

The dynamical architecture and habitable zones of the quintuplet planetary system 55 Cancri *

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Abstract We perform numerical simulations to study the secular orbital evolution and dynamical structure of the quintuplet planetary system 55 Cancri with the self-consistent orbital solutions by Fischer and coworkers. In the simulations, we show that this system can be stable for at least 10^8 yr. In addition, we extensively investigate the planetary configuration of four outer companions with one terrestrial planet in the wide region of $0.790 \text{ AU} \leq a \leq 5.900 \text{ AU}$ to examine the existence of potential asteroid structure and Habitable Zones (HZs). We show that there are unstable regions for orbits about 4:1, 3:1 and 5:2 mean motion resonances (MMRs) of the outermost planet in the system, and several stable orbits can remain at 3:2 and 1:1 MMRs, which resembles the asteroid belt in the solar system. From a dynamical viewpoint, proper HZ candidates for the existence of more potential terrestrial planets reside in the wide area between 1.0 AU and 2.3 AU with relatively low eccentricities.

Key words: celestial mechanics — methods: n-body simulations — planetary systems — stars: individual (55 Cancri)

1 INTRODUCTION

The nearby star 55 Cancri (55 Cnc) is of spectral type K0/G8V with a mass of $0.92 \pm 0.05 M_{\odot}$ (Valenti & Fischer 2005). Marcy et al. (2002) reported a second giant planet with a long period of ~ 14 yr after the first planet was discovered in 1997. The 55 Cnc system could be very attractive, firstly because it hosts a distant giant Jupiter-like planet about 5.5 AU resembling Jupiter in our solar system. The second interesting thing is that this system may be the only known planetary system in which two giant planets are close to the 3:1 orbital resonance, and researchers have extensively studied the dynamics and formation of the 3:1 MMR in this system (see Beaugé et al. 2003; Ji et al. 2003; Zhou et al. 2004; Kley, Peitz & Bryden 2004; Voyatzis & Hadjidemetriou 2006; Voyatzis 2008). The additional collection of follow-up observations and the increasing precision of measurements (at present $\sim 1 \text{ ms}^{-1}$ to 3 ms^{-1}) have indeed identified more planets. McArthur et al. (2004) reported the fourth planet with a small minimum mass $\sim 14 M_{\oplus}$ that orbits the host star with a short period of 2.8 d, by analyzing three sets of radial velocities. The improvement of the observations will actually induce an additional discovery.

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Hence, it is not difficult to understand that more multiple planetary systems or additional planets in multiple systems can be dug out of supplemental data.

More recently, Fischer et al. (2008) (hereafter Paper I) reported a fifth planet in the 55 Cnc system with Doppler shift observations over 18 yr, and showed that all five planets are in nearly circular orbits and four have eccentricities under 0.10. It is really one of the most extreme goals for astronomers devoted to searching for extrasolar planets to discover a true solar system analog, which may hold one or two gas giants orbiting beyond 4 AU that can be compared to Jupiter and Saturn in our own solar system (Butler 2007, private communication; see also Gaudi et al. 2008). This indicates that several terrestrial planets may move in the so-called Habitable Zones (HZs) (Kasting et al. 1993; Jones et al. 2005), and potential asteroid structure could exist. Considering the probability of the coplanarity and nearly circular orbits for the five planets (Paper I), the 55 Cnc system is suggested to be a comparable twin of the solar system. Hence, firstly, from a dynamical viewpoint, one may be concerned about the stability of the system over a secular timescale. On the other hand, small bodies, such as terrestrial objects may exist in this system and are able to be detected with forthcoming space-based missions (*Kepler*, *SIM*). In this paper, we focus on understanding the dynamical structure and finding suitable HZs for life-bearing terrestrial planets in this system.

