Could the 47 UMa Planetary System be a Second Solar System: predicting the Earth-like planets

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ABSTRACT

We numerically investigated the dynamical architecture of 47 UMa with the planetary configuration of the best-fit orbital solutions by Fischer et al. We systematically studied the existence of Earth-like planets in the region 0.05 AU \( \leq a \leq 2.0 \) AU for 47 UMa with numerical simulations, and we also explored the packed planetary geometry and Trojan planets in the system. In the simulations, we found that "hot Earths" at 0.05 AU \( \leq a < 0.4 \) AU can dynamically survive at least for 1 Myr. The Earth-like planets can eventually remain in the system for 10 Myr in areas involved in the mean motion resonances (MMR) (e.g., 3:2 MMR) with the inner companion. Moreover, we showed that the 2:1 and 3:1 resonances are on the fringe of stability, while the 5:2 MMR is unstable. Additionally, the 2:1 MMR marks out a remarkable boundary between chaotic and regular motions, inside, most of the orbits can survive, outside, they are mostly lost in the orbital evolution. In a dynamical sense, the most likely candidate for habitable environment is Earth-like planets with orbits in the ranges 0.8 AU \( \leq a < 1.0 \) AU and 1.0 AU \( < a < 1.30 \) AU (except 5:2 MMR and several unstable cases) with relatively low eccentricities. The Trojan planets with low eccentricities and inclinations can secularly last at the triangular equilibrium points of the two massive planets. Hence, the 47 UMa planetary system may be a close analog to our solar system, bearing a similar dynamical structure.

\textit{Subject headings:} celestial mechanics-methods:n-body simulations-planetary systems-stars:individual (47 UMa)

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1. Introduction

The main sequence star 47 UMa is of spectral type G0 V with a mass of $1.03 M_\odot$. Butler & Marcy (1996) reported the discovery of the first planet in the 47 UMa system which has become one of the most eye-catching systems particularly after the subsequent release of an additional companion (Fischer et al. 2002). It is sometimes thought to be a close analog of our own solar system: for example, the mass ratio of the two giant companions in 47 UMa is $\sim 2.62$ (see Table 1), as compared to that of Jupiter-Saturn (JS) of 3.34; and the ratios of two orbital periods are close to each other. Following the analogy, one may wonder whether there exists additional members in 47 UMa system. Multi-planet systems seem to be common in nature (Fischer et al. 2003; hereafter Paper I) more than ten of such systems have been detected in Doppler surveys to date. Moreover, if the solar system is a typical one, how are we to understand the analogous structures in other multi-planet systems, e.g., the presence of the inner low-mass terrestrial planets, the asteroidal belts or Kuiper belts (e.g. Spitzer Mission) around central stars? The pioneering numerical experiments (Adams & Laughlin 2003) showed that planet-planet scattering can yield planetary orbits with $a \sim 1$ AU for a packed system consisting of 10 planets with widely spaced orbits. However, from an observational viewpoint, because of the variability of stellar atmospheres, the current ground-based observational precision $\sim 2-3$ m s$^{-1}$ (Butler et al. 2003) indeed places a fundamental limit on the discovery of Earth-mass planets$^1$ around 1 AU (even smaller), and the preference detection of planets with masses of several $M_\oplus$ should benefit from future space projects that can carry out high resolution astrometric measurements (e.g., SIM and GAIA). Nevertheless, in the current stage, this leaves room for researchers to study the dynamical structure of such planets or their formation that may possibly reside in the systems, in advance of the observing missions.

