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Earth-size planet formation in the habitable zone of circumbinary stars

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ABSTRACT

This work investigates the possibility of close binary (CB) star systems having Earth-size planets within their habitable zones (HZs). First, we selected all known CB systems with confirmed planets (totaling 22 systems) to calculate the boundaries of their respective HZs. However, only eight systems had all the data necessary for the computation of HZ. Then, we numerically explored the stability within HZs for each one of the eight systems using test particles. From the results, we selected five systems that have stable regions inside HZs, namely Kepler-34, 35, 38, 413, and 453. For these five cases of systems with stable regions in HZ, we perform a series of numerical simulations for planet formation considering discs composed of planetary embryos and planetesimals, with two distinct density profiles, in addition to the stars and host planets of each system. We found that in the case of the Kepler-34 and 453 systems, no Earth-size planet is formed within HZs. Although planets with Earth-like masses were formed in Kepler-453, they were outside HZ. In contrast, for the Kepler-35 and 38 systems, the results showed that potentially habitable planets are formed in all simulations. In the case of the Kepler-413 *system*, in just one simulation, a terrestrial planet was formed within HZ.

Key words: planets and satellites: formation – binaries: close.

1 INTRODUCTION

Today, there are around 4100 exoplanets confirmed in more than 3000 stellar systems, most of which were discovered by the Kepler probe (Borucki et al. 2010; Howell et al. 2014). From these systems with planets, around 600 are multiplanetary, that is, with at least two confirmed planets. In addition to recent discoveries in single-star systems, planets have also been discovered in multiple (at least three stars) and binary-star systems, and about 50 per cent of Sun-type stars are in binary or multiple systems (Raghavan et al. 2010). In the binary case, there are known 22 stellar systems with planets in circumbinary orbits, i.e. planets around the barycentre of the binary pair, and none of them is a terrestrial (Table 1). The effect of the binary companion on the formation of these planets, however, remains unclear. On the other hand, recent works (Quintana & Lissauer 2006, 2010; Haghighipour & Raymond 2007; Quintana et al. 2007) explored the terrestrial planet formation around close binary (CB) and have shown that it is possible to form planets in this context.

Some works (Gorlova et al. 2006; Furlan et al. 2007; Trilling et al. 2007) based on spectral radiation characteristics in the infrared region and the radial velocity method have suggested the existence of binary stellar systems with massive protoplanetary discs. Indirect observations suggest the existence of disc material around one of the stars or the components of the system of stars (D'Alessio, Calvet & Hartmann 1997; Stapelfeldt et al. 1998; Jensen & Akeson 2003; Osorio et al. 2003; Akeson & Jensen 2014). Jensen & Mathieu (1997) showed that protoplanetary discs are common around binary stars with less separation than a few astronomical units. Observations of pairs of stars in the main sequence by the *Spitzer Space Telescope* revealed stable circumferential protoplanetary discs around pairs of stars with spacings between 0.04 and 5.31 AU in 14 systems (Trilling et al. 2007), with two of the systems having planets. Although binary systems have only gaseous planets, this evidence demonstrates the possibility of them forming terrestrial planets.

In Domingos, Winter & Carruba (2012), it was shown that in regions of the disc close to a binary system, bodies could be captured in mean motion resonances, which, according to recent studies (Verrier & Evans 2008; Farago & Laskar 2010), could be a potential mechanism of instability and disc failure. In addition, if the disc is tilted relative to the orbit plane of the binary system, the disc bodies

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Table 1. CB stars systems with confirmed planets (Schwarz et al. 2016).

System	Discovery year	Number of planets
DP Leo	2009	1
FW Tauri	2013	1
HD 106906	2013	1
HU Aqr	2011	1
Kepler-16	2011	1
Kepler-34	2012	1
Kepler-35	2012	1
Kepler-38	2012	1
Kepler-47	2012–2019	3
Kepler-413	2013	1
Kepler-451	2015	1
Kepler-453	2014	1
Kepler-1647	2015	1
NN Ser AB	2010	2
NY Vir AB	2011	2
OGLE-2007-BLG-349	2016	1
PSR B1620-26	2003	1
Ross 458	2010	1
Roxs 42	2013	1
RR Cae	2012	1
SR 12 AB	2011	1
TOI-1338 AB	2020	1

Note. The Kepler-47 system has two discovery dates, 2012 and 2019, because two planets in the system were confirmed in 2012 and another in 2019.

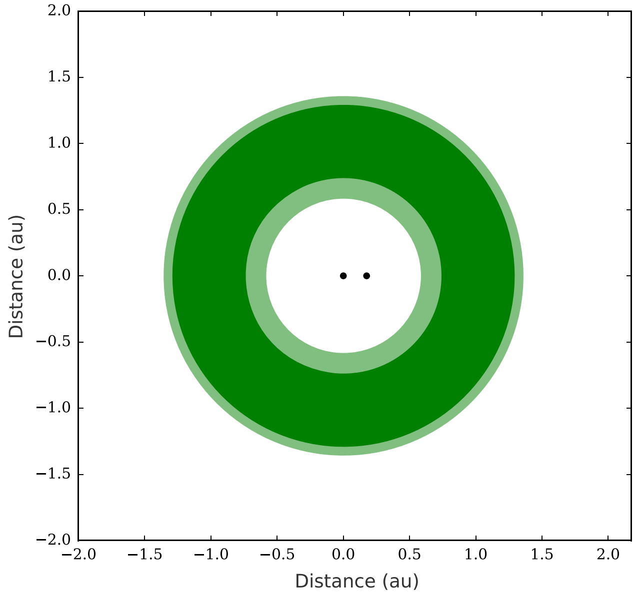

Figure 1. Example of a HZ of the system Kepler-453 (Haghighipour & Kaltenegger 2013). This figure was generated using the interactive website http://astro.twam.info/hz/. The figure is centred on the centre of mass of the pair of stars in black. The conservative and extended HZ are in dark green and light green, respectively.

close to the binary system must undergo the hovering effect of the node (Verrier & Evans 2009; Domingos, Winter & Izidoro 2015), which, depending on the inclination of the disc, should be stronger than the Kozai–Lidov effect. Therefore, the node's libration tends to stabilize the system, which results in a stable region. However, the orbits are tilted, which could make the planetary formation process longer when compared to single-star systems (Domingos et al. 2015).

The search for life is one of the great motivators of humanity for the exploration of our Solar system and other planets outside it. The knowledge of regions that make possible its existence as we know is fundamental for this search. HZ is defined as a region where Earth-like planets could support life. This zone is defined as a circumstellar region where planets with an atmosphere composed of $CO_2-H_2O-N_2$ can sustain liquid water on its surface (Huang 1959; Hart 1978; Kasting, Whitmire & Reynolds 1993; Underwood, Jones & Sleep 2003; Selsis et al. 2007; Kaltenegger & Sasselov 2011). In Haghighipour & Kaltenegger (2013), a generalized model that estimates the limits of HZ for binary systems shows that they have these well-defined limits; see Fig. 1.

In Shevchenko (2017), it is shown that CB systems are better able to harbour life, since a system that has two Sun-type stars has a wider HZ than systems of only one star of the same type; moreover, in a biological context, they do not need to have a large Moon-type satellite (as in the case of Earth) to be habitable. This favours the possibility that a Earth-type planet has life, given the extremely low probability of it having a Moon (Lissauer 1997).

From an observational point of view, Borucki & Summers (1984) show that eclipsing binaries are good targets for detecting planets through transit searches. It is shown that eclipsing binaries have three advantages in detecting planets. (1) The orbital plane of the planetary system must be close to the line of sight because is expected that the angular moment vector of the binary pair rotating around the common centre of mass between them is greater than in systems with only one star with equal mass of just one of the binary components. (2) Each one of the stars may have planets, considering systems where the stars are wide separated; and (3) planets orbiting CB stars will have a shorter orbital period than if they were orbiting a star of the same spectral class. In addition, they will have two stars to transit instead of one, giving a lot more information. In the case of CB systems that already have a planet in transit (which is the core of our present work), Kratter & Shannon (2014) showed that this configuration is a strong indicator that other planets must also be in transit. With that, knowing the possibility of CB Earth-type planets being formed and their locations in real systems with planets already detected can contribute to the detection of the first planet of this type in a binary system and with the possibility of having life.