2 DYNAMICAL ANALYSIS

In this paper, we adopt the orbital parameters of the 55 Cnc system provided by Paper I (see their table 4). For convenience of narration, we relabel the planets according to the ascendant semi-major axes in the order from the innermost to the outermost planet (e.g., B, C, D, E, F), while the original names discovered in chronological order are also provided, but in braces (see Table 1). Furthermore, McArthur et al. (2004) derived the orbital inclination $i = 53^\circ \pm 6.8^\circ$ with respect to the line of sight for the outermost planet from *HST* astrometric data by measuring the apparent astrometric motion of the host star. In the simulations, we adopt this estimated orbital inclination of 53° and further assume all the orbits to be coplanar. With the planetary masses $M \sin i$ reported in Table 1, we then obtain their true masses. Specifically, the masses of five planets are respectively, $0.03 M_{\text{Jup}}$, $1.05 M_{\text{Jup}}$, $0.21 M_{\text{Jup}}$, $0.18 M_{\text{Jup}}$ and $4.91 M_{\text{Jup}}$, where $\sin i = \sin 53^\circ = 0.7986$. Thus, we take the stellar mass M_c of $0.94 M_\odot$ (Paper I), and the planetary masses mentioned above in the numerical study, except where noted. We utilize N-body codes (Ji, Li & Liu 2002) to perform numerical simulations by using RKF7(8) and symplectic integrators (Wisdom & Holman 1991) for this system. In the numerical runs, the adopted time stepsize is usually $\sim 2\% - 5\%$ of the orbital period of the innermost planet. In addition, the numerical errors are effectively controlled over the integration timescale, and the total energy is generally conserved to be 10^{-6} for the integrations. The typical timescale of simulations of the 55 Cnc system is from 100 Myr to 1 Gyr.

2.1 The Stability of the 55 Cancri Planetary System

2.1.1 Case 1: 5-p for 10^8 yr

To explore the secular stability of this system, firstly, we numerically integrated the five-planet system on a timescale of 10^8 yr, using the initials listed in Table 1. In Figure 1, a snapshot of the secular orbital evolution of all planets is illustrated, where $Q_i = a_i(1 + e_i)$, $q_i = a_i(1 - e_i)$ (with the subscripts $i = 1 - 5$, individually, denoting Planet B, C, D, E, and F) are, respectively, the apoapsis and periapsis distances. In the secular dynamics, the semi-major axis a_1 and a_2 remain unchanged to be 0.0386 and 0.115 AU, respectively, for 10^8 yr, while a_3 , a_4 and a_5 slightly librate about 0.241, 0.786, and 6.0 AU with quite small amplitudes over the same timescale. The variations of eccentricities during long-term evolution are followed, where $0.23 < e_1 < 0.28$, $0.0 < e_2 < 0.03$, $0.034 < e_3 < 0.069$, $0.0 < e_4 < 0.013$, and $0.056 < e_5 < 0.095$, implying that all the eccentricities undergo quasi-periodic modulations.

Table 1 Orbital Parameters of 55 Cancri Planetary System^a

Planet	$M \sin i$ (M_{Jup})	P (d)	a (AU)	e	ϖ (deg)	T_p
Planet B (e)	0.0241	2.796744	0.038	0.2637	156.500	2447578.2159
Planet C (b)	0.8358	14.651262	0.115	0.0159	164.001	2447572.0307
Planet D (c)	0.1691	44.378710	0.241	0.0530	57.405	2447547.5250
Planet E (f)	0.1444	260.6694	0.785	0.0002	205.566	2447488.0149
Planet F (d)	3.9231	5371.8207	5.901	0.0633	162.658	2446862.3081

^a: The parameters are taken from table 4 of Fischer et al. (2008). The mass of the star is $0.94 M_{\odot}$.

In Figure 1, we note that the time behaviors of Q_i and q_i show regular motions of bounded orbits for all five planets and indicate that their orbits are well separated during the secular evolution due to small mutual interactions, which again reflect the regular dynamics of the eccentricities over the secular timescale. In the numerical study, we find the system could be dynamically stable and last at least 10^8 yr. Thus, our numerical outcomes strengthen and verify those of Paper I for the integration of 10^6 yr, which also showed that the system could remain stable over 1 Myr and the variations of all planetary eccentricities are modest.