2. Formation scenario

The planetary formation scenarios may be replayed as follows: in the standard model of core-accretion scenario (Safronov 1969; Lissauer 1993), solid cores (or planetary embryos) rapidly grow larger by the accretion of kilometer-sized planetesimals via runaway growth (Kokubo & Ida 1998; Ida & Lin 2004), leading to the formation of the gaseous giant planets through the accretion of disk gas onto Earth-mass solid cores and more planetesimals into

$^1$however, the recent discovered Neptune-mass planets with close-in orbits ($a < 0.1$ AU) (Butler et al. 2004; McArthur et al. 2004; Santos et al. 2004) are grouped as a new category linking giant gaseous planet and Earth-mass planet.
an envelope. When they formed outside the ice boundary $\sim 3$ AU (Ida & Lin 2004) in the system, two giant planets may migrate inward through disk-planet interactions (Ward 1997; Kley 2000; Nelson et al. 2000; Papaloizou 2003), and such migration process may not halt until the two planets are eventually captured into $\sim 8:3$ mean motion resonance (Laughlin, Chambers & Fischer 2002; hereafter Paper II), see also the 2:1 resonant capture scenario for two massive planets in GJ 876 (Lee & Peale 2002; Kley, Peitz, & Bryden 2004). In the migration scenario, the giant protoplanets may clear up wide gaps about their orbits (Goldreich, Lithwick, & Sari 2004) and cease accreting small bodies. But the giant planets may make the residual unaccreted planetesimals in the debris disk move inward or outward through gravitational scattering mechanism, even with the eccentricities and inclinations of these planetesimals excited by sweeping secular resonance (Nagasawa & Ida 2000), thus the orbits of the small bodies can undergo mutual crossings and then they are either directly cleared up or collided into fragments in the post-formation stage. Another possible fate for these isolated members is that they may be captured into mean motion resonances with the giant planets under migration (e.g., the capture of the KBOs in the Neptune migration [Malhotra, Duncan, & Levison 2000]), and such resonant swarm may outline the structure of asteroidal belts in the system. In consequence, a dynamically quasi-stable configuration with spaced orbits may be achieved to support further secular evolution, which may determine the resulting destinies of those members, leading to the final assemblage of the planetary system (Lin 2004).

Paper II and Gozdziewski (2002) studied the long-term stability of 47 UMa and pointed out that the secular apsidal resonance can help stabilize the two giant planets in an aligned configuration with the libration of their relative periapse longitudes (Ji et al. 2003), then the eccentricities are well maintained to free from larger vibrations due to this mechanism, as a result, this system can even survive for billion years (Barnes & Quinn 2004). Several pioneer works were concentrated on the structure of the system and presented a preliminary understanding of this issue. Jones, Sleep & Chambers (2001) investigated the existence of Earth-mass planets in the presence of one known giant planet, and subsequently Paper II and Asghari et al. (2004) further studied the stability of massless test particles about the so-called Habitable Zones (HZ) according to some earlier solutions (Fischer et al. 2002), where the dynamical model was treated as a restricted multi-body problem. Nevertheless, as the terrestrial planets possess significant masses, they can interact with the two giant planets by mutual gravitation, which may result in secular effects for the planetary system. Accordingly, we should take into account the masses of terrestrial bodies in the model when exploring the dynamical architecture. In this paper, we performed extensive simulations to examine the dynamical architecture in both the HZ and extended areas, for Earth-like planets (with masses from $0.1 M_\oplus$ to $10 M_\oplus$) of 47 UMa with stable coplanar planetary
configuration, based on the best-fit orbital parameters given by Paper I. These new reliable orbital solutions are derived from additional follow-up observations, hence they can represent the actual motions of the system under study. On the other hand, as mentioned previously, the discovery of three close-in Neptune-mass planets demonstrates that it may be possible for less massive planets ($\sim M_{\oplus}$) to move close to the star. Therefore, in the extended study, we also explored low-mass planets in the region $0.05 \, \text{AU} \leq a < 0.4 \, \text{AU}$ and we found that the secular resonance arising from the inner giant planet can render the eccentricity excitations for the Earth-like planets (see §3.2). In addition, we also carried out two other runs to predict potential bodies in 47 UMa: In §3.1, to compare with the inner solar system, we further investigated the planetary configuration of 2 giant planets plus 4 terrestrial planets, and in §3.3 we examined the case of presence of Trojan planets with respect to the two giant planets. The results suggest that the 47 UMa system may have a similar architecture to the solar system.

