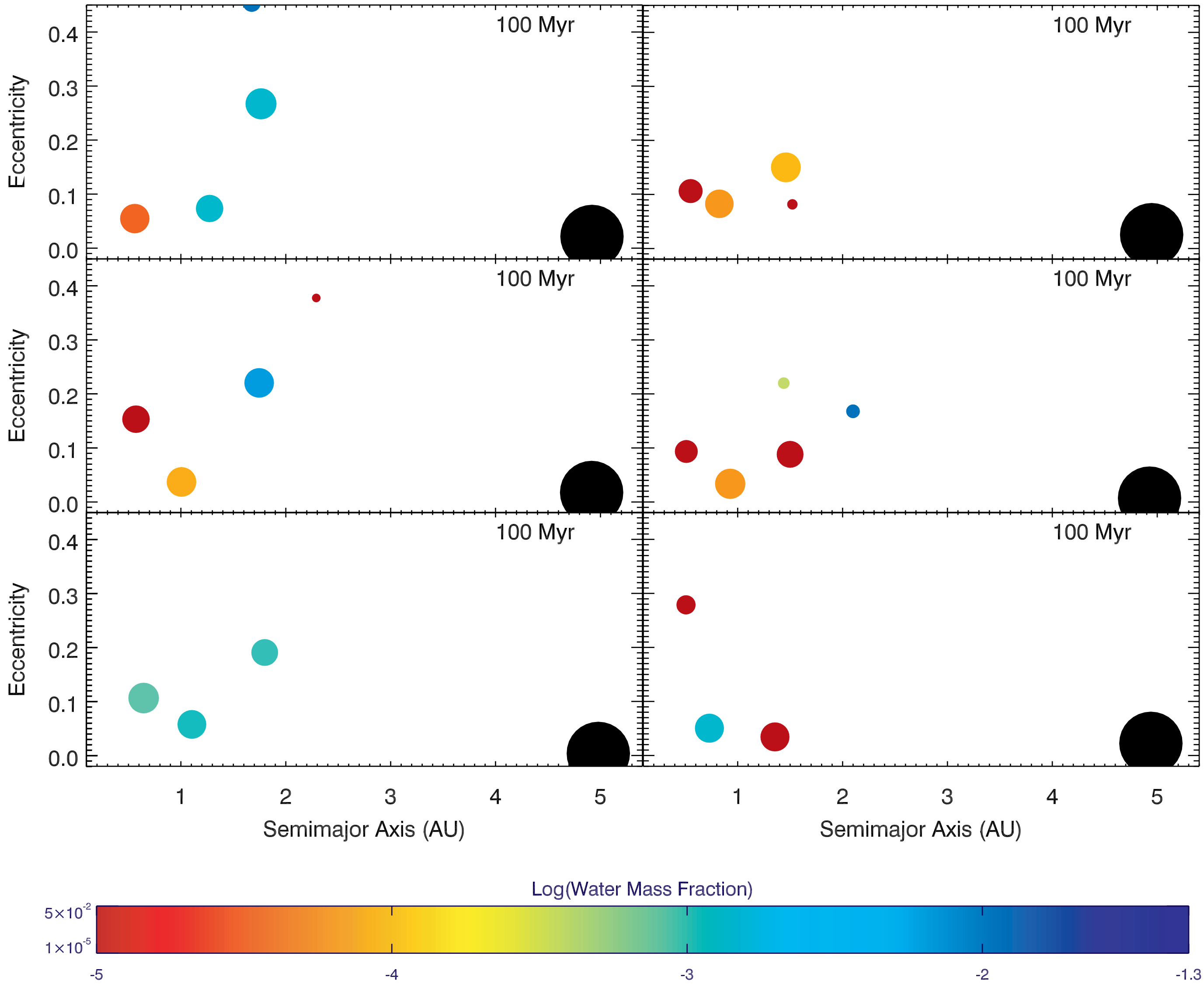

FIG. 4.—Stochasticity of simulations. The left column depicts the results of three simulations with random distribution of protoplanetary objects in a binary system with a Sun-like star as its secondary and in a circular orbit with a radius of 30 AU. The right column shows the results of simulations for similar distributions of planetary embryos in a system with a 1.0 $M_\odot$ secondary star in an orbit with a semimajor axis of 40 AU and eccentricity of 0.2. As shown in each column, different distribution of planetary embryos may result in the formation of different number of planets with different water to mass ratios.

The outer edge of this region may in fact be at larger distances. As shown by Forget & Pierrehumbert (1997) and Mischna et al. (2000), the outer boundary of the habitable zone of the Sun may be at approximately 2.4 AU from this star. In this study we adopt a relatively moderate approach and consider a habitable zone between 0.9 and 1.5 AU for our primary star.

2. We consider the giant planet of our system to be a 1 $M_{\rm Jup}$ object. Since we would like to study how the orbital dynamics of the secondary star affects the interactions of planetary embryos, we assume that the orbit of this planet is circular. We also consider the semimajor axis of this object to be at 5 AU, outside the habitable zone of the primary star.