Therefore, in this work, we are looking for real CB systems with confirmed planets, Earth-like conditions, and, consequently, Earth-like life. Then, in the next section, we checked from among all confirmed circumbinary planets those having enough data needed for our study. With the selected systems, we computed their HZ. In Section 3, we checked the stability of massless particles within the limits of HZs. In Section 4, we used numerical simulations to explore the formation of terrestrial planets within the stable regions determined in Section 3. In the last section, we make our final remarks.

2 BINARY STARS SYSTEMS AND THEIR HZ

As we are exploring the formation of planets within HZ of their systems, we first select all binary systems that have planets to compute their HZ; see Table 1. However, not all systems chosen had the data required for this calculation or were not stars of the main sequence, such as the *PSR B1620-26* system, which is a pulsar. Only some of the binary systems detected by the Kepler probe remain (Kepler-16, 34, 35, 38, 47, 413, 453, and 1647). The data of these systems are given in Table 2. For the selected systems, we computed the boundaries of their respective HZ using two different models

Table 2. The main parameters of the eight selected binary systems with the potential to form Earth-like planets in their HZ. M_A and M_B, a_{bin}, and e_{bin} are the masses, semi-major axis, and eccentricity from the binary pair, respectively, and a_p, e_p, M_p, and i_p are the semi-major axis, eccentricity, mass, and inclination with respect to the binary plane of the planet of each system, respectively.

System	M_A ($M_\odot$)	M_B ($M_\odot$)	a_{bin} (au)	e_{bin}	a_p (AU)	e_p	M_p (M_j)	i_p (°)	References
Kepler-16	0.689	0.203	0.224	0.159	0.705	0.007	0.333	0.308	Doyle et al. (2011)
Kepler-34	1.048	1.021	0.229	0.521	1.089	0.182	0.220	0.497	Welsh et al. (2012)
Kepler-35	0.890	0.810	0.176	0.142	0.603	0.042	0.127	0.336	Welsh et al. (2012)
Kepler-38	0.949	0.249	0.147	0.103	0.464	0.030	0.016	0.182	Orosz et al. (2012b)
Kepler-47	1.043	0.362	0.084	0.023	0.297	0.035	0.028	0.270	Orosz et al. (2012a)
					0.989	0.411	0.061	1.160	Orosz et al. (2012a)
					0.699	0.024	0.060	0.000	Orosz et al. (2019)
Kepler-413	0.820	0.542	0.102	0.037	0.355	0.118	0.210	4.073	Kostov et al. (2014)
Kepler-453	0.944	0.195	0.185	0.052	0.790	0.036	0.030	2.258	Welsh et al. (2015)
Kepler-1647	1.221	0.968	0.128	0.159	2.721	0.0581	1.520	2.986	Kostov et al. (2016)

Note. M_A and M_B, a_{bin}, and e_{bin} are the masses, semi-major axis, and eccentricity from the binary pair, respectively, and a_p, e_p, M_p, and i_p are the semi-major axis, eccentricity, mass, and inclination with respect to with the binary plane of the planet of each system, respectively.

Table 3. Selected CB stars systems with their respective HZs using two models to determine their bounds.

Systems	Haghighipour & Kaltenegger				Mason et al.			
	Narrow HZ		Wide HZ		Narrow HZ		Wide HZ	
	Inner (AU)	Outer (AU)	Inner (AU)	Outer (AU)	Inner (AU)	Outer (AU)	Inner (AU)	Outer (AU)
Kepler-16	0.39	0.65	0.30	0.70	0.45	0.82	0.36	0.87
Kepler-34	1.55	2.73	1.20	2.90	1.62	2.83	1.28	2.98
Kepler-35	1.10	1.98	0.89	2.09	1.18	2.07	0.93	2.18
Kepler-38	1.60	2.85	1.30	3.00	0.91	1.61	0.72	1.61
Kepler-47	0.89	1.58	0.69	1.65	0.89	1.57	0.70	1.66
Kepler-413	0.50	0.85	0.40	0.88	0.57	1.04	0.45	1.10
Kepler-453	0.70	1.25	0.55	1.31	0.75	1.33	0.59	1.41
Kepler-1647	2.10	3.79	1.57	4.00	2.34	4.08	1.85	4.30

present in Haghighipour & Kaltenegger (2013) and Mason et al. (2015); see Table 3. We can note that boundaries of HZ of each system are very similar using the two models. So, in our plots and analyses, we will take into account only the model of Haghighipour & Kaltenegger (2013).

3 STABILITY INSIDE THE HZ

With known HZ, since our objective is to study the possibility of formation of terrestrial planets within these regions, we first check if they are stable or at least have stable parts. The stability study will be important because the results of these tests will be the initial conditions for the formation simulations. Using an adaptation made by us [called MINOR-MERCURY package (Amarante, Winter & Sfair 2019)] of the numerical integrator of n-body MERCURY (Chambers 1999) based on Chambers et al. (2002), with the hybrid integrator option for binary systems, we performed numerical simulations with test particles (particles that do not interact gravitationally with each other), the binary pair, and the host planets of each system.

3.1 Initial conditions of the test particles

The parameters of the eight systems selected are the ones shown in Table 2. The particles were distributed randomly along HZ with an extra margin of 20 per cent of the total width of HZ for each side, i.e. internal and external, with eccentricity equal to zero and coplanar with the orbital plane of the binaries. The number of particles for each system varied according to the width of each region to be distributed. For this, we use a density of particles per AU^2 of ≈160. Particles were removed from the simulation if their semi-major axis exceeded 10 AU. Thus, eight simulations were performed with the integration final time of 1 Myr.

The internal and external limits for HZ of each system can be checked in Table 3. We consider the limits of empirical (wider) HZ to distribute the particles. The extra limits where the particles were distributed can be checked in Fig. 2, where they are represented by dashed black lines.

3.2 Results

3.2.1 Kepler-16

The sum of the masses of the binary pair equals approximately 0.9 $M_\odot$, so it is the least massive pair in our simulations. Thus, it is the system that has the narrowest and closest HZ to the system's barycentre, causing much disturbance in the particle disc by the motion of the stars. Another factor that increases disc disturbance is the semi-major axis of the stars, which is the second largest of our test cases, equal to 0.224 AU. Also, the system planet is inside of HZ. These ingredients cause all particles to be ejected within a few thousand years. Only some coorbitant particles to the host planet survived in the simulation(see Fig. 2), which indicates that the habitable region of the system is unstable. This result shows us that forming a planet in HZ is difficult, but this does not exclude the possibility of any body orbiting these regions. Since this system has unstable HZ, we do not simulate the formation of planets in this case.

Although this system is unstable throughout its HZ, it is possible to note that the system has bodies coorbital to the host planet; see Fig. 2. This is an important result mainly for two reasons.