In the simulations, we use an N-body codes (Ji, Li & Liu 2002) of direct numerical simulations with the RKF7(8) and symplectic integrators (Wisdom & Holman 1991). We always take the stellar mass and the minimum planetary masses from Table 1. The adopted time stepsize is usually $\sim 1\%-2.5\%$ of the orbital period of the innermost planet, which is sufficiently small for the integration. Additionally, the numerical errors were effectively controlled over the integration timescale, and the total energy is generally conserved to $10^{-6}$ - $10^{-8}$ for the integrations. Our main results now follow.

3. Simulations Results

3.1. 2 Giants plus 4 terrestrial planets

The announcement of the fourth planet in the 55 Cancri system (McArthur et al. 2004) suggests that multiple planetary systems resembling our solar system could be quite common in the galaxy. In the first runs, we examine the configuration consisting of 2 giant planets (2G) and 4 terrestrial planets (4T) to study the coexistence of multiple bodies. Specifically, this means that we directly place Mercury, Venus, Earth and Mars into the 47 UMa system to simulate ”the inner solar system”, where the orbital elements for above terrestrial planets are calculated from JPL planetary ephemerides DE405 at Epoch JD 2448750.9 corresponding to the outer companion (see Table 2), e.g., the semi-major axes are respectively, 0.387, 0.723, 1.00 and 1.523 AU. The giant planets are always assumed to be coplanar in the simulations, thus the inclinations for 4T refer to the fundamental plane of the 2G’s orbits. In Figure 1a, the orbital evolution of 4T is shown, where $Q = a(1 + e)$, $q = a(1 - e)$ are, respectively, the apoapsis and periapsis distances. The simulation results indicate that the orbits of
these low-mass planets become chaotic after $2 \times 10^5$ yr: Mars leaves its initial orbit in less than $10^4$ yr and its $Q$ can amount to $\sim 10^3$ AU at $t > 1.5 \times 10^5$ yr. Such dynamical instability stems from strong perturbation by 47 UMa b (see also §3.2.4), and the Hill radius is $R_H = [M_1/(3M_c)]^{1/3}a_1$ ($M_c$, the stellar mass; $M_1, a_1$, the planetary mass and semi-major axis of Companion B), then $3R_H \approx 0.6$ AU, showing that the orbit of Mars is quite close to the outskirts of $3R_H$ sphere. In addition, as of its eccentricity grows, Venus begins to cross the orbits of Earth and Mercury at $t > 2.0 \times 10^4$ yr, which leads to eventual destruction of the system.

However, as the two giant planets in 47 UMa are much closer to the central star than the JS-pair to the Sun, for perfect analogy with the inner solar system, the semi-major axes of 4T should be shifted to 0.15, 0.29, 0.40 and 0.61 AU. Bearing this in mind, we restarted a new run for the 2G-4T system, where we adopted the rescaled semi-major axes for 4T together with all the other initial values in Table 2. In this numerical experiment, we found that the 2G-4T system can be dynamically stable and can last at least for 20 Myr (see Figure 1b), where the time behaviors of $Q$ and $q$ for 4T show regular motions that their semi-major axes and eccentricities do not dramatically change in their secular orbital evolution. More terrestrial planets can be possibly created in the later stage of planetary formation, Chambers (2001) studied the accretion of $\sim 150$ planetary embryos with lunar-to-Mars masses in giant planets systems and recovered 4T similar to those in the solar system. However, Levison & Agnor (2003) underlined that the population and masses of the resulting terrestrial planets may be affected by the giant planets, because the growth and evolution of the planetary embryos are determined by the possibly experienced dynamical mechanisms (e.g., secular resonances).

### 3.2. Terrestrial planets in Habitable zones

The Habitable Zones are generally conceived as places where the biological evolution of life is able to develop on planetary surfaces in environment of liquid-water, subtle temperature and atmosphere components of CO$_2$, H$_2$O and N$_2$ (Kasting et al. 1993); at the same time, the planetary habitability is also related to the stellar luminosity and the age of the star-planet system (Cuntz et al. 2003). The HZ could be considered to be centered at $\sim 1$ AU ($M_c/M_\odot$)$^2$. For 47 UMa, the inner and outer boundaries of HZ range from 0.7 AU to 1.3 AU (Menou & Tabachnik 2003), however, in our practical simulations, we extended the HZ to other areas for the purpose of a more comprehensive study.