3. We choose the mass of the secondary star to be 0.5, 1.0, and 1.5 $M_\odot$. We consider the semimajor axis of this object to have the values of 20, 30, and 40 AU, and its eccentricity to be 0, 0.2, and 0.4. Since we are interested in the formation of habitable planets at the presence of the Jovian-type planet of the system, it is necessary to ensure that, for any combination of these parameters, the giant planet will have a long-term stable orbit. As shown by Holman & Wiegert (1999) in order for a planet in a circular orbit, to be stable in a binary star system, its semimajor axis cannot exceed the critical value (a_c) given by

$$\begin{aligned} a_c/a_b = {} & (0.464 \pm 0.006) + (-0.380 \pm 0.010)\mu_b \\ & + (-0.631 \pm 0.034)e_b + (0.586 \pm 0.061)\mu_b e_b \\ & + (0.150 \pm 0.041)e_b^2 + (-0.198 \pm 0.074)\mu_b e_b^2. \end{aligned} \quad (1)$$

In this equation, a_b and e_b are the semimajor axis and orbital eccentricity of the stellar companion, and $\mu_b = M_2/(M_1 + M_2)$, where M_1 and M_2 are the masses of the primary and secondary stars, respectively. Figure 1 shows the graph of a_c in terms of the eccentricity of the binary. In this figure, $\mu_b = 0.5$ and $a_b = 20$, 30, and 40 AU. As shown here, a giant planet with a semimajor axis of 5 AU will not have a stable orbit in an equal-mass binary with a separation of 20 AU and an eccentricity of 0.2 or higher. A similar situation exists for a 30 AU binary with a 0.4 or larger eccentricity. We use equation (1) to identify the combinations of the mass and orbital parameters of the secondary star for which the giant planet of the system becomes unstable, and simulate the

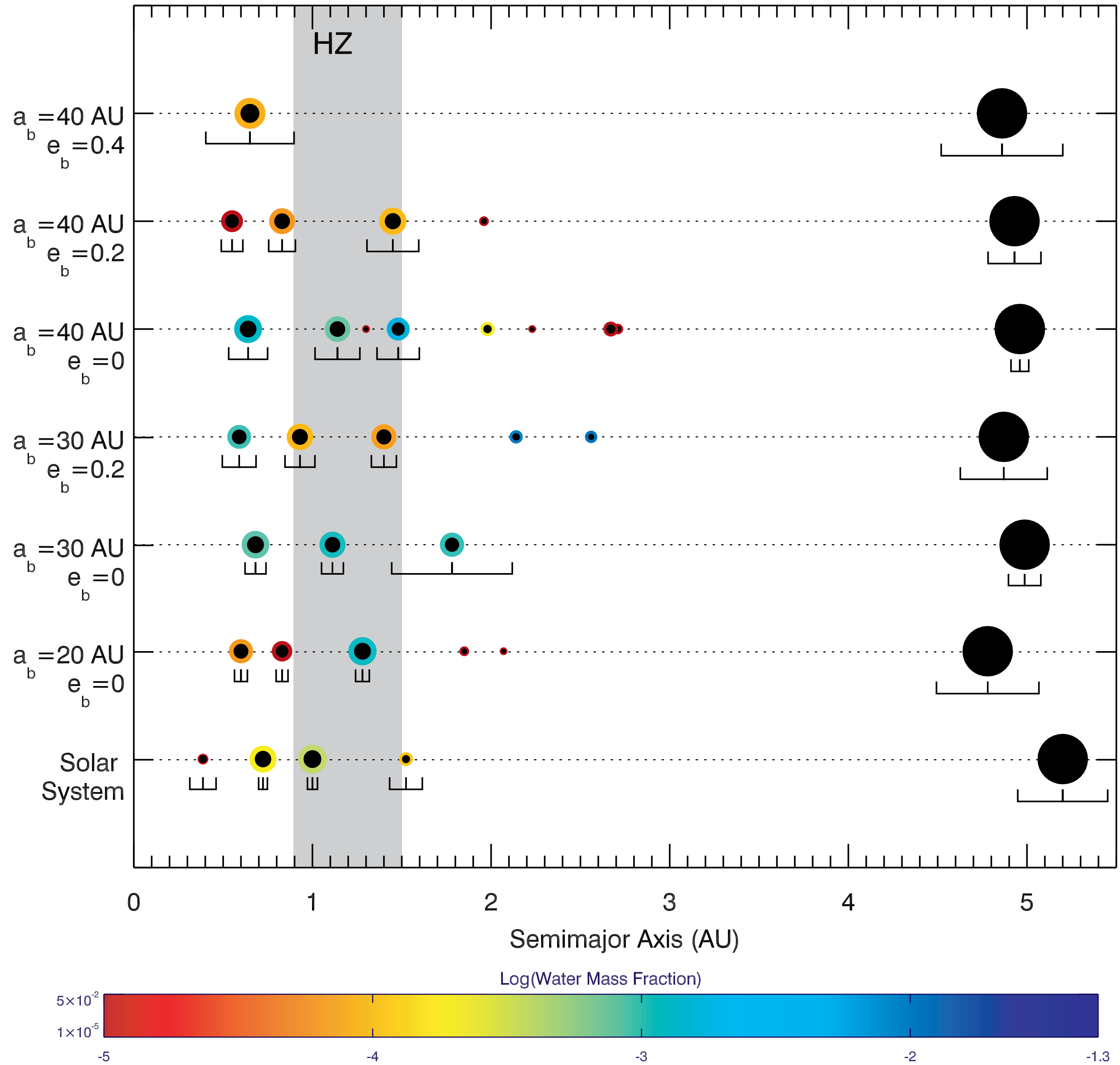

FIG. 5.—Results of simulations in a system with $\mu_b = 0.5$ for different values of the eccentricity (e_b) and semimajor axis (a_b) of the stellar companion.

formation of habitable planets for those combinations of these parameters that result in a stable orbit for this object.

4. We assume that planetary embryos have already formed in the region between the primary and the giant planet. We consider a disk of 115 Moon- to Mars-sized bodies, with masses ranging from 0.01 to 0.1 $M_\oplus$, randomly distributed, by 3–6 mutual Hill radii, between 0.5 and 4 AU from the primary star. The masses of embryos increase with their semimajor axes (a) and the number of their mutual Hill radii (Δ) as $a^{3/4}\Delta^{3/2}$ (Raymond et al. 2004). The surface density of our disk model, normalized to a density of 8.2 g cm^{-2} at 1 AU, varies as $r^{-1.5}$, where r is the radial distance from the primary star. The total mass of our disk model is approximately 4 $M_\oplus$. Figure 2 shows the graph of one of such disks.