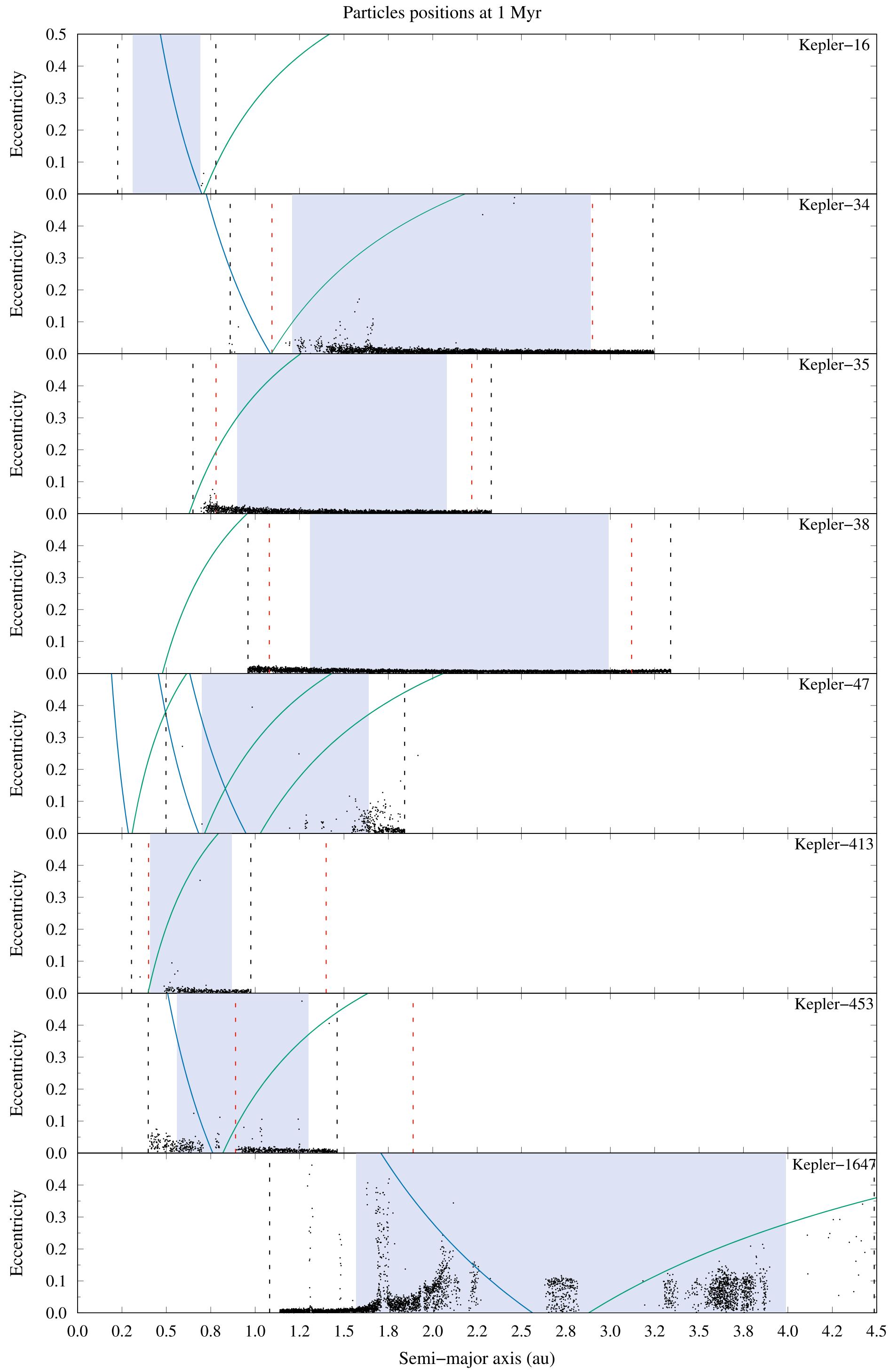

Figure 2. Final positions of the test particles for the selected systems (Kepler-16, 34, 35, 38, 47, 413, 453, and 1647). The region shaded in blue indicates HZ of each system. The green lines in each sub-figure represent the apocentre of the host planets of each system as a function of the pericentre of the particles given by $a = [a_p(1 + e_p)]/(1 - e)$, and the blue lines represent the pericentre of the planet as a function of the apocentre of the particles, given by $a = [a_p(1 - e_p)]/(1 + e)$. a_p and e_p represent the semi-major axis and eccentricity of the host planet, respectively, and a and e are the same for the particles. The black dashed lines indicate the limits of the initial distribution of the test particles and the red dashed lines indicate the limits of the stable region to be used for the distribution of bodies to the planetary formation study.

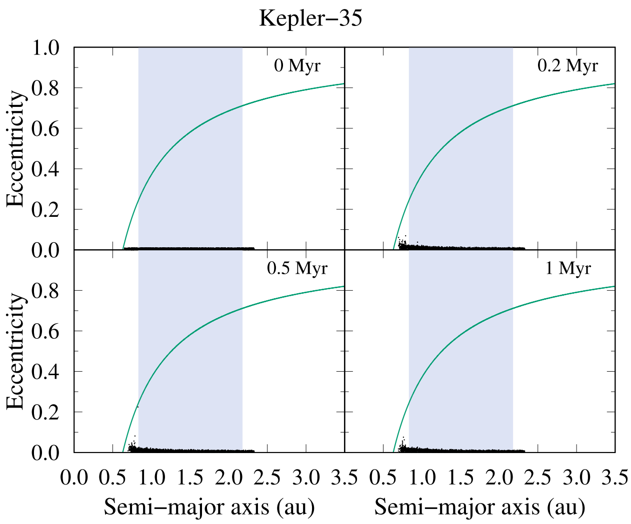

Figure 3. Snapshots in time of the dynamic evolution of particles in the Kepler-35 system. The horizontal and vertical axes are the semi-major axis and the eccentricity, respectively. The black dots are the particles and the green line is the apocentre of the host planet of the system in function of the pericentre of the particle, given by $a = [a_p(1 + e_p)]/(1 - e)$. The shaded region in blue represents HZ of the system.

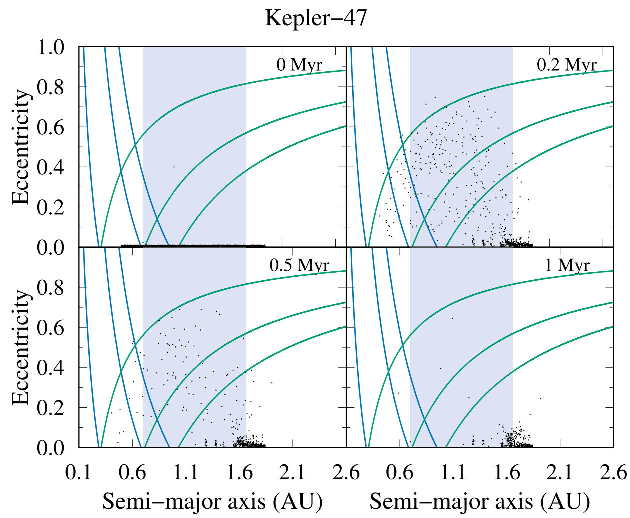

Figure 4. Snapshots in time of the dynamic evolution of particles in the Kepler-47 system. The horizontal and vertical axes are the semi-major axis and the eccentricity, respectively. The black dots are the particles and green lines represent the apocentre of the host planets of the system in function of the pericentre of the particle, given by $a = [a_p(1 + e_p)]/(1 - e)$, and the blue lines represent the pericentre of the planet as a function of the apocentre of the particles, given by $a = [a_p(1 - e_p)]/(1 + e)$. The shaded region in blue represents HZ of the system.

(1) It demonstrates the condition of binary systems having bodies coorbital to the host planets. (2) As in this case, the planet is within HZ, consequently, coorbital bodies will also be. Thus, even if HZ is dynamically unstable, the system can still have bodies within HZ sharing the orbit with the host planet.

3.2.2 Kepler-34

The system's HZ is away from the system centre of mass. This makes the disc not very disturbed by the stars. The dominant disc disturbance comes from the confirmed planet. The planet is positioned at the beginning of HZ and consequently on the particle disc; see Fig. 2. This causes further disturbance in the early part of the disc. Even with the planet's presence, HZ is practically entirely stable. Therefore, the system presents stability conditions to study the formation of planets in HZ.

3.2.3 Kepler-35

The Kepler-35 system is very similar with Kepler-34. The system also has the planet very close to the interior of the habitable region, which makes the planet the main disturbing agent of the disc. Although close, the planet never orbits within to HZ as in the previous case, which makes it completely stable, and the particles practically did not vary their positions. This can be checked in Fig. 3, where snapshots of the evolution of the semi-major axis and eccentricity in the Kepler-35 system are shown. Only the particles closest to the planet were ejected, giving us a large region for the study of planetary formation.