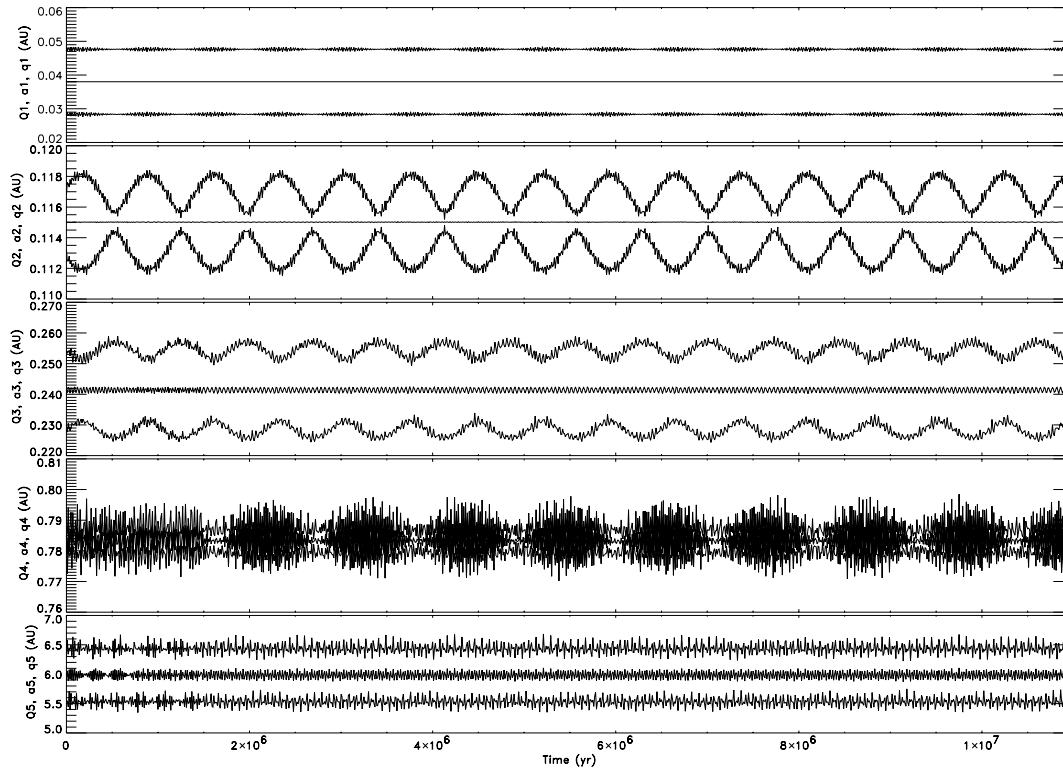


Fig. 1 A snapshot of the secular orbital evolution of all planets is illustrated, where $Q_i = a_i(1 + e_i)$, $q_i = a_i(1 - e_i)$ (the subscripts $i = 1 - 5$, stand for Planets B, C, D, E and F) are, respectively, the apoapsis and periapsis distances. a_1 and a_2 remain unchanged at 0.0386 and 0.115 AU, respectively, while a_3 , a_4 and a_5 slightly librate about 0.241, 0.786, and 6.0 AU with smaller amplitudes for 10^8 yr. The simulations indicate the secular stability of 55 Cnc.