In the second series of runs, we extensively investigated the case of two giant companions with one terrestrial planet in the HZ. The mass of the assumed terrestrial planet ranges
from \(0.1\, M_\oplus\) to \(10\, M_\oplus\). And the adopted initial orbital parameters are as follows: numerical scanning was carried out for \([a, e]\) space by direct integrations, where the low-mass bodies were placed at equal intervals of 0.01 AU for \(0.05\, AU \leq a \leq 2.0\, AU\), the eccentricities were uniformly spaced every 0.01 for \(0.0 \leq e \leq 0.2\) (for \(0.05\, AU \leq a < 0.4\, AU\), where \(0.0 \leq e \leq 0.1\)), the inclinations are \(0^\circ < I < 5^\circ\), and the other angles were randomly distributed between \(0^\circ\) and \(360^\circ\). Thus, over 3000 simulations were exhaustively performed for typical integration spans from 1 Myr to 10 Myr, totalling several \(10^{10}\, yr\).

### 3.2.1. 0.05 AU \(\leq a < 0.4\, AU\)

In these runs, we explored the secular evolution of 385 ”hot Earths” or ”hot Neptunes” for a time span of 1 Myr. All the simulations are dynamically stable for \(10^6\, yr\), and 96% of the orbits bear \(e_{\text{final}} < 0.20\). However, Figure 2a shows that the eccentricities for the bodies at \(\sim 0.30\, AU\) are excited to \(\sim 0.40\), where the secular resonance \(\nu_1 (41.11/yr)\) of the inner companion (similar to \(\nu_5\) for Jupiter) is responsible for the excitation of eccentricity. The debris disk at \(\sim 0.30\, AU\) is also shown by Malhotra (2004), who presented similar results of the eccentricity excitation of massless bodies by nonlinear analytic theory for secular resonance. In addition, even more terrestrial planets with spaced orbits can simultaneously survive for longer lifetime (e.g., the second simulation of 2G-4T system in §3.1). Nevertheless, one can easily see that this region is not a good location for habitability, due to extra high temperature. Recently, Narayan, Cumming, & Lin (2005) discussed the detectability of low-mass objects with orbital periods \(P \leq 10\, days\), and they estimated the present threshold for detecting planets with close-in orbits is \(\geq 10 - 20 M_\oplus\), depending on the number of the observations and the precision of Doppler measurements. Indeed, the improvement of precision of the ground-based observations will lead to the discovery of additional low-mass planets (\(\sim 10 M_\oplus\)) in other known planetary systems (G. W. Marcy 2004, private communication).

However, it brings about great difficulty in catching the planetary formation for hot planets that move so close to their host stars. Although the gas giant planets may undergo inward orbital migration from several AU to the vicinity of host stars, Ida & Lin (2004) found that a large fraction (90%-95%) of the planets that have migrated to \(a < 0.05\, AU\) must perish, because the tidal heating can make the planetary radius inflate (Gu, Lin, & Bodenheimer 2003) and the body may be directly engulfed by the star (Israelian et al. 2001) or survive only as rocky ”cores” with the gas envelope removed due to the mass loss of the planet through the material exchange at the Roche radius. Nevertheless, it is hopeful to detect such planets with \(a \geq 0.05\, AU\) in future space missions (e.g., COROT, KEPLER,
TPF), while the survival of the short-period terrestrial planets (Mardling & Lin 2004) is also related to the relativistic potential of the star.