3.2.4 Kepler-38

This system is the most stable of all studied in this work, as can be seen in Fig. 3. This feature comes from the great distance that HZ is from the planet and, consequently, from the stars. In addition, the planet is the least massive of all eight selected, with a reasonable mass of 0.016 Jupiter masses. Throughout the simulation, no particles were ejected, and as we can see from Fig. 3, only the early disc particles had a slight increase in eccentricity. Thus, the system has a large region for the study of planetary formation within its HZ.

3.2.5 Kepler-47

The Kepler-47 system has already been the subject of a stability study in some works before the third planet was confirmed. In Kratter & Shannon (2014), the system was used as a case study to verify that the system is dynamically packed with the three planets. In Hinse et al. (2015), a stability study was performed using the MEGNO technique to predict the third planet.

In our work, with the confirmation of the three planets, we used the three to test the dynamic stability of HZ. Thus, this case is the only multiplanetary system present in our stability test. The most recent confirmation is from the planet Kepler-47d (Orosz et al. 2019). One of the planets is orbiting within HZ, which causes great instability in that region. We can check in Figs 2 and 4 that almost all particles were ejected at 1 Myr, with only a few particles remaining on the outside of HZ. Thus, we can conclude that HZ is unstable to its full extent and does not provide conditions to study the ability of this system to form a planet within HZ.

Together with the Kepler-16 system, this case is the most unstable HZ of our simulations. In addition to the instability present in both cases, one of the host planets also has a coorbital body to it; see Fig. 2.

3.2.6 Kepler-413

This system has a very narrow HZ and a host planet on its inner edge. In this case, the particles that are in the innermost region of the disc are ejected because they are very close to the planet. Although many particles have been ejected and collided with the planet, a reasonable fraction of HZ of the Kepler-413 system has stability.

3.2.7 Kepler-453

The planet of the system orbits within to HZ, which causes a lot of ejections and collisions of the particles. We can see in Fig. 2 two regions, one at the beginning and one at the end of HZ that have stability, the largest being the outermost region. So even though it has no stability to its full extent, the system has parts that are stable.

Besides the system having a stable part of HZ, the same result of the Kepler-16 system can be noticed in this case; see Fig. 2. The system has bodies coorbital to the host planet as well.

3.2.8 Kepler-1647

The Kepler-1647 system has the largest exoplanet in binary systems with approximately 1.5 Jupiter masses. In addition to the planet, stars also have the largest mass sum in our work, which makes HZ farther and wider. The planet is in the middle of HZ, causing many particles to be ejected. In Fig. 2, we can see three sub-regions within HZ. An inner region, an coorbital region, and another outer region in relation to the planet. In this case, because it is a peculiar and complex system, we will study the formation of terrestrial planets within these three regions in a future work.

With the stable regions found in the above systems, we can now study the ability to form terrestrial planets in these regions. Some systems, as in the case of Kepler-16, 47, and 1647, do not have a stable region sufficient for this study. Others, such as the Kepler-413 and 453 systems, do not have completely stable HZ, but we can study at least some parts of these regions. The red dashed lines in Fig. 2 are the inner and outer limits where we distribute the embryos and planetesimals to explore the terrestrial planet formation.

4 PLANETARY FORMATION

Because our work is to explore terrestrial planet formation around binary stars systems, we followed the classical paradigm of terrestrial planet formation in single-star systems because theories about the stages of planetary formation and, consequently, formation of terrestrial planets in binary systems do not yet exist. Our simulations are performed starting with two different surface density profiles given by $\Sigma_1 r^{-x}$, where $x = 1.5$ and 2.5. Σ_1 is a solid surface density at 1 AU. Σ_1 was adjusted to fix the total mass of 2.5 $M_\oplus$ (Quintana 2004; sum of the masses of the terrestrial planets in Solar system) in the stable and habitable region.

In our simulations, we assumed that the growth of dust grains and planetesimals occurred during the first stages of planetary accretion. Thus, we used a bimodal disc composed of embryos (60 per cent of the disc's mass) and planetesimals (40 per cent of the disc's mass; Izidoro et al. 2015). It was assumed that embryos are formed by oligarchic growth and are thus spaced randomly by 5–10 mutual Hill radii (Kokubo & Ida 1998, 2000) with a density of 3 g cm^{-3}. The mass of each planetesimals is $\approx$ 0.002 $M_\oplus$. In the numerical integrations, the planetesimals do not have gravitational interactions with themselves but only with stars, planets, and protoplanetary embryos. The protoplanetary embryos masses scale as $M \approx r^{3(2-x)/2} \Delta^{3/2}$ (Kokubo & Ida 2002; Raymond, Quinn & Lunine 2005; Raymond et al. 2009; Izidoro et al. 2015), where Δ is the mutual Hill radii separations between embryos orbits. As we are using distinct systems with different parameters, the number of embryos and planetesimals are not the same among the systems; see Table 4. Fig. 5 shows the initial conditions of $x = 1.5$ and 2.5, for all our simulations. Discs with $x = 2.5$ have embryos more massives in the inner region of the disc, and with 1.5 in the outer region. We chose these two values of the parameter x, besides being used frequently in some works (Raymond, Quinn & Lunine 2004; Raymond et al. 2005; Izidoro et al. 2014a, 2015; Izidoro, Morbidelli & Raymond 2014b; Izidoro & Raymond 2018), to study the dynamic evolution in discs that have mass growing as a function of the orbital radius of the bodies and in cases where the mass decreases as a function of the orbital radius (see Fig. 5). This is an important point because we have some systems where the giant planet is in the inner region of the disc and others in the outer region. So we needed to consider the two cases for all systems. The orbital inclination of the embryos and planetesimals is chosen randomly between $10^{-4\,\circ}$ and $10^{-3\,\circ}$ with respect to the binary plane, and the eccentricity is chosen between 0 and 0.01.

Table 4. The approximate number of planetesimals and embryos of each system for two different value of x (1.5 and 2.5).

Systems	Number of planetesimals	Number of embryos
	$x = 1.5$	
Kepler-34	480	40
Kepler-35	480	40
Kepler-38	480	35
Kepler-413	470	48
Kepler-453	450	20
	$x = 2.5$	
Kepler-34	475	40
Kepler-35	470	40
Kepler-38	440	35
Kepler-413	470	47
Kepler-453	440	20

In our simulations, were used the parameters from the stars and planets hosts of each system given in Table 2. For each surface density profile, five simulations were performed with a few differences generated randomly for the initial disc, totalling 50 simulations. Thus were integrated for 200 Myr (Quintana 2004) using an adaptation of the MERCURY package (Chambers 1999), made by us following the work of Chambers et al. (2002), as previously mentioned. Collisions between planetary embryos and with planetesimals are considered inelastic such that in each collision mass and linear momentum are conserved and a new body is formed.