5. We assume that the water to mass ratios of embryos follow the current distribution of water in primitive asteroids of the asteroid belt (Abe et al. 2000). That is, embryos inside 2 AU are taken to be dry, the ones between 2 and 2.5 AU are considered to contain 1% water, and those beyond 2.5 AU are assumed to have a water to mass ratio of 5% (Raymond et al. 2004, 2005a, 2005b, 2006a; Raymond 2006). We also consider an initial iron content for each embryo. This value is obtained by interpolating between the values of the iron contents of the terrestrial planets (Lodders & Fegley 1998; Raymond et al. 2005a, 2005b), with a dummy value of 40% in place of Mercury because of its anomalously high iron content.

3. NUMERICAL SIMULATIONS

Using the N-body integration package MERCURY (Chambers 1999), we numerically integrated the equations of motion of the planetary embryos of our disk model for different values of the mass, semimajor axis, and eccentricity of the secondary star. We allowed the protoplanetary objects to collide with one another and assumed that each collision was perfectly inelastic. We also assumed that no debris was generated during a collision, and that the effect of the energy released during an impact, on the morphology and structure of the colliding objects, was negligible.

We carried out a total of 46 simulations, each with a time step of 6 days.[5] Figure 3 shows the results of one of such simulations. In this figure, the separation of the binary is 30 AU, its eccentricity is 0.2, and the mass of the secondary star (not shown in the figure) is 0.5 $M_\odot$. As shown here, after 100 Myr, a terrestrial-sized object (1.1 $M_\oplus$), with substantial amount of water, is formed in the habitable zone of the primary star. The orbit of this object has a semimajor axis of approximately 1.18 AU and an eccentricity of ~0.06. The Jupiter-sized planet of the system is shown as a big black circle.

Similar to the simulations of terrestrial planet formation around single stars (Morbidelli et al. 2000; Raymond et al. 2004), our simulations are stochastic. That is, for a given set of the orbital parameters of the binary companion, different initial distributions of protoplanetary objects produce different results. For this reason, for each set of the initial orbital parameters of the binary companion, we carried out simulations for three different random distributions of planetary embryos. Figure 4 shows the final results of such simulations for two different cases. The case on the left corresponds to a binary with a separation of 30 AU and a secondary of 1.0 $M_\odot$ in a circular orbit. The case on the right represents the results of simulations in a system in which the same secondary star is now in an orbit with a semimajor axis of 40 AU and an eccentricity of 0.2. Each simulation, from top to bottom, corresponds to different distribution of planetary embryos with the simulations on the same rows having similar initial distributions of protoplanetary objects.

In addition to the stochasticity of simulations, Figure 4 also shows the relation between the orbital eccentricity of the stellar companion and the water contents of the final bodies. As shown here, for identical initial distributions of planetary embryos (i.e., simulations on the same rows), the total water content of the system on the left, where the secondary star is in a circular orbit, is higher than that of the system on the right, where the orbit of the secondary is eccentric. Figure 5 shows this for several other simulations. As depicted by this figure, for a given separation of the binary, the accumulative water content of the final planets decreases as the eccentricity of the binary becomes larger.

The fact that the final assembly of terrestrial planets in a system with an eccentric secondary star contains less water implies that prior to the formation of these objects, most of the water-carrying embryos have left the system. Our simulations indicate that on average 90% of embryos in these systems were ejected during the course of the integration (i.e., either their semimajor axes exceeded 100 AU, or their orbital eccentricities became larger than unity) and among them, 60% collided with other protoplanetary bodies prior to their ejection from the system. A small fraction of embryos (~5%) also collided with the primary or secondary star, or with the Jupiter-like planet of the system.

The destabilizing effect of an eccentric secondary star in a binary system has also been reported by Artymowicz & Lubow (1994) and David et al. (2003). As shown by these authors, in binaries with small perihelia, the interactions of small bodies with the secondary star shorten the lifetimes of these objects and

[5] Slightly smaller than 1/20 of the orbital period of the closest embryo at 0.5 AU.

