Boletim da Sociedade Astronômica Brasileira, **30**, no. 1, 48-49

Earth-size planet formation in the 'habitable zone' of binary stars systems

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Abstract. It is well known that most of the stellar systems have two or more stars. From the binary cases only about 20 have planets in P-type orbits, i.e. in circumbinary trajectories. In the present work we are concerned with the possibility of having Earth-like planets in the habitable zone of circumbinary star systems. These systems have planets with masses in the range from mini-Neptunes to a few times the Jupiter's mass. Then, the work was divided into two parts. The first was to study the stability of the habitable zone of each system. The second one was to explore the possibility of formation of an Earth-like planet in the habitable zone. The stability was studied considering the permanence or not of massless particles in the habitable zone. Therefore, considering the last stage of planetary formation, we explored the evolution of a disk of planetesimals and planetary embrios that under collision with each other accrete and grow. The results are presented in terms of simulations of different disk profiles in order to identify conditions that could possibly form planets with mass similar to the Earth in the habitable zone.

Resumo. É bem sabido que a maioria dos sistemas estelares tem duas ou mais estrelas. Dos casos binários, apenas cerca de 20 têm planetas em órbitas de tipo P, ou seja, em trajetórias circumbinárias. No presente trabalho, estamos preocupados com a possibilidade de ter planetas parecidos com a Terra na zona habitável de sistemas estelares circumbinários. Estes sistemas têm planetas com massas na gama de mini-Neptunes para algumas vezes a massa de Júpiter. Então, o rabalho foi dividido em duas partes. O primeiro foi estudar a estabilidade da zona habitável de cada sistema. O segundo foi explorar a possibilidade de formação de um planeta terrestre na zona habitável. A estabilidade foi estudada considerando a permanência ou não de partículas sem massa na zona habitável. Portanto, considerando a última etapa da formação planetária, exploramos a evolução de um disco de planetesimais e embriões planetários que, sob colisão, se acumulam e crescem. Os resultados são apresentados em termos de simulações de diferentes perfis de disco para identificar condições que poderiam formar planetas com massa semelhante à Terra na zona habitável.

Keywords. Celestial mechanics – Stars binaries: general – Planets and satellites: formation – Methods: numerical

1. Introduction

Recent research has shown that most planetary systems are composed of multiple stellar systems of which 50% are binary. Thus, questions concerning the formation of planets in these systems and the possible existence of life bring us many issues and challenges. In Haghighipour & Kaltenegger (2013), a generalization model of the Habitable Zone (HZ) calculation was proposed in circumbinary systems (P-Type), in which planets rotate around the center of mass of the binaries. This calculation shows the internal and external limits in which a planet of the Earth type (the same mass of the Earth) is capable of harboring life as we know it. However, our work seeks to study the possibility of formation of terrestrial planets in these regions.

2. Methods

We aim to study the last stage of formation of binary stellar systems through computational simulations. For this, we initially studied all binary stellar systems and calculated their HZ's for Earth-like planets (Earth's same mass), and selected the systems that had the possibility of forming and harboring planets within their HZ's, Table 1.

3. Initial Conditions

With the selected systems, the total mass of the protoplanetary disk was distributed within its habitable zones of each system.

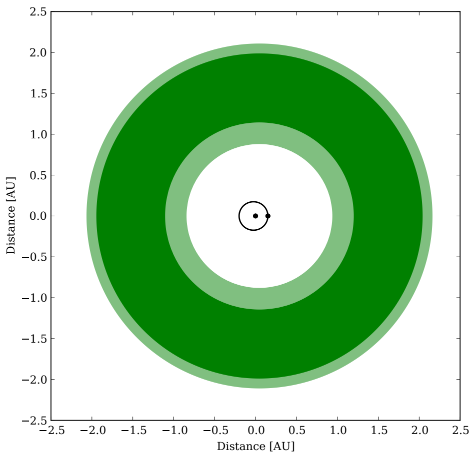

Figure 1. HZ of the binary system Kepler-35 using http://astro.twam.info/hz/.

We used a bi-modal distribution of mass, composed of planetesimals and embryos, 50% of the mass of the disk is formed by planetesimals and 50% by embryos. The radius of the bodies is given from an assumed density of 3.344 gcm^{-3}, and all other elements besides the mass and semi-major axis were randomly distributed, with eccentricity varying between 0-0.01 and inclination between 0^o-0.5^o relative to the plane of the binaries. We used discs with surface profilesgiven by $\Sigma_1 r^{-x}$, where x = 1.5.

System	M_A ($M_\odot$)	M_B ($M_\odot$)	a_{bin} (AU)	e_{bin}	a_p (AU)	e_p	M_p (M_j)	HZ range (AU)
K-34	1.048	1.021	0.229	0.521	1.089	0.182	0.220	1.25-2.80
K-35	0.890	0.810	0.176	0.142	0.603	0.042	0.127	0.90-2.10
K-38	0.949	0.249	0.147	0.103	0.464	0.030	0.380	1.25-2.95
K-38*	0.949	0.249	0.147	0.103	0.464	0.030	0.016	1.25-2.95
K-413	0.820	0.542	0.102	0.037	0.355	0.118	0.210	0.30-0.90
K-453	0.944	0.195	0.185	0.052	0.790	0.036	0.030	0.51-1.30
K-1647	1.221	0.968	0.128	0.160	2.720	0.058	1.520	1.40-4.00

Table 1. Selected binary systems with the potential to form Earth-like planets in their HZ and their respective parameters. The diference between K38 and K38* is the mass, where the mass of K38 is a superior limit and K38* is the reasonable mass.