4.1 Results and discussion

In this section we will see the individual results of the numerical simulations of each system, addressing the different values of the coefficient x (1.5 and 2.5). It is important to remember that x = 1.5 results in a disc in which the mass of the embryos is increasing according to the semi-major axis of the embryo, and values of x = 2.5 provide discs with decreasing embryo mass along the disc (Fig. 5). The results of our numerical simulations, referring to all systems, are present in Figs 6 and 7, referring to the final integration time with $x = 1.5$ and 2.5, respectively. These figures show the semi-major axis of the planets formed in five simulations for each system. The size of each circle in the plots is proportional to the mass of the planet generated in the simulation and the colours provide their mass with respect to the mass of the Earth. As the limits of HZ vary

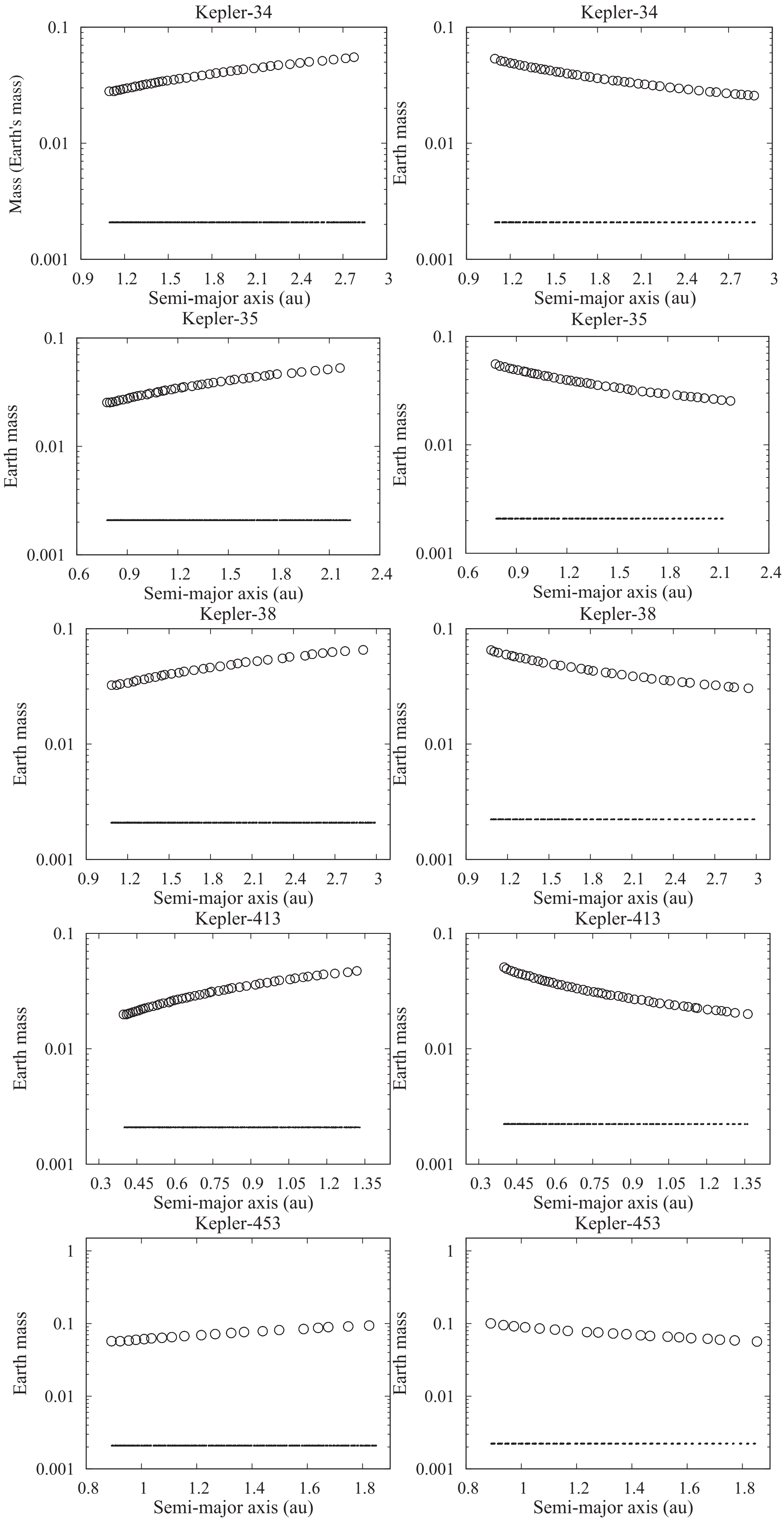

Figure 5. Initial conditions for the selected binary systems. In the left- and right-hand panels are the initial distributions of planetesimals and embryos for $x = 1.5$ and 2.5, respectively.

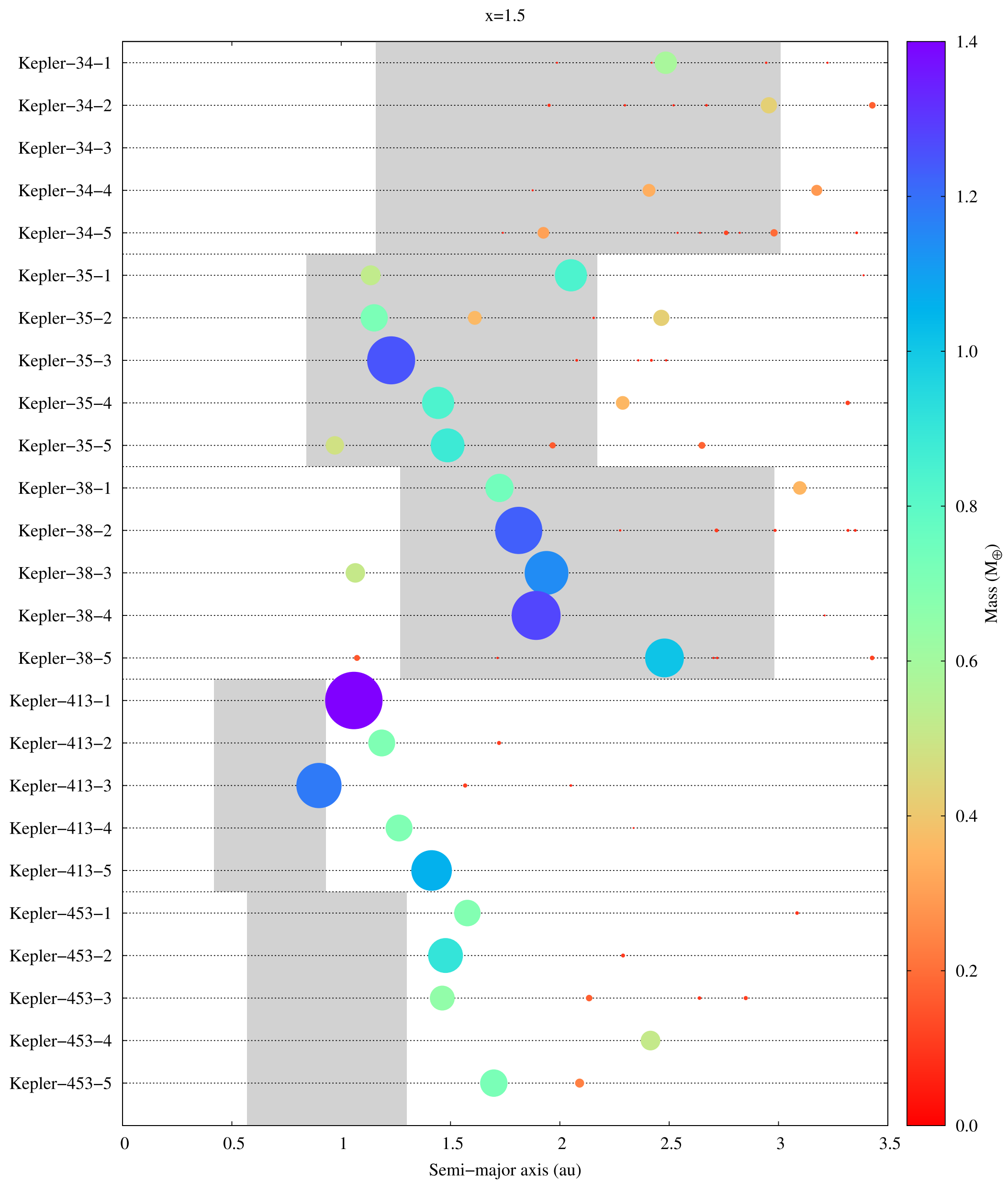

Figure 6. Final orbital configuration of 25 simulations of the systems using $x = 1.5$. The circles represent the bodies formed in the simulations and their sizes are proportional to their masses. The colour of the plants represent their mass in terms of Earth masses, and the shaded regions are HZs of each system.

with the mass of the planet (Kopparapu et al. 2014), we consider as an Earth-size a planet that has mass varying between 0.80 and 1.20 $M_\oplus$.