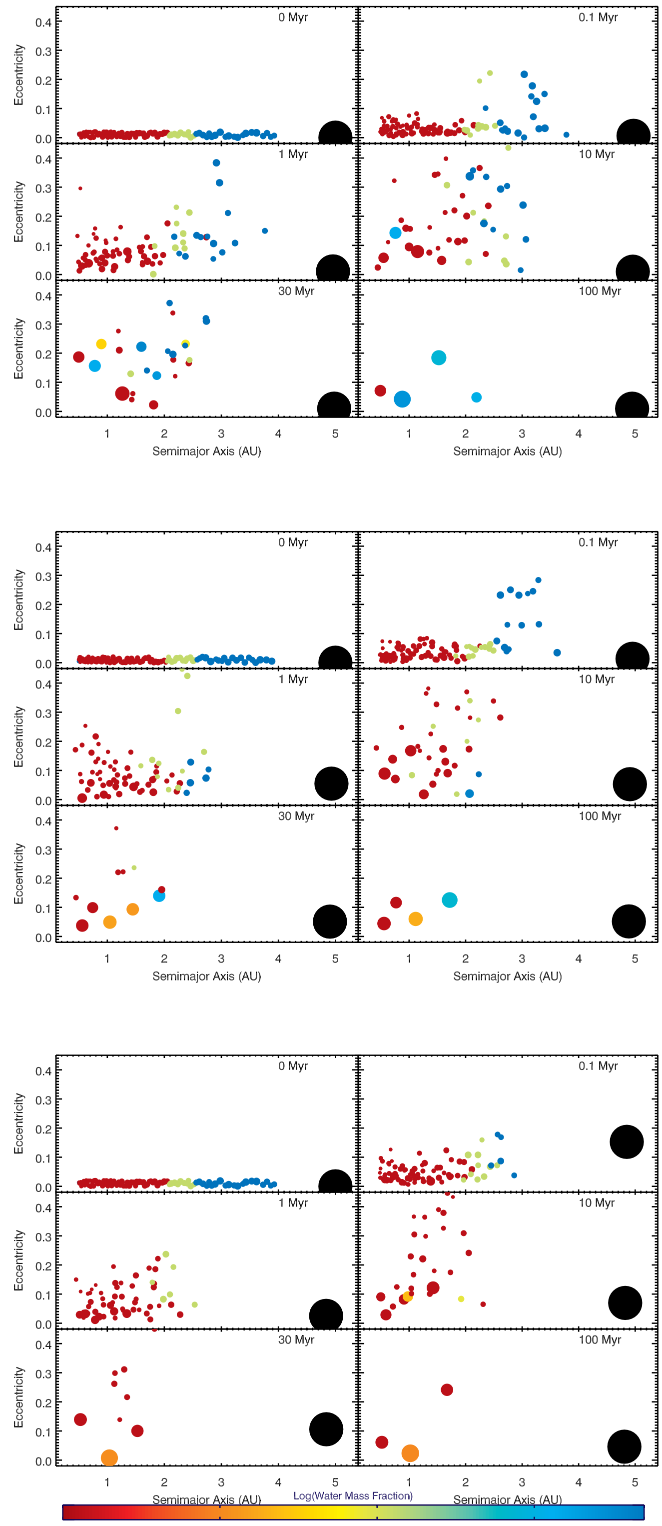

Fig. 6.—Variation of water contents with the eccentricity of the stellar companion. The secondary star has a mass of 0.5 $M_\odot$, the semimajor axis of the binary is 30 AU, and its eccentricity is equal to 0,0.2, and 0.4, from top to bottom.

enhance the disk truncation. In binary planetary systems, in addition to the perturbation from the stellar companion, similar to our solar system, (Chambers & Cassen 2002; Levison & Agnor 2003; Raymond et al. 2004; Raymond 2006), planetesimals and protoplanetary objects are also subject to the perturbative effect of the giant planet of the system. In such systems, the Jovian-type

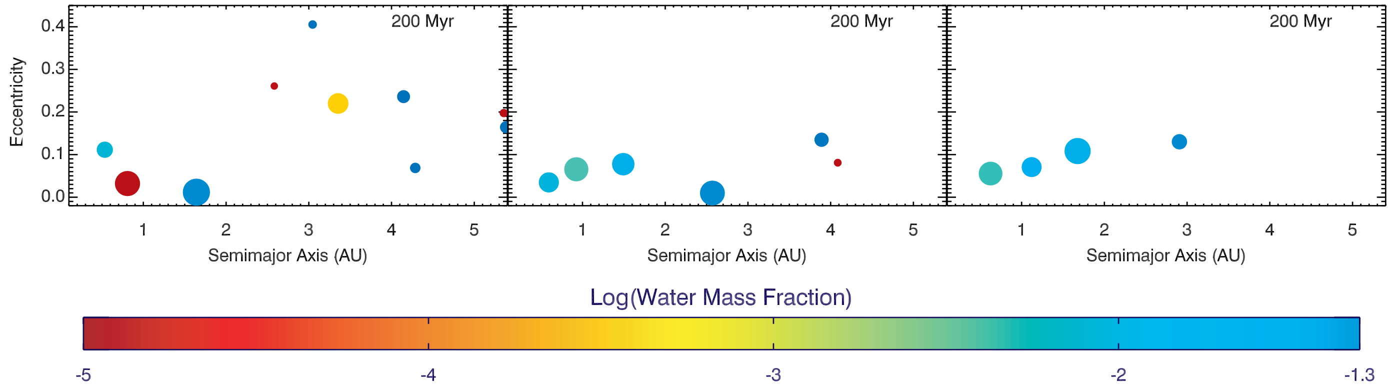

FIG. 7.—Results of simulations in binary systems with no Jupiter-like planet. The stars of each binary are Sun-like and their separations are 30 AU. The orbital eccentricity of the secondary star is 0, 0.2, and 0.4, for the systems on the left, middle, and right, respectively. Note that the time of integration has been increased to 200 Myr.

planet plays the important role of transferring angular momentum from the secondary star to planetary embryos and strongly affects the motion and radial mixing of these objects. Figure 6 shows this in more details. The systems simulated here are binaries with 0.5 $M_\odot$ secondary stars and separations of 30 AU. The binary eccentricity in these systems is equal to 0, 0.2 and 0.4, from top to bottom. As shown here, as the eccentricity of the binary companion increases, its perihelion becomes smaller and its interaction with the giant planet becomes stronger. The latter causes the eccentricity of the giant body to increase and results in its closer approach to the disk of planetary embryos and enhancing collisions and mixing among these objects. The eccentricities of embryos, at distances close to the outer edge of the protoplanetary disk, rise to higher values until these bodies are