3.2.2.  $0.4 \, AU \leq a < 1.0 \, AU$

We carried out 1260 integrations in this region for 5 Myr and we found that none of the orbits escaped during this time span and 94% of them were in the resulting $e < 0.25$, see the final status shown in Figure 2b. We find that the eccentricities of the orbits with $0.70 \, AU < a < 0.78 \, AU$ can be pumped up and in the 2:9 MMR at $\sim 0.76 \, AU$, $e$ can reach $\sim 0.90$, indicating that there may exist a gap near this resonance. Most of the Earth-like planets about 1:4 MMR at $\sim 0.82 \, AU$ move stably in bounded motions with low-eccentricity trajectories, except for two cases where the eccentricities eventually grow to high values. Paper II pointed out that the secular resonance $\nu_2$ arising from the outer companion (similar to $\nu_6$ for Saturn) can remove the test bodies. Would the $\nu_2$ also influence the Earth-like planets in this system? Nevertheless, we did not find this mechanism at work at about $\sim 0.85 \, AU$ (see Paper II) when we examined the results, because the terrestrial planets under study that all bear finite masses that may change the strength of this resonance; on the other hand, the location of the secular resonance is changed due to the orbital variation of the outer companion. For a terrestrial planet with a mass of $10M_\oplus$, the region for $\nu_2$ secular resonance is now shifted to $\sim 0.70 \, AU$, where two eigenfrequencies for the terrestrial body and outer giant planet given by the Laplace-Lagrange secular theory are, respectively, $211.37/\text{yr}$ and $225.48/\text{yr}$. This indicates that both planets almost have the same secular apsidal precession rates in their motion. At the new location, the $\nu_2$ resonance, together with the mean motion resonance, can work at clearing up the planetesimals in the disk (see Fig. 2b) by the excitation of the eccentricity; qualitatively, our results are in accord with those of Paper II.

While the inner edge of HZ marks out a narrow unstable area, it is very possible to discover Earth-like planets in this wider area, $0.4 \, AU < a < 1.0 \, AU$, in future surveys, which are to be the best candidate of habitable places for biological evolution of intelligent beings.

3.2.3.  $1.0 \, AU \leq a < 1.3 \, AU$

There were 630 simulations in this region for 10 Myr and we found that 88% survived the integration, confirming the results given in Paper II that most of the test particles with
$a < 1.3$ AU can eventually remain in the system. Here, for the 3:1 resonance at $\sim 1.0$ AU, Figure 3a shows that there are stable orbits in the zones about 1 AU with $e \leq 0.1$, which agrees with the work by Rivera & Haghighipour (2004) who showed that a test particle can last 100 Myr at 1 AU in 47 UMa; while for $0.1 < e \leq 0.2$, the orbits tend to be in unstable state owing to the excitation of the eccentricities. The simulations may imply that the Earth-mass planets near 3:1 resonance are possibly on the edge of stability. However, the previous studies on this system showed that the 3:1 resonance is a gap with no survivors. Let us mention that such differences may arise from the adopted initial planetary configurations, and here we adopt the reliable best-fit orbital solutions given in Paper I that can describe the exact motions for the two giant planets. Hence, a comparative run was carried out to examine this, again we ran 630 simulations for 10 Myr but with the earlier orbital elements for the two massive planets to reproduce the previous results at the 3:1 resonance. Our results with the earlier data show that most of the Earth-mass planets about 3:1 resonance are unstable for the investigated time, and their eccentricities can be pumped up to $\sim 1$ through resonance; besides, the inclinations are excited to high values ranging 90° to 180°, indicating that the orbits of the Earth-mass planets become retrograde in the dynamical evolution and cross those of the prograde giant planets before they terminate their dynamical lifetimes. Thus, we may safely conclude that the stability of the terrestrial planets is dependent on the initial planetary configuration.

In Fig.3a, a narrow unstable stripe appears at the 5:2 MMR at $\sim 1.13$ AU, although several of them can be luckily left behind, most of the Earth-size planets are removed at $\sim 1$ Myr due to the perturbation of 47 UMa b, and in this sense it is analogous to the situation in the solar system. However, a wider area between 3:1 and 5:2 MMR is assumed to be a qualified candidate habitable environment where the Earth-mass planet will not encounter the problem of dynamical stability, and this is almost true for the region (1.13 AU, 1.30 AU) with $e \leq 0.1$, except several unstable islands near 7:3 MMR at 1.18 AU. The smaller eccentricity (near-circular orbits) may not cause dramatic variations of temperature on the planet’s surface, so favoring habitability. Therefore, in a dynamical sense, if the 47 UMa system can be adopted as a candidate target for SIM, it is also possible to detect other Earths with stable orbits about 1 AU.