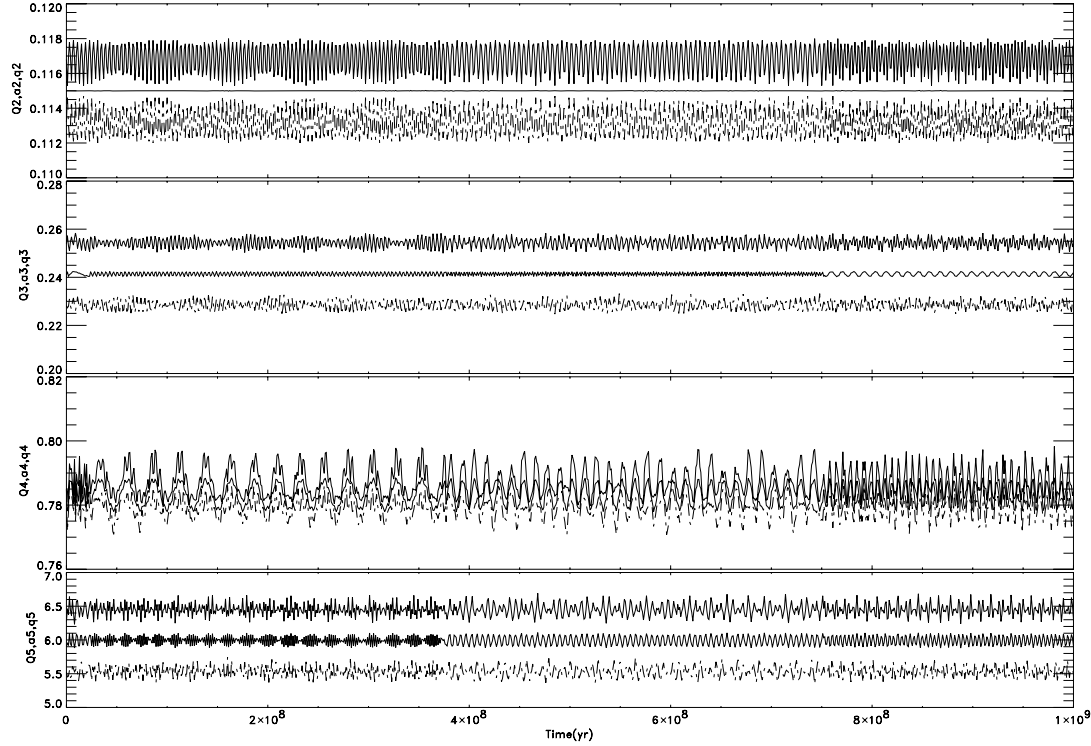


Fig. 2 Numerical simulations of four outer planets for 10^9 yr. The apoapsis and periapsis distances: $Q_i = a_i(1 + e_i)$, $q_i = a_i(1 - e_i)$ (the subscripts $i = 2 - 5$ stand for Planets C, D, E and F). Long-term simulation shows that the system could remain stable over 1 Gyr.

Secondly, we further performed an extended integration for the planetary configuration simply consisting of four outer planets over a timescale up to 1 Gyr (see Fig. 2). The longer integration again reveals that the orbital evolutions of the four planets are quite similar to those exhibited in Figure 1, and this strongly supports the secular stability of this system. In a recent study, Gayon et al. (2008) show that the 55 Cnc system may remain in a stable chaotic state as the planetary eccentricities do not grow over a longer timescale. Therefore, it is safe to conclude that the 55 Cnc system remains dynamically stable during the lifetime of the star.

In order to assess the stability of 55 Cnc with respect to the variations of the planetary masses, we first adjust $\sin i$ in increments of 0.1 from 0.3 to 0.9. In the additional numerical experiments, we simply vary the masses but keep all orbital parameters (Table 1), and again restart new runs of integration for the five-planet system for 100–1000 Myr with the rescaled masses. As a result, we find that the system could remain definitely stable for the above investigated timescale with slight vibrations in the semi-major axes and eccentricities for all planets, indicating the present configuration is not so sensitive to the planetary masses. Subsequently, we again examine the stabilities of different orbital configurations within the error range of the Keplerian orbital fit given by Paper I. Herein, 100 simulations are carried out for 10 Myr, and the numerical results show that all the runs are stable over the simulation timescale, indicating that this five-planet system is fairly robust with respect to the variational planetary configurations.

2.1.2 Case 2: 7-p for 10^8 yr

However, Paper I argued that 6 or more planets could exist and maintain dynamical stability in the large gap between Planets E and F in this system. Next, we integrate the 55 Cnc system with additional planets (2 massive terrestrial planets, Earth at 1 AU and Mars at 1.52 AU) to mimic the situation of the inner solar system. In this run, we examine a configuration consisting of 5 planets and 2 terrestrial bodies to study the coexistence of multiple objects. This means that we directly place Earth and Mars into the 55 Cnc system to simulate “the inner solar system,” where the orbital elements for the above terrestrial planets are calculated from JPL’s planetary ephemerides DE405 at Epoch JD 2446862.3081 corresponding to the outermost companion (see Table 2), e.g., the semi-major axes are respectively, 1.00 and 1.524 AU. The five planets are always assumed to be coplanar in the simulations, thus the inclinations for 2 terrestrial planets refer to the fundamental plane of their orbits. In this numerical experiment, we find that the 7-p system can remain dynamically stable and last for at least 10^8 yr.