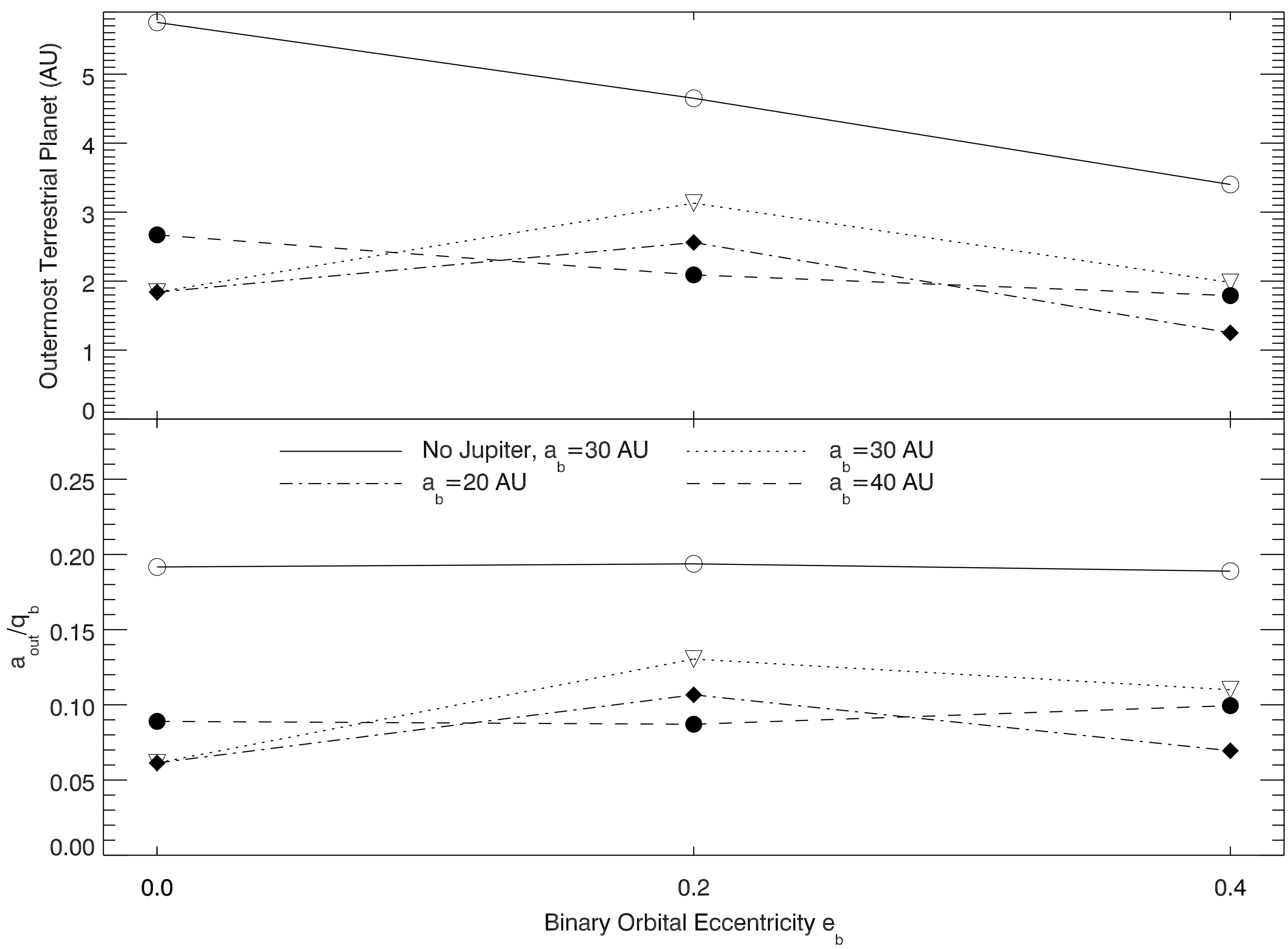

FIG. 8.—*Top panel:* Semimajor axis of the outermost terrestrial planet. *Bottom panel:* The ratio of the semimajor axis of this object to the perihelion distance of the binary. The secondary star is 1 $M_\odot$.