4.1.1 *Kepler-34*

The Kepler-34 system has two stars with masses close to the Sun (see parameters in Table 3), which, consequently, belong to spectral class G with an age of 5–6 Gyr. They complete an orbital period in about 28 d (Welsh et al. 2012). This system has one giant planet with ≈ 22 per cent of the mass of Jupiter, 76 per cent of the radius of Jupiter, and is known as Kepler-34b. The Kepler-34 system has its planet very close to the disc of planetesimals and embryos. This makes the planet the main disturber. This causes a lot of disc mass to be lost as early as the first thousand of years of integration, especially in the early part of the disc. At $x = 1.5$, 24 per cent of the initial mass was lost, while in the case of $x = 2.5$, 36 per cent of the mass was lost at the same length of time. The percentage is higher in the case of $x = 2.5$ because in this case the most massive embryos are at the inner part of the disc, the most disturbed region. Thus, being ejected or collided with the planet. With both mass-scale parameters, protoplanets are formed within HZ in all simulations. The closest to a terrestrial mass appears in the case Kepler-34-1 (with $x = 1.5$), where a planet with a mass of about 0.6 $M_\oplus$ is formed in the simulation; see Fig. 6. In all others, with both values of x, only bodies with masses < 0.4 $M_\oplus$ are formed; see Figs 6 and 7. Therefore, from our initial conditions, this system can form a terrestrial planet with up to 0.6 Earth mass within HZ.

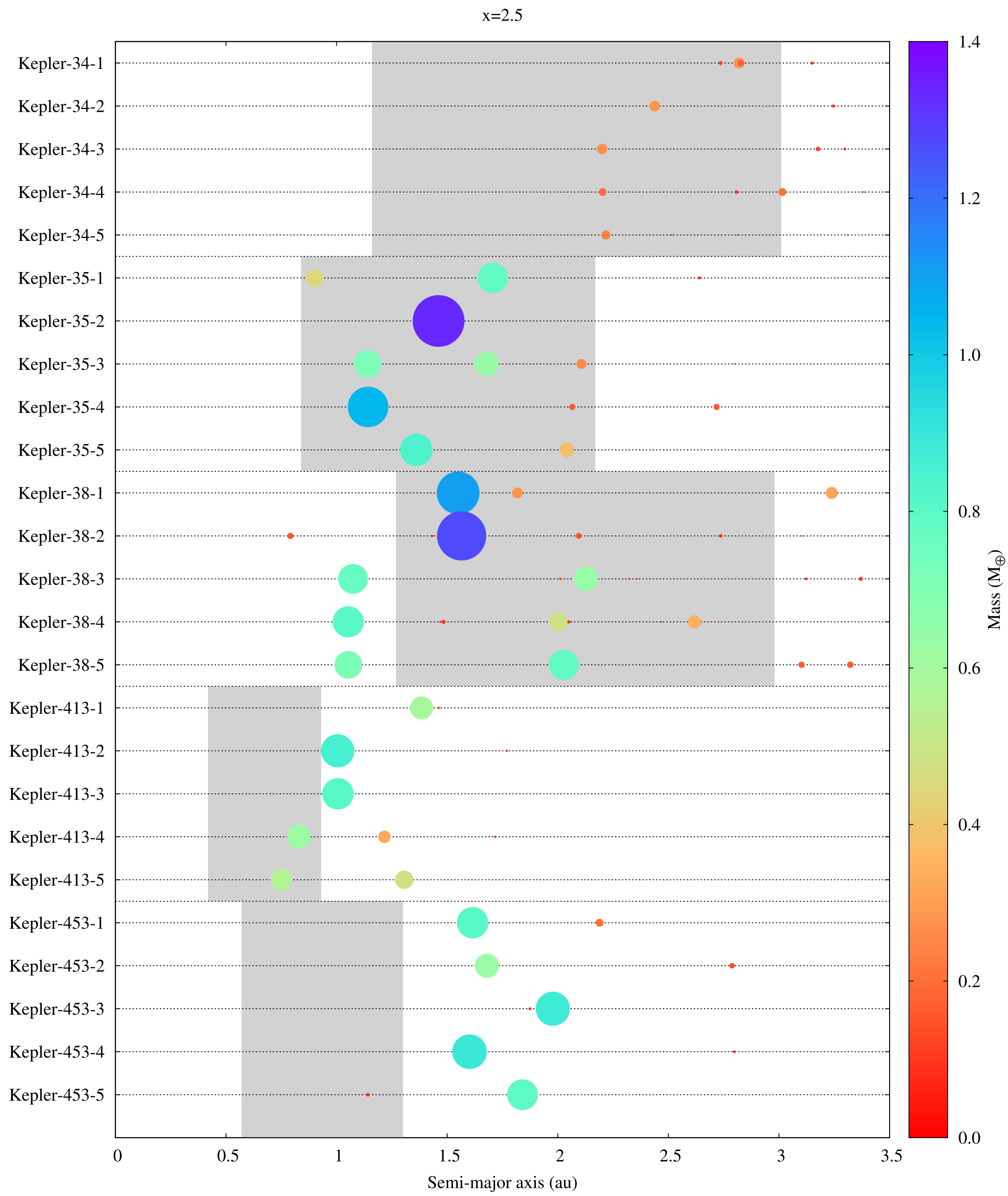

Figure 7. Final orbital configuration of 25 simulations of the systems using $x = 2.5$. The circles represent the bodies formed in the simulations and their sizes are proportional to their masses. The colour of the plants represent their mass in terms of Earth masses, and the shaded regions are HZs of each system.

4.1.2 Kepler-35

This system also has stars with mass close to that of the Sun, with this also belonging to the spectral class G. These stars have a 0.176-au semi-major axis and an orbital period of 21 days with an age of 8–12 Gyr (Welsh et al. 2012). The host planet of the system, known as Kepler-35b, has 13 per cent of the mass and 73 per cent of the radius of Jupiter (Welsh et al. 2012), it is ≈ 0.3 AU away from the beginning of the disc. In the stability test within HZ, we saw that the test particles hardly changed in their semi-major axis and eccentricities and thus little mass is lost.

In the case of $x = 1.5$, at least one planet with mass > 0.7 $M_{\oplus}$ has been formed; see Fig. 6. Analysing only the bodies that were formed in the simulation inside HZ, we have that in the Kepler-35-1 simulation, two bodies with masses of 0.6 and 0.85 $M_{\oplus}$ are formed. The Kepler-35-2 simulation is the case in which less massive bodies are formed, which are approximately 0.6 and 0.3 $M_{\oplus}$. In Kepler-35-3, the largest planet is formed, with a mass equal to 1.2 $M_{\oplus}$. The Kepler-35-4 and Kepler-35-5 simulations have very similar results, where, in both cases, planets with about 0.85 Earth mass were formed in the simulation and with similar semi-major axis. Fig. 8 shows snapshots in time of the dynamic evolution of the semi-major axis and the eccentricity of embryos and planetesimals of the Kepler-35-5 simulation.