Table 2 Orbital Elements for 2 Terrestrial Planets at JD 2446862.3081 (from DE405)

Planet	a (AU)	e	I (deg)	Ω (deg)	ω (deg)	M (deg)
Earth	1.000	0.0164	0.002	348.33	115.231	61.647
Mars	1.524	0.0935	1.850	49.60	286.352	85.614

In Figure 3 are shown the time behaviors of Q (yellow lines) and q (black lines) for Mars, Earth and Planet E. The numerical results show regular bounded motions where their semi-major axes and eccentricities do not dramatically change in their secular orbital evolution, and this is also true for the other four planets in 55 Cnc. It is not so surprising for one to realize that two additional terrestrial planets could exist for a long time because gravitational perturbations arising from other planets are much

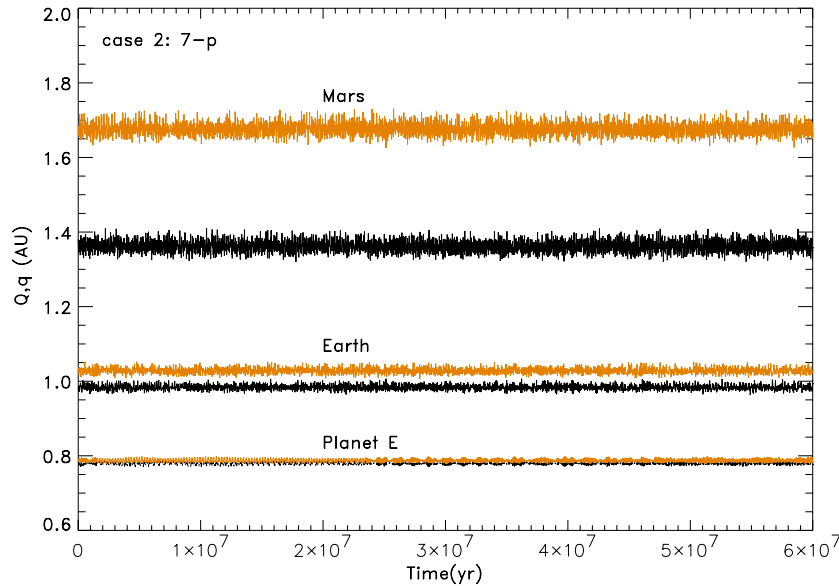


Fig. 3 Simulation for the 7-p case. The system could be dynamically stable and last at least 10^8 yr. The time behaviors of Q (yellow lines) and q (black lines) are shown for Mars, Earth and Planet E. The results show that their semi-major axes and eccentricities do not dramatically change in secular orbital evolution, and this is also true for the other four planets in 55 Cnc.

smaller. In the following section, we will extensively explore this issue for the dynamical architecture of Earth-like planets in the system.

3 DYNAMICAL ARCHITECTURE AND POTENTIAL HZS

To investigate the dynamical structure and potential HZs in this system, we extensively performed additional simulations with a planetary configuration of coplanar orbits of four outer companions with one terrestrial planet. In this series of runs, the mass of the assumed terrestrial planet was selected randomly in the range $0.1 M_{\oplus}$ to $1.0 M_{\oplus}$. The initial orbital parameters are as follows: numerical investigations were carried out in $[a, e]$ parameter space by direct integration, and for a uniform grid of 0.01 AU in the semi-major axis ($0.790 \text{ AU} \leq a \leq 5.900 \text{ AU}$) and 0.01 in eccentricity ($0.0 \leq e \leq 0.2$), the inclinations are $0^\circ < I < 5^\circ$. The angles of the nodal longitude, the argument of periastron, and the mean anomaly are randomly distributed between 0° and 360° for each orbit. Then each terrestrial mass body was numerically integrated with four outer planets in the 55 Cnc system. In total, about 10 750 simulations were exhaustively run for typical integration time spans from 10^5 to 10^6 yr (about 10^6 – 10^7 times the orbital period of Planet C). Our main results now follow.