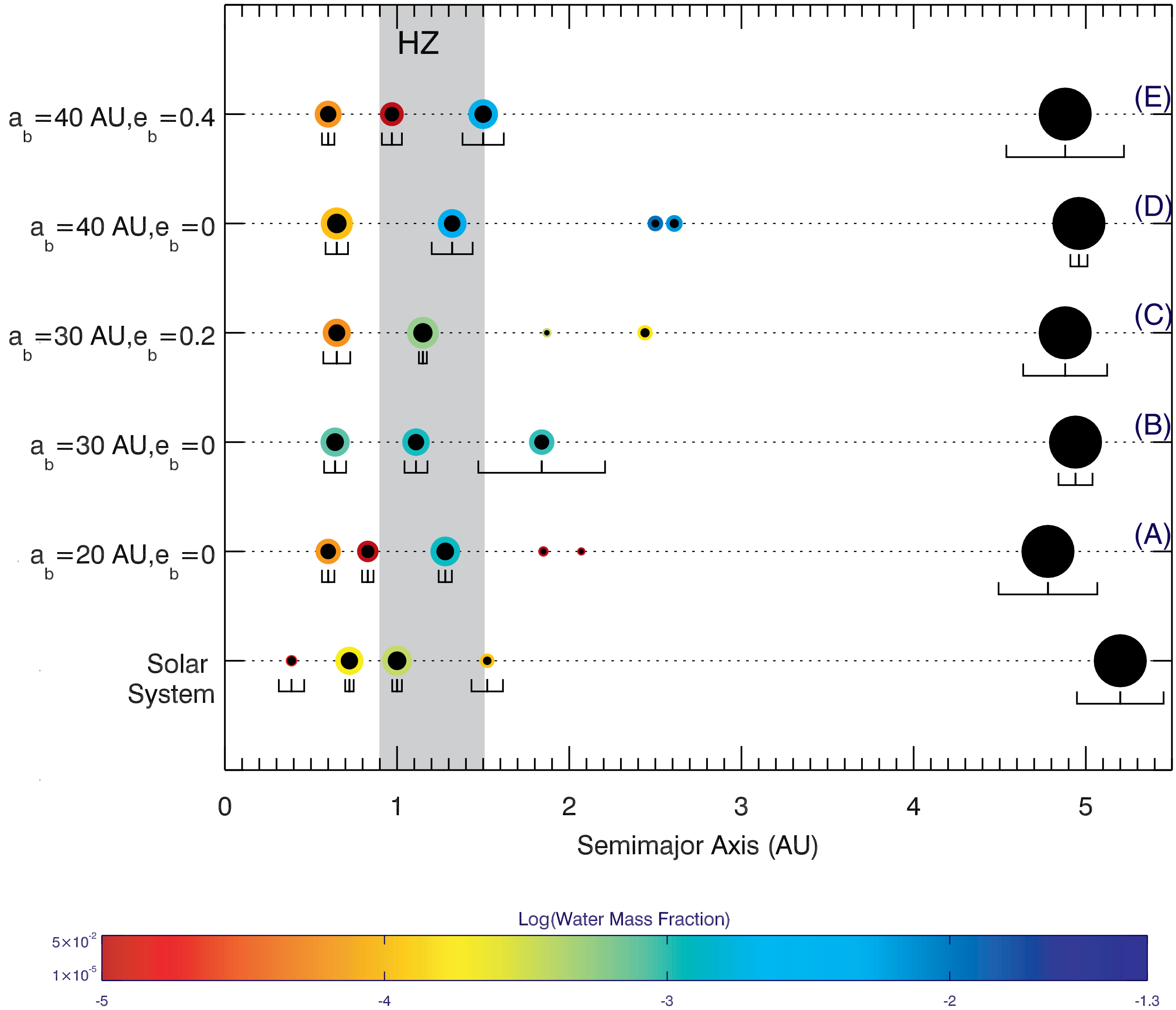

FIG. 9.—Earth-like objects in the habitable zone of the primary star. The mass of the secondary star in all simulations is 1 $M_\odot$.

ejected from the system. In binaries with smaller perihelia, the process of the transfer of angular momentum by means of the giant planet is stronger and the ejection of protoplanets occurs at earlier times. As a result, the total water to mass ratios of such systems become smaller as the eccentricities of their stellar companions increase.

To further study the effect of the stellar companion on the dynamics and radial mixing of embryos, we carried out several simulations without the Jupiter-like planet of the system. Results indicate that it is indeed possible to form terrestrial-class planets, with significant amounts of water, in the habitable zone of the primary star. However, because of the lack of the intermediate effect of the Jovian-type planet, the interaction of embryos is slower and terrestrial planet formation takes longer. Figure 7 shows this for three systems. The separation of the binary in each system is 30 AU, and the mass of the secondary star is 1 $M_\odot$. The eccentricity of the secondary star is equal to 0, 0.2, and 0.4 in simulations from left to right, respectively.

An interesting result depicted by Figure 7 is the decrease in the number of the final terrestrial planets, and increase in their sizes and accumulative water contents with increasing the eccentricity of the secondary star. The simulation on the left, in which the secondary is in a circular orbit, shows that, since in this system, the transfer of angular momentum from the stellar companion to protoplanetary objects, by means of the Jupiter-like planet of the system, is nonexistent, the radial mixing of embryos is slow and inefficient. In binaries with larger eccentricities, the close approach of the stellar companion to the disk of protoplanets increases the rate of the interaction of these objects and enhances their collisions and radial mixing. As a result, in such systems, more of the water-carrying embryos participate in the formation of the final terrestrial planets. It is important to emphasize that, as explained below, this process is efficient only in moderately eccentric binaries. In binary systems with high eccentricities (small perihelia), embryos may be ejected from the system (David et al. 2003), and terrestrial planet formation may become inefficient.

An important result shown by Figure 7 is the existence of a trend between the binary perihelion distance and the location of the outermost terrestrial planet. Figure 8 shows this for a set of different simulations. The top panel in this figure represents the