In the case where we have $x = 2.5$, we also found that in all simulations, at least one planet with mass greater than 0.6 $M_{\oplus}$ is formed inside HZ; see Fig. 7. Looking at these planets, we have that in the Kepler-35-1 case, two planets with masses of 0.44 and 0.78 $M_{\oplus}$ are formed. In Kepler-35-2, the largest of them is formed, with

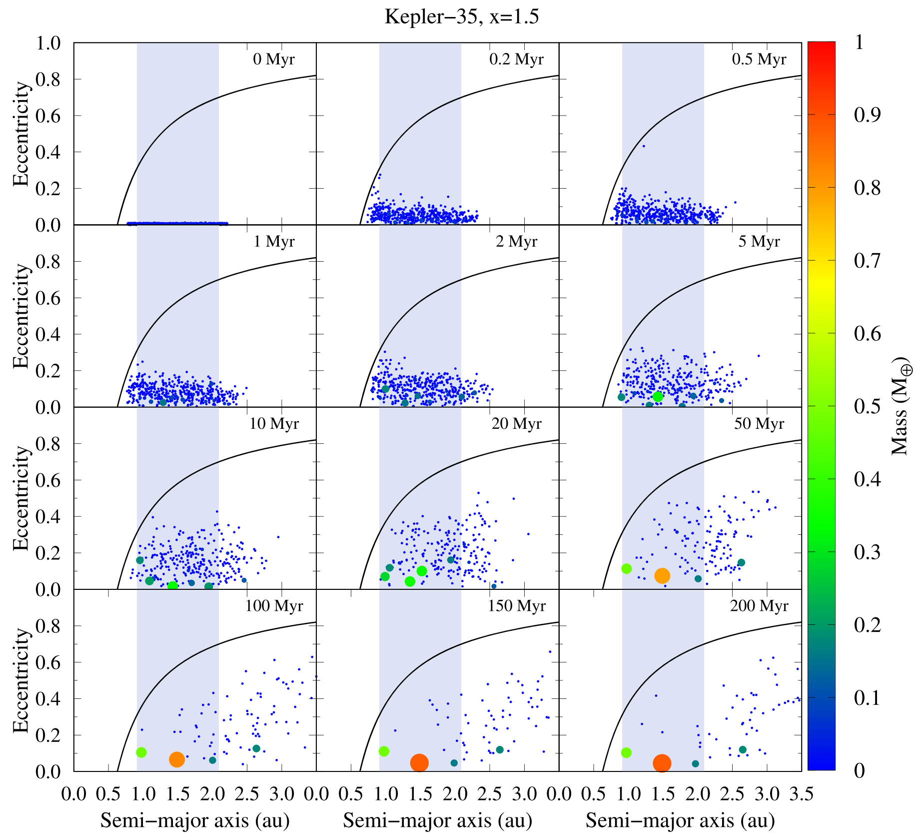

Figure 8. Snapshots in time (case Kepler-35-5) of the dynamic evolution of embryos and planetesimals of the Kepler-35 system. The horizontal and vertical axes are the semi-major axis and the eccentricity, respectively. The coloured circles represent the embryos and planetesimals and their sizes are proportional to their masses, and the black line is the apocentre of the host planet of the system in function of the pericentre of the particle, given by $a = [a_p(1 + e_p)]/(1 - e)$. The shaded region in blue represents HZ of the system.

mass equal to 1.33 $M_{\oplus}$. In the Kepler-35-3 simulation, two planets with very similar masses were formed (0.65 $M_{\oplus}$). The Kepler-35-4 simulation has an Earth size with a mass of 1.04 $M_{\oplus}$, Fig. 9 shows snapshots in time of the dynamical evolution of the semi-major axis and eccentricity of embryos and planetesimals. Finally, in the case Kepler-35-5, two planets are formed, the largest with a mass of 0.75 $M_{\oplus}$.

The results shown above showed that with both values of x (1.5 and 2.5) terrestrial planets were formed within HZ. Therefore, we can conclude that this system has a great potential to house a habitable Earth-type planet.

4.1.3 Kepler-38

The binary star system Kepler-38 has two stars with masses of 95 and 25 per cent solar masses, respectively. The brighter star is spectral class G, while the secondary has spectral class M. The stars have semi-major axis 0.147 AU and complete an eccentric orbit around a common centre of mass every 18.8 d (Orosz et al. 2012b). The system has a planet called Kepler-38b, known as a Neptune-sized type. Since it has not yet noticeably perturbed the stellar orbits, the planet does not have exact mass, being it an upper limit of 122 Earth masses, being its reasonable mass equal to 21 Earth masses,[1] which was used in our work as can be seen in Table 2. The system has the most stable HZ. The planet is 0.7 AU away from the disc, in addition to being a planet with mass $0.016M_j$, that is, the smallest of the planets studied in our work. With this, the planet causes little disturbance to the disc. At $x = 1.5$, the first ejection occurred at 7 million yr and at $x = 2.5$ in only 10 million yr. In addition, this small disturbance causes collisions to occur in a longer time-scale and, consequently, the formation of planets is slower.

For $x = 1.5$, Fig. 6 shows that planets with Earth-like mass are formed in all simulations within HZ. The Kepler-38-1 simulation is the one containing the smallest planet formed, with a mass of 0.74 $M_{\oplus}$. The Kepler-38-2, 3, and 4 cases have the largest ones, with masses of 1.23, 1.14, and 1.27 $M_{\oplus}$, respectively. In addition to these three simulations having planets with similar masses, the positions in which they were formed are also similar. The Kepler-38-5 case has the planet with the largest semi-major axis being 2.5 AU with mass approximately equal to 1.01 $M_{\oplus}$.

In the cases for $x = 2.5$, all simulations have at least one planet inside HZ; see Fig. 7. Regarding these planets, in the Kepler-38-1 simulation, a planet with mass 1.1 $M_{\oplus}$ was formed. In the case Kepler-38-2, one planet with mass equal to 1.26 $M_{\oplus}$ is formed in the same position as the previous case. The final configuration of the other three cases is quite similar. In these cases, three planets were formed outside HZ and three others inside. The semi-major axis of HZ's three external are close to 1 AU with masses around 0.65 $M_{\oplus}$ and the three interns have semi-major axis close to 2 AU with masses ranging from 0.4 to 0.65 $M_{\oplus}$.

[1]This mass is found assuming that the planet follows the empirical mass–radius relationship of $M_b = (R_b/R_{\oplus})^{2.06}\ M_{\oplus}$ (Lissauer et al. 2011), where M_b and R_b are, respectively, the mass and the radius of the planet.

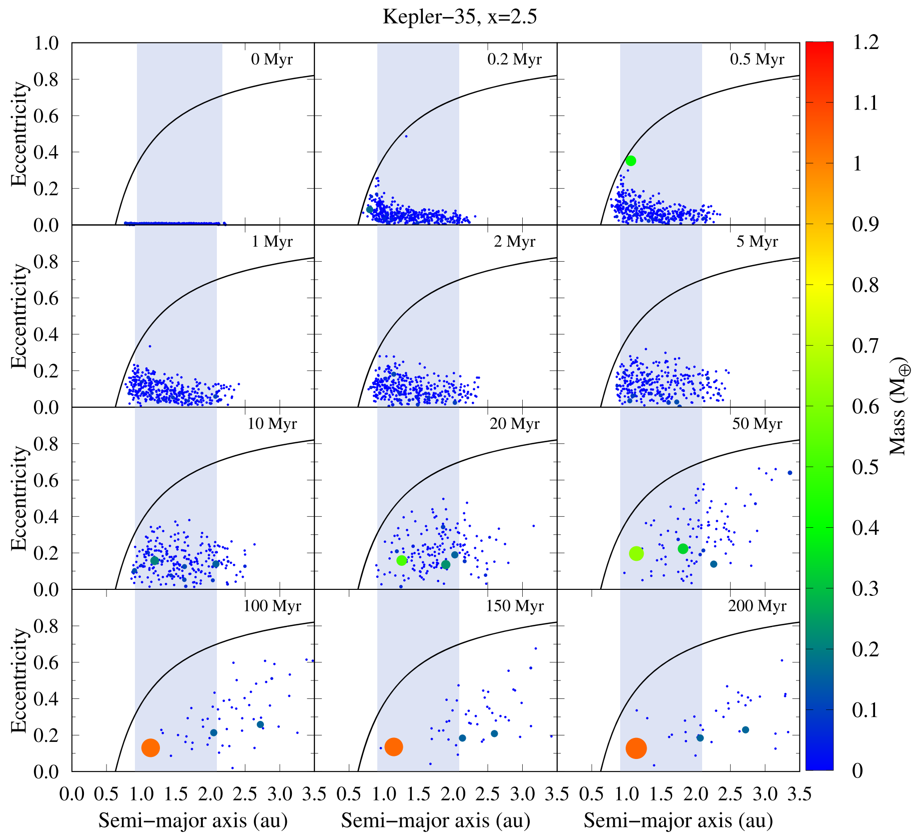

Figure 9. Snapshots in time (case Kepler-35-4) of the dynamic evolution of embryos and planetesimals of Kepler-35 system. The horizontal and vertical axes are the semi-major axis and the eccentricity, respectively. The coloured circles represent the embryos and planetesimals and their sizes are proportional to their masses, and the black line is the apocentre of the host planet of the system in function of the pericentre of the particle, given by $a = [a_p(1 + e_p)]/(1 - e)$. The shaded region in blue represents HZ of the system.