3.2.4. $1.3 \text{ AU} \leq a \leq 1.6 \text{ AU}$

We performed 651 simulations for 10 Myr, and found the dynamical structure in this regime to be quite complicated: 14% of them can finally survive for this time span, and 86% are lost by ejection into hyperbolic trajectories, indicating the chaotic nature for these bodies.
In Figure 3b, we can notice that the 2:1 MMR region is at $\sim 1.31$ AU and also close to the outer edge of HZ, and the orbits with $0.0 < e < 0.10$ are unstable, while for $0.10 \leq e \leq 0.20$, there are stable islands where fictitious planets can remain in bounded motions in the final system. We observe that the 2:1 resonance marks out a remarkable boundary between chaotic and regular orbits, indicating that orbits with $a < 1.31$ AU can have much larger surviving rates than those of $a > 1.31$ AU. However, there are wider stable region about 9:5 MMR at $\sim 1.40$ AU for low eccentricities $0.0 < e \leq 0.05$. Most of the unstable orbits are in the region $1.43$ AU $< a < 1.56$ AU, using resonance overlapping criterion (Murray & Dermott 1999), the separation in semi-major axis $\Delta a \approx 1.3(M_1/M_c)^{2/7}a_1 \approx 0.496$ AU, thus, the inner boundary $R_O$ for 47 UMa b is at $\sim 1.58$ AU, and the orbits in this zone become chaotic during the orbital evolution because the planets are both within $3R_H$ and also close to $R_O$. And the characterized ejecting time $\tau \sim 1$ Myr, which means the apparent gap (e.g., 5:3 MMR at $\sim 1.48$ AU) in the inner belt, except for several stable islands. Another possible population for terrestrial planets is located at 3:2 resonance $\sim 1.59$ AU for $0.04 < e < 0.20$, and 18 small bodies can last for 10 Myr and confirm the results of Paper II. The 3:2 MMR zone in 47 UMa is reminiscent of the Hilda asteroids in the solar system moving in a stable region.

3.2.5. $1.6$ AU $< a \leq 2.0$ AU

840 Earth-like planets are placed in this region for integration for 10 Myr, and the simulation revealed that 98% are removed from the system within a typical ejection time $\tau < 3 \times 10^4$ yr, which is much shorter than for $1.3$ AU $\leq a \leq 1.6$ AU, implying a thoroughly chaotic situation in this area. It is not difficult to understand that these terrestrial planets are entirely thrown out by the gravitational influence of the inner giant planet, using the $3R_H$ stability criterion.

3.3. Trojan planets

In the solar system, at present there are 1690 Jupiter Trojans (1062 preceding and 628 trailing Jupiter) located at L4 and L5. Hence, a fascinating issue is that whether there exist "extrasolar Trojan planets" in other planetary systems, and if such planets can occur in the system harboring only one gas giant with $a \sim 1$ AU (Dvorak et al. 2004), it may essentially help understand their presence in the HZ. Laughlin & Chambers (2002) found

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2http://cfa-www.harvard.edu/iau/lists/JupiterTrojans.html
the equilateral configuration consisting of a star and two equal-mass planets can be linearly stable for mass ratios less than 0.03812 and showed that a pair of Saturn-mass planets can sustain the stability in the 1:1 orbital resonance.

In the third series of runs, we let the experimental planets with masses of 0.1 $M_\oplus$ to 10 $M_\oplus$ initially orbit about the triangular equilibrium points of the two giant companions, for each giant planet there are 100 orbits distributed near L4 (or L5) point. Then, we implemented 400 dynamical simulations to explore their secular evolution on the timescale of $10^7$ yr. The starting conditions for the Trojan bodies are: $0.00 < e < 0.10, 0^\circ < I < 1^\circ$ and $|\lambda - \lambda_{1,2} - 60^\circ| < 1^\circ$ (where $\lambda$, and $\lambda_{1,2}$, respectively, the mean longitudes of the Trojan, the inner and outer companions). For the inner planet of 47 UMa b, the survival rates for the low-mass bodies about L4 and L5 points are, respectively, 96% and 98%, which is quite similar to the Trojans and Greeks for Jupiter; while for the outer planet (47 UMa c), the survival proportion goes down to 80% and 70% near L4 and L5 region, as a comparison Saturn has no co-orbital bodies. Obviously, the star-planet mass ratios $\mu \sim 10^{-3} < 0.0385$ (Murray & Dermott 1999) both satisfy the linear stability condition for the triangular points. In addition, it is also suggested that the stable triangular region for the inner planet is wider than that of the outer planet, and this can be easily understood as this width depends on the value $\sim \mu^{1/2}$ of the tadpole region.