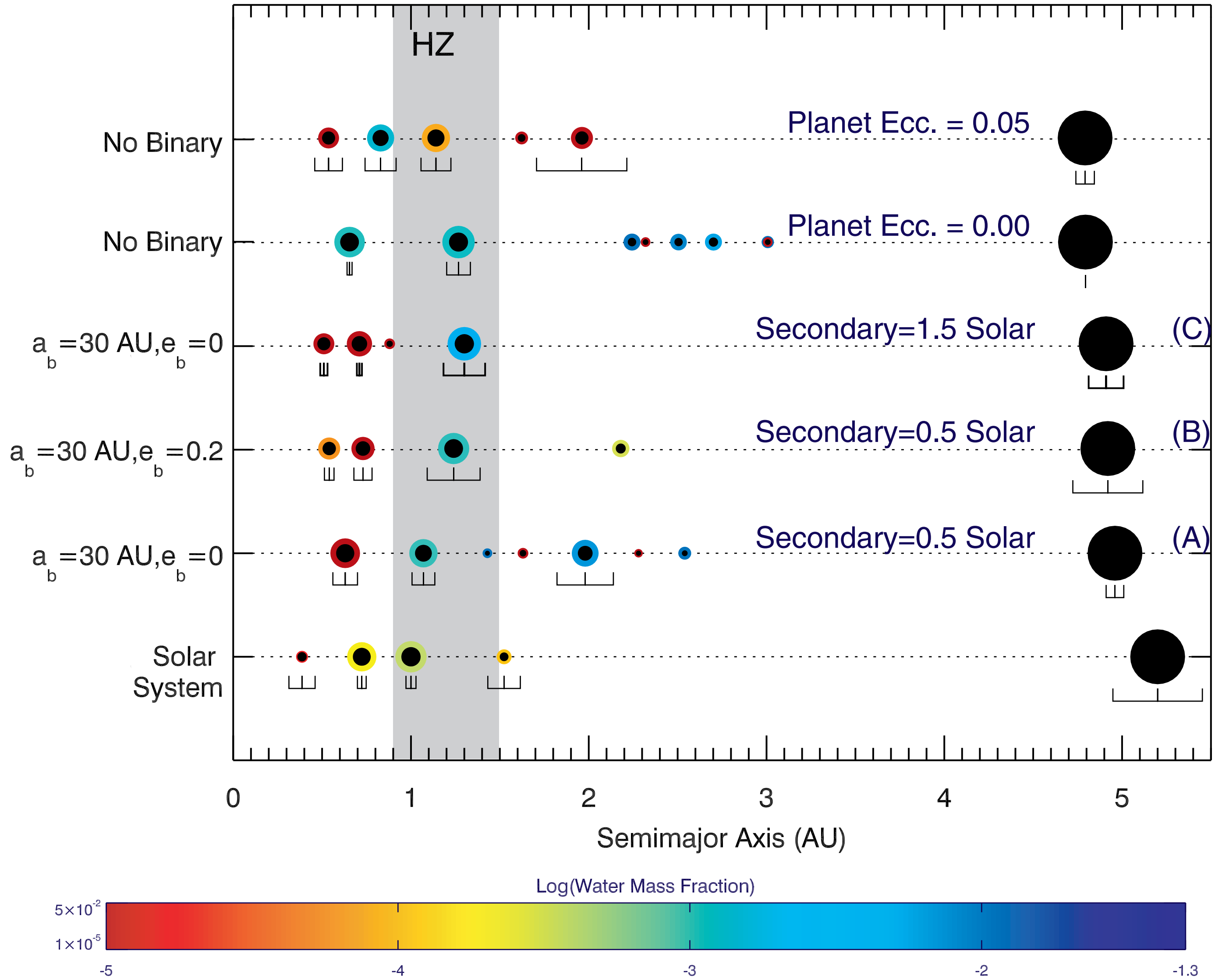

FIG. 10.—Habitable planet formation in binary planetary systems with 0.5 and 1.5 $M_\odot$ secondary stars. For comparison, simulations with no binary companion have also been included.

semimajor axis of the outermost terrestrial planet, a_{out}, as a function of the binary eccentricity, e_b. The bottom panel shows the ratio of this quantity to the perihelion distance of the binary, q_b. As shown here, simulations with no giant planet follow a clear trend: terrestrial planet formation seems to favor the region interior to roughly 0.19 times the binary perihelion distance. This has also been noted by Quintana et al. (2007, see their Fig. 9) in their simulations of terrestrial planet formation in close binary star systems. Given the location of the inner edge of the habitable zone (i.e., 0.9 AU), our simulations indicate that for the binaries considered in this study, comparable to the estimate by Quintana et al. (2007), a perihelion distance of approximately $0.9/0.19 = 4.7$ AU or larger may be necessary to allow habitable planet formation. Our results seem to imply that Sun-like primaries with companions with perihelion distances smaller than $\sim$5 AU may not be favorable candidates for habitable planet formation. This, of course, is not a stringent condition, and is neither surprising since a moderately close binary with a perihelion distance of $\sim$5 AU would be quite eccentric, and as indicated by Holman & Wiegert (1999), the orbit of a terrestrial-class object in the region around 1 AU from the primary of such a system will be unstable. It is, also, important to note that because the stellar luminosity, and therefore the location of the habitable zone, are sensitive to stellar mass (Kasting et al. 1993; Raymond et al. 2007), the minimum binary separation necessary to ensure habitable planet formation will vary significantly with the mass of the primary star.

In simulations with giant planets, Figure 8 indicates that terrestrial planets form closer in. The ratio a_{out}/q_b in these systems varies between approximately 0.06 and 0.13, depending on the orbital separation of the two stars. The accretion process in such systems is more complicated since the giant planet's eccentricity and its ability to transfer angular momentum are largely regulated by the binary companion.

4. HABITABLE PLANET FORMATION

Despite the stochasticity of the simulations and the large size of the parameter space, many of our integrations resulted in the formation of Earth-sized objects, with substantial amounts of water, in the habitable zone of the primary star. Figures 9 and 10 show the results of some of these simulations. For the sake of comparison, we have also included two simulations with no binary companion. The orbital parameters of the final objects and their water contents are listed in Table 1. It is important to mention that in comparing the water contents of the Earth-like planets

TABLE 1
CHARACTERISTICS OF THE EARTH-LIKE PLANETS OF FIGURES 9 AND 10 (SUN'S HABITABLE ZONE: 0.9–1.50 AU)

Simulation	Planet Mass ($M_\oplus$)	Semimajor Axis (AU)	Eccentricity	Water/Mass
9-A	0.95	1.28	0.03	0.00421
9-B	0.75	1.11	0.06	0.00415
9-C	1.17	1.16	0.03	0.00164
9-D	0.86	1.33	0.09	0.01070
9-E	0.95	1.50	0.08	0.00868
10-A	0.74	1.07	0.06	0.00349
10-B	0.99	1.26	0.12	0.00366
10-C	1.23	1.30	0.09	0.00103

of our simulations with those of the Earth, we consider the water to mass ratio of the Earth to be 0.001. Since the exact amount of water in the Earth's mantle is unknown (between 1–10 Earth's ocean), such an estimate of Earth's water-mass fraction is equivalent to considering one ocean of water ($\sim 1.5 \times 10^{24}$ g) on the Earth's surface and three oceans in its mantle.