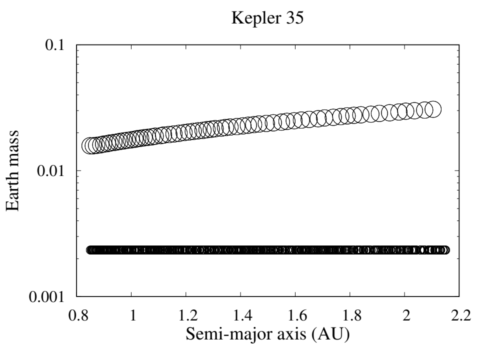

Figure 2. Initial conditions for a disk of the system Kepler-35 containing 65 embryos and 597 planetesimals. Embryos and more massives than planetesimals with their sizes proportional to their mass.

The Σ_1 is the solid surface density at 1 AU and was used to ajusted to fix the total mass in the disc of each HZ region at $2.8 M_\oplus$, comparable to the sum of the masses of the terrestrial planets. Planetary embryos are assumed to have formed by oligarchic growth and are thus randomly spaced by 3.5–6.5 mutual Hill radii. Individual planetesimals were given masses of $7.04\text{x}10^{-9}$ $M_\odot$ ($\approx 2.34\text{x}10^{-3}$ $M_\oplus$). Planetesimals are assumed to interact gravitationally only with the protoplanetary embryos, giant planets and the stars, but not with each other. The masses of the planetary embryos scale as $M \approx r^{3(2-x)/2}\Delta^{1.5}$ (Kokubo & Ida 2002; Raymond et al. 2009; Izidoro et al. 2009) where Δ is the number of mutual Hill radii separating adjacent orbits. This amounts to roughly 60 planetary embryos and 600 planetesimals. Figure 2 shows the initial mass distribution of our simulations.

4. Numerical Simulation

In our simulations are used the planets belonging to each of the systems with their respective real parameters. For each system we performed 5 simulations with slightly different randomly generated initial conditions for planetary embryos and planetesimals. The simulations were integrated for 200 Myr using an adaptation (made by us) in the MERCURY package (Chambers 1999; Chambers et al. 2002).

5. Results

Figure 3 shows in 60 Myr a Earth-like planet with semi-major axis = 1.8 AU, eccentricity = 0.05 and 1.2 $M_\oplus$ in the HZ.

6. Concluding Remarks

One of the most important things for the impossibility of the formation of planets within the HZ is the gravitational effect

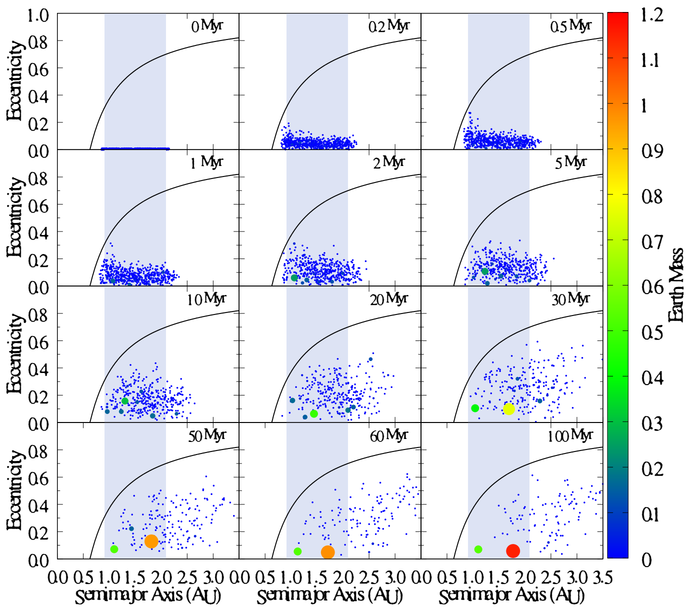

Figure 3. Snapshot in the time of the Kepler-35 system. The size of the each body is proportional to its mass. The region shaded in blue represents the HZ range and the black line represents the semi-major axis as a function of the eccentricity given by $a = [a_p(1 + e_p)]/(1 - e)$.

caused by the planet present in each system. Thus in the case of Kepler-34 and Kepler-1647 systems, we will need to increase the mass in the disk in the next steps to compensate for the ejections caused by the planet's presence of the system. Figure 3 shows that is possible to form a Earth-like planet in the HZ of a real binary star system (Kepler-35 in the case). In the systems Kepler-38, 413 and 453 we can see the same results (planets with mass varying between 0.8-1.3 $M_\oplus$).

Acknowledgements. The authors acknowledge the financial support by CAPES, CNPq and FAPESP.

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