Figure 4 shows the contours of the survival time for the Earth-like planets (*Upper*) and the status of their final eccentricities (*Lower*) for the integration over 10^5 yr, and the horizontal and vertical axes represent initial a and e of the orbits. Figure 4 (*Upper*) shows that there are stable zones for the Earth-like planets in the region between 1.0 and 2.3 AU with final low eccentricities of $e < 0.10$. The extended simulations (10^6 yr) for the objects in the above region also exhibit the same results. This zone may be strongly recommended to be one of the potential candidate HZs in 55 Cnc, and our results coincide with those of Jones et al. (2005), who showed possible HZs of $1.04 \text{ AU} < a < 2.07 \text{ AU}$. Also, the outcomes presented here have confirmed those in Section 2.1.2, where we show the stable configuration of Earth at 1.00 AU and Mars at 1.523 AU in this five-planet system. The sixth planet or additional habitable bodies may be expected to be revealed in this region by future observations¹.

In general, planetary embryos or planetesimals may be possibly captured into the mean motion resonance regions or thrown into HZs by a giant planet under migration due to planet-disk interaction and could survive during final planetary evolution over the secular timescale after complex scenarios of secular resonance sweeping, gravitational scattering, and late heavy bombardments (Nagasawa et al. 2005; Thommes et al. 2008). We note that there are strongly unstable orbits² for the low-mass planets initially distributed in the region $3.9 \text{ AU} < a < 5.9 \text{ AU}$, where the planetary embryos have a very short dynamical survival time. In the meantime, the eccentricities can be quickly pumped up to a high value ~ 0.9 (see Fig. 4, *Lower*). We note that the orbital evolution is not so sensitive to the initial masses. In fact, these planetary embryos are involved in many MMRs with the outermost giant in the 55 Cnc system, e.g., 7:4 (4.063 AU) and 3:2 MMRs (4.503 AU). The overlapping resonance mechanism (Murray & Dermott 1999) can reveal their chaotic behaviors of being ejected from the system in short dynamical lifetime $\sim 10^2 - 10^3$ yr; furthermore, the majority of the orbits are within the sphere of 3 times the Hill radius ($R_H = (M_5/(3M_c))^{1/3} a_5$, $3R_H \doteq 2.10 \text{ AU}$) of the 14-yr planet. Using resonance overlapping criterion (MD99; Duncan et al. 1989), the separation in the semi-major axis $\Delta a \approx 1.5(M_5/M_c)^{2/7} a_5 \doteq 1.95 \text{ AU}$, the inner boundary $R_O = a_5 - \Delta a$ for Planet F is at $\sim 3.95 \text{ AU}$. Also, the orbits in this zone become chaotic during the evolution because the planets are both within $3 R_H$ and in the vicinity of R_O . Similarly, there exist unstable zones for the nearby orbits around Planet E ($0.78 \text{ AU} < a < 0.90 \text{ AU}$), which may not be habitable from a dynamical viewpoint.

¹ The semi-amplitude of wobble velocity $K \propto M_p \sin i / \sqrt{a(1-e^2)}$ (with $M_p \ll M_c$); herein M_c , M_p , a , e and i are, respectively, the stellar mass, the planetary mass, the orbital semi-major axis, the eccentricity and the inclination of the orbit relative to the sky plane. This means that planets with larger masses and (or) smaller orbits could have larger K . For example, a planet of $1.0 M_{\oplus}$ at 1 AU in a nearly circular orbit may cause stellar wobble of about 0.10 m s^{-1} . In this sense, much higher Doppler precision is required to discover such Earth-like planets in the future.

² We define an unstable orbit as when an Earth-like planet is ejected far away or moves too close to the parent star or the giant planets, meeting the following criteria: (1) the eccentricity approaches unity, (2) the semi-major axis exceeds a maximum value, e.g., 1000 AU, (3) the assumed planet collides with the star or enters the mutual Hill sphere of the known giant planets.