A detailed analysis of the results depicted by Figures 9 and 10 indicates that the systems shown in these figures have relatively large perihelia. Figure 11 shows this for simulations with $\mu_b = 0.5$, in terms of the semimajor axis and eccentricity of the stellar companion. The circles in this figure represent those systems whose parameters were chosen from Figure 1 (i.e., stable giant planets) and their simulations resulted in the formation of habitable bodies. The number associated with each circle corresponds to the mean eccentricity of the giant planet during the simulation. For comparison, the systems in which the giant planet is unstable have also been marked. Given that at the beginning of each simulation, the orbit of this planet was considered to be circular, a nonzero value for its average eccentricity is the result of its interaction with the secondary star. The fact that Earth-like objects were formed in systems where the average eccentricity of the giant planet is small implies that this interaction has been weak. In other words, binaries with moderate to large perihelia and with giant planets on low-eccentricity orbits are most favorable for habitable planet formation. Similar to the

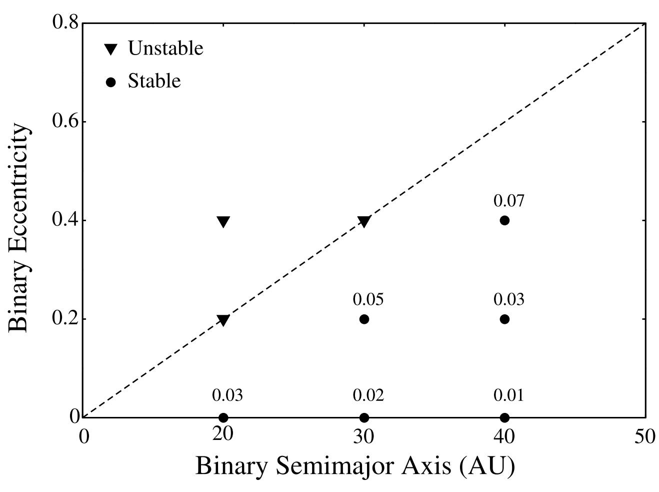

FIG. 11.—Habitable planet formation in the (e_b, a_b) space of an equal-mass binary planetary system. Circles correspond to binaries with initial parameters chosen from Fig. 1, in which habitable planets are formed. Triangles represent systems in which the giant planet is unstable. The number associated with each circle represents the mean eccentricity of the giant planet of the system during the simulation.

formation of habitable planets around single stars, where giant planets, in general, play destructive roles, a strong interaction between the secondary star and the giant planet in a binary planetary system (i.e., a small binary perihelion) increases the orbital eccentricity of this object, and results in the removal of the terrestrial planet-forming materials from the system.

5. SUMMARY AND CONCLUSIONS

We presented the results of the numerical simulations of the formation of Earth-like bodies in the habitable zones of moderately close binary planetary system. The systems of our interest had binary separations equal to or smaller than 40 AU, their primary stars hosted Jupiter-like planets, and their habitable zones were closer to their primaries than the orbits of their Jupiter-like objects. We simulated the late stage of terrestrial planet formation in such systems, and studied the effect of the binary companion on the interaction of planetary embryos and the formation, dynamical evolution, and physical characteristics of the final terrestrial bodies. Our results indicate that terrestrial-class planets can form in the habitable zones of binary planetary systems, and their final assembly, as well as their water contents, strongly depends on the separation of the binary and the eccentricity of the stellar companion.

Our simulations show that, similar to the formation of Earth-like objects at the presence of Jupiter in our solar system, where the eccentricity of the giant planet becomes the key factor in delivering water to the habitable zone (Chambers & Cassen 2002; Raymond et al. 2004), the orbital dynamics of this object, and its intermediate role in transferring the perturbative effect of the secondary star to protoplanetary objects, in a binary planetary system, have strong effects on the radial mixing of embryos and the water delivery process. As shown by S. N. Raymond (2007, in preparation), giant planets are, in general, unfavorable for delivery of water from asteroidal regions to the habitable zone. In a binary system, the interaction between this object and the secondary star, particularly in eccentric binaries, increases its orbital eccentricity and makes the process of water delivery inefficient. Our calculations show that to form habitable planets at the presence of a Jupiter-like planet in a binary star system, this interaction has to be weak. Water delivery is more efficient when the perihelion of the binary is large (Quintana et al. 2007) and the orbit of the giant planets is close to a circle (Raymond 2006a).

As mentioned in the introduction, this study was based on two fundamental assumptions: (1) terrestrial planet formation in binary planetary systems follows the same process as in single stars, (2) planetary embryos have already formed through oligarchic growth, and terrestrial-class objects are formed through the gravitational interaction of these bodies. Despite the observations of circumstellar disks around the components of several binary star systems, such assumptions may not be entirely viable. It is, in fact, necessary to study how the presence of a stellar companion affects the formation of planetary embryos, and also how the chemical structure of a disk of protoplanetary objects changes at the presence of a second close-by star.

The final water contents of the terrestrial planets is also an issue that requires detailed considerations. In our simulations, we assumed that all collisions were perfectly inelastic, and the water contents of the resulted planet would be equal to the sum of the water contents of the impacting bodies. This is an assumption that sets an upper limit for the water budget of terrestrial planets, and ignores the loss of water due to the impact. In fact, as shown by Genda & Abe (2005) and Canup & Pierazzo (2006) portions of the water of the impacting bodies will be lost due to the impact and the motion of the ground of an impacted body. The total water budget of the final bodies of Figures 9 and 10 may in fact be 5–10 times smaller than those reported in Table 1 (Raymond et al. 2004).

The simulations presented here are low resolution. Our model includes only large objects. A more realistic model would contain smaller bodies such as kilometer-sized planetesimals, as well. For this reason, the results of our integrations may not reveal detail characteristics of the final planetary systems, as they would be obtained from high-resolution simulations (e.g., see Raymond et al. 2006). However, as shown by Agnor et al. (1999) and Chambers (2001) for the simulations of our solar system, such integrations can produce the main general properties of the final assembly of the planetary bodies. That, combined with the fact that the speed of computational simulations varies as N^2, where N is the number of involved objects, makes the low-resolution simulations ideal for exploring the system's parameter space.

Despite of its limitations, our study shows that habitable planet formation can be efficient in moderately close binary planetary systems. The favorable systems seem to be binaries with moderate to large perihelia and giant planets outside the habitable zones of their primary stars and in low-eccentricity orbits. This points to the fact that, to develop a more comprehensive understanding of the formation of habitable planets in such environments, it is important to obtain a better knowledge of the formation of giant planets in these systems.

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