From the results found, we can conclude that the system has conditions of forming and housing a habitable Earth-type planet. With less massive discs on the inside (with $x = 1.5$), we show that in almost all cases (except simulation 1), Earth-like planets form inside HZ. In the cases where the simulations had more massive discs inside, only the simulations 1 and 2 Earth-type planets inside HZ were formed.

4.1.4 *Kepler-413*

In this system, the two stars Kepler-413A and Kepler-413B have masses of 82 and 54 per cent of the mass of the Sun, respectively. The brightest is a K dwarf spectral type while its companion a M dwarf, which results in the thinnest HZ of the systems present in our simulations. In this system, we have the second least massive host planet of the systems treated in our work. However, unlike the Kepler-38 system that has a planet that is ≈0.6 AU from the disc, and thus resulting in a disc in which the collisions happen slowly, in this case, the planet is at the inner boundary of HZ and very close to the disc (≈ 0.05 AU), causing great disturbance. Much of the mass present in the innermost region of the disc is ejected as early as the first instants of the simulation. In the simulations where $x = 1.5$, 24 per cent of the total disc mass was lost in 0.5 Myr, while for $x = 2.5$, 38 per cent of the total mass was lost in the same length of time.

In the case of $x = 1.5$, where the outermost part of the disc are conserved, thus forming more massive planets; see Fig. 6. In the Kepler-413-1 simulation, the largest one is formed with mass close to 1.4 $M_\oplus$, but outside of HZ. In simulation 2 of this system, a planet with 0.6 Earth mass is formed, also outside of HZ. In simulation Kepler-413-3, a planet with 1.1 $M_\oplus$ is formed inside HZ very close to the outer boundary. In the following two cases, Kepler-413-4 and 5, a planet was formed in each case with masses of 0.6 and 1 $M_\oplus$, respectively.

In simulations with $x = 2.5$, due to the factors mentioned above, less massive planets were formed; see Fig. 7. In simulation 1, one planet with 0.6 Earth mass forms far from HZ. In simulations 2 and 3, two planets with similar masses, approximately 0.75 $M_\oplus$, are formed outside HZ in similar regions. In cases 4 and 5, two planets also with similar masses, approximately 0.6 $M_\oplus$, are formed within HZ.

Thus, we can conclude that the system is capable of housing habitable Earth-like planets within HZ in some cases. These cases occur when the system has a less massive embryo and planetesimal disc in its internal region ($x = 1.5$).

4.1.5 *Kepler-453*

The system Kepler-453 has two stars, Kepler-453A and Kepler-453B. The brightest is similar to our Sun, containing 94 per cent of its mass, while the smaller star, Kepler-453B, has about 20 per cent of its mass. Stars orbit one another every 27.3 d (Welsh et al. 2015). This system has a giant planet that is within HZ of the system with ≈ 0.8 mass of Jupiter. It is important to remember that not every planet within HZ of a system can harbour life since the boundaries of these regions are calculated on the basis of the flow of energy received at the top of Earth's atmosphere. In calculating the stableness of the habitable region, we discovered a small band on which it was possible to distribute a disc. Thus, the beginning of the disc of material is at approximately 0.85 AU, meaning that the planet has a semi-major axis equal to 0.790 AU. This way the disc is very affected by the presence of the planet so close. As in previous cases, in simulations with $x = 1.5$, on average, less mass was ejected. In this case, 10 per cent of the disc mass was lost to 0.5 Myr, and 16 per cent mass was lost in the same time interval to $x = 2.5$. Although the planet is extremely close to the disc, and even within HZ, due to its low eccentricity (0.036), not as much mass is ejected as in the case of the Kepler-34 system. Thus, planets with masses close to Earth's mass (0.6–0.9 $M_\oplus$) are formed in all simulations, but all outside of HZ; see Figs 6 and 7.

5 FINAL REMARKS

In this work, we numerically investigate the possibility that planets with Earth mass are formed within HZ of real CB systems with detected planets. With this, our work seeks to show which systems are capable of containing an Earth-type planet capable of harbouring life.

For this, we first selected all systems with this configuration and first filtered out systems that had sufficient data for the calculation of those regions and subsequently those that had reasonable stability for a circumstellar mass disc to be distributed in those regions. Our simulations were carried for 200 Myr. The orbital parameters and masses of the stellar systems were taken from the literature specified in the text. As previously mentioned, our discs follow a bimodal configuration, composed of planetary embryos, whose mass scales along the disc with two distinct parameters, and planetesimals. In our simulations, all bodies gravitationally interact with each other, except for the planetesimals that interact only with the other bodies, but do not interact gravitationally between them. The discs of each system extend over their HZ; however, not all systems have stability throughout the region, thus being partially distributed in the most stable part, as in the case of the Kepler-34, 413, and 453 systems.

In order to present our results, each system has a particular evolution of the disc bodies. In the Kepler-34 system, the high eccentricity and proximity of the host planet to HZ of the system makes the formation of planets with mass nearly equal to that of the Earth in the innermost parts of the disc difficult, especially on discs where more massive embryos are in these regions because they are ejected more easily. On the other hand, discs with masses greater than 2.5 $M_\oplus$ make it possible for the system to harbour an Earth-like planet within HZ.

The Kepler-35 system, in both cases of x, Earth-like planets are formed within HZ in our simulations. The host planets are not so close to the disc and their mass is also not so high, which provides enough excitation to promote collisions and consequently accretions of mass on the disc. And given the system age of approximately 8–12 Gyr, the existence of a planet with conditions to harbour life is possible in this system from our initial conditions. By having the broadest HZ of all systems studied in this work, and together with the high capacity to form terrestrial planets within that region, this system has the capacity to harbour one habitable planet, as can be seen in Figs 6 and 7.

The Kepler-38 system, along with the Kepler-35 system, has the best ingredients for the formation of planets within HZ. Of all the systems studied in this work, this is the one that has the least massive host planet and, consequently, the most stable HZ of all. For this reason, this system has the slowest planetary formation process, given by the low perturbation of the planet, resulting in a cold disc. However, we show that the formation of Earth-like planets within HZ is possible in this system in most cases for both x values.

Because it has the smallest HZ of the systems, the chances of formation of planets within this region becomes smaller in the case of the Kepler-413 system. Still, planets with masses between 0.6 and 0.8 masses of Earth are formed in our simulations and, in one case, a planet with 0.7 $M_\oplus$ is formed within that region for $x = 2.5$. For $x = 1.5$, more massive planets are formed. In one of the simulations, a planet with 1 $M_\oplus$ is formed inside HZ and another with a mass of 1.4 $M_\oplus$, but this is outside HZ.

In the Kepler-453 system, planets with mass ranging from 0.6 to 0.9 $M_\oplus$ were formed. However, none of these planets within HZ. This occurred due to the system having a too small HZ and also by the position of the host planet within HZ, causing the bodies to be thrown out of this region.

We can conclude from our simulations that terrestrial planets can be formed in some known CB systems. To date, no such planet has been detected in this type of system. In addition, it is shown that these planets are within HZ of the systems. Knowing the location where these planets may be located, and mainly that their existence is possible, from an observational point of view, more precise searches can be performed on the systems shown. Another important result that we show is that some systems, at the end of the stability test, had coorbital bodies to their host planets. This can be seen in Fig. 2 in the systems Kepler-16, 47, 453, and 1647. With that, if the planet is within HZ, which occurs in these systems mentioned, the coorbital bodies will also be. In other words, this result shows that even if a gaseous giant planet, unable to harbour life as we know it, is within HZ, if an Earth-type planet is sharing the same orbit as it, it can still be habitable.

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