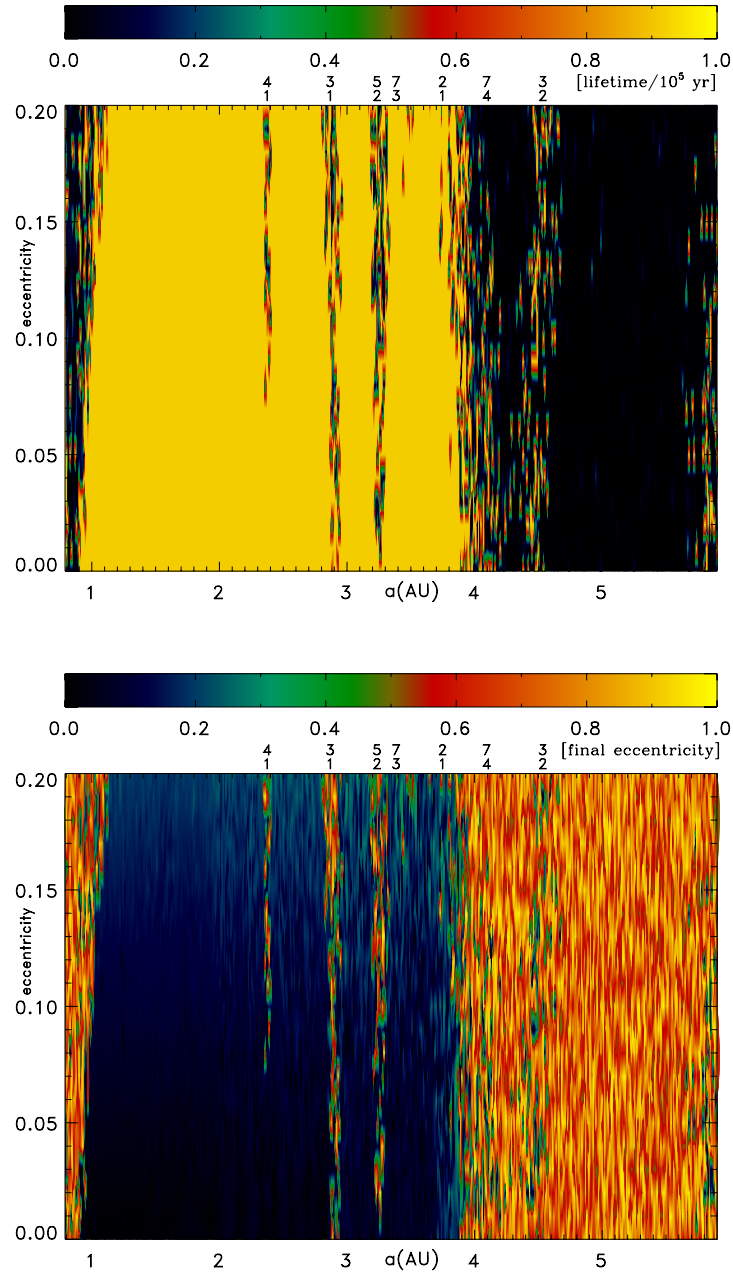


Fig. 4 *Upper:* Contour of the survival time for Earth-like planets for an integration of 10^5 yr. *Lower:* Status of their final eccentricities. Horizontal and vertical axes are the initial a and e . Stable zones for Earth-like planets in the region between 1.0 and 2.3 AU with final low eccentricities of $e < 0.10$. Unstable islands, e.g., 3:1 and 5:2 MMRs, have separated the region of $2.4 \text{ AU} < a < 3.8 \text{ AU}$. Strong chaos happens for the low-mass bodies initially distributed in $3.9 \text{ AU} < a < 5.9 \text{ AU}$, and their eccentricities can be quickly pumped up to a high value ~ 0.9 .

It is suggested that MMRs could play an important role in determining the orbital dynamics of terrestrial bodies which are either stabilized or destabilized in the vicinities of the MMRs. The outermost giant, like Jupiter, may shape and create the characteristics of the dynamical structure of the small bodies. Most of the initial orbits for the planetary embryos located about 3:1 (2.837 AU), 5:2 (3.204 AU), and 4:1 MMRs (2.342 AU), are quickly cleared off by perturbations from Planet F. In the region of $2.4 \text{ AU} < a < 3.8 \text{ AU}$, stable zones are separated by the mean motion resonance barriers, e.g., 3:1 and 5:2 MMRs. Note that the initial orbits for a relatively low eccentricity (under 0.06) for 4:1 MMR can remain stable over the simulation timescale. However, the terrestrial bodies about 7:3 MMR (3.354 AU) and 2:1 MMR (3.717 AU) are both on the edge of stability, and the former are close to 5:2 MMR, while the latter just travel around the inner border of $3R_H$ at $\sim 3.80 \text{ AU}$. The extended longer integrations show that their eccentricities can be further excited to a high value and a large fraction of them lose stabilities in the final evolution. The above gaps apparently resemble those of the asteroid belt in the solar system. In the simulations, several stable orbits can be found about 3:2 MMR at 4.503 AU, which is analogous to the Hilda group for asteroids in the solar system, surviving at least for 10^6 yr . In addition, the other several stable cases are the so-called Trojan planets (1:1 MMR), residing at $\sim 5.9 \text{ AU}$. Studies show that stable Trojan configurations may possibly be common in extrasolar planetary systems (Dvorak et al. 2004; Ji et al. 2005; Gozdziewski & Konacki 2006). Indeed, terrestrial Trojan planets with circular orbits $\sim 1 \text{ AU}$ could potentially be habitable, and are worthy of further investigation in the future.

4 SUMMARY AND DISCUSSION

In this work, we have studied the secular stability and dynamical structure and HZs of the 55 Cnc planetary system. We now summarize the main results as follows:

(1) In the simulations, we show that the quintuplet planetary system could remain dynamically stable at least 10^8 yr and that the stability would not be greatly influenced by shifting the planetary masses. Accounting for the nature of near-circular well-spaced orbits, the 55 Cnc system may be a close analog of the solar system. In addition, we extensively investigated the planetary configuration of four outer companions with one terrestrial planet in the region $0.790 \text{ AU} \leq a \leq 5.900 \text{ AU}$ to examine the existence of potential Earth-like planets and further study the asteroid structure and HZs in this system. We show that unstable zones are about 4:1, 3:1 and 5:2 MMRs in the system, and several stable orbits can remain at 3:2 and 1:1 MMRs. The simulations not only present a clear picture that resembles the asteroid belt in the solar system, but also may possibly provide helpful information to identify the objects when modeling multi-planet orbital solutions (Paper I) by analyzing RV data. Dynamical examinations are helpful in searching for best-fit stable orbital solutions to consider the actual role of the resonances, where some of the best-fit solutions close to unstable islands of MMRs can be dynamically ruled out in the fitting process. As is well-known, the extensive investigations of planetary systems (Menou & Tabachnik 2003; Érdi et al. 2004; Ji et al. 2005, 2007; Pilat-Lohinger et al. 2008; Raymond et al. 2008) show that dynamical structure is correlated with mean motion and secular resonances. The eccentricities of the planetesimals (or terrestrial planets) can be excited by sweeping secular resonance (Nagasawa & Ida 2000) as well as mean motion resonances, thus the orbits of the small bodies can undergo mutual crossings and then they are directly cleared up in the post-formation stage. In conclusion, the mentioned dynamical factors and perturbations from the giant planets will influence and determine the characteristic distribution of the terrestrial planets in the late stage formation of the planetary systems, to make the remaining residents in the final system settle down.

(2) As the stellar luminosity of 55 Cnc is lower than that of the Sun, the HZs should shift inwards compared to our solar system. It seems that the newly-discovered planet at $\sim 0.783 \text{ AU}$ could reside in an HZ (Rivera & Haghighipour 2007), and this planet may be habitable provided that it bears a surface atmosphere to sustain the necessary liquid water and other suitable life-developing conditions (Kasting et al. 1993). In the dynamical consideration, proper HZ candidates for the existence of more potential terrestrial planets reside in the wide area between 1.0 AU and 2.3 AU for relatively low eccentricities, and the maintenance of low eccentricity can play a vital role in avoiding large seasonal climate variations (Menou & Tabachnik 2003) for the dynamical habitability of the terrestrial planets. Moreover,

our numerical simulations also suggest that additional Earth-like planets (Sect. 2.1.2) could also coexist with the other five known planets in this system over the secular timescale. This should be carefully examined by abundant measurements and space missions (e.g. *Kepler* and *TPF*) for this system in the future.

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