Figure 4 displays the long-term orbital evolution for the low-mass planets moving about L4 (black line) and L5 (yellow line) points for 47 UMa, where $a$ and $e$ both perform small modulations for $10^7$ yr, and $\lambda - \lambda_{1,2}$ also librate about $60^\circ$ and $300^\circ$, respectively, with low amplitudes for the same time span.

4. Summary and discussions

In this work, we have systematically studied the existence of Earth-like planets in the region for $0.05 \text{AU} \leq a \leq 2.0 \text{AU}$ for 47 UMa by numerical simulations. In addition, we also investigated the packed system and Trojan planets in this system. We now summarize the main results as follows:

(1) The ”hot Earths” can dynamically survive for $10^6$ yr for $0.05 \text{AU} \leq a < 0.4 \text{AU}$, and they are probably detected by transit time variations (Agol et al. 2005; Holman & Murray 2005) via their interaction with the transiting planet$^3$. These techniques may become a

$^3$Laughlin G. and his collaborators are now maintaining the website (see http://www.transitsearch.org/) to search for transiting ”hot Jupiter” planets through the worldwide cooperative observational cam-
vital and effective observational strategy to discover more transiting objects around main sequence stars.

(2) The Trojan planets with low eccentricities and inclinations can last out at the triangular equilibrium points of the two massive planets of 47 UMa. In this sense, it is analogous to the case in solar system. Nevertheless, if they really exist, the formation of these bodies is still a mystery and needs further study.

(3) The Earth-like planets can eventually remain in the system for 10 Myr in the areas associated with mean motion resonance (e.g., 3:2 MMR) with the inner companion. We also showed that the 2:1 and 3:1 resonances could be on the fringe of stability, but the 5:2 MMR is unstable and the bodies can be ejected as “extrasolar comets”. And this may sketch out an asteroidal belt structure similar to the solar system. Moreover, the 2:1 MMR (near the outer boundary of HZ at 1.30 AU) marks out a significant barrier between chaotic and regular motions, implying that a large fraction of the orbits inside this resonance can be survive, while most of them are lost in the simulations outside the 2:1 resonance. Again, considering the inner boundary of HZ and dynamical stability, we point out that the most likely candidate for mean motion resonance is terrestrial planets with orbits in the ranges $0.8 \leq a < 1.0$ AU and $1.0 < a < 1.30$ AU (except 5:2 MMR, and several unstable cases) with low eccentricities (e.g., $0.0 \leq e \leq 0.1$). However, in our own solar system there are no terrestrial planets from the 1:4 MMR out to Jupiter, although there are stable orbits there. This may suggest that although some orbits are stable, conditions are such that terrestrial planets cannot form so close to giant planets. Perhaps this is because runaway growth is suppressed due to the increased eccentricities from the perturbations of the giant planet. In 47 UMa, the corresponding region runs from 0.82 AU on out (see Figure 2), almost completely covering the HZ. Hence, it would be reasonable to conclude that the only proper place to find habitable planets in this system would be at about 0.8 AU. But this should be carefully examined by forthcoming space measurements (e.g., SIM) capable of detecting low-mass planets.

In a word, we can see that the 47 UMa planetary system may bear a similar dynamical structure to our solar system, in that it can also own several terrestrial members resembling the inner solar system. A comparative study can be performed in other planetary systems with two giant planets (Érdi et al. 2004; Raymond & Barnes 2005) to explore whether Earth-like planets can exist there, and to locate less massive planets (Malhotra 2005, in preparation) in general planetary systems. The dynamical habitability is relevant to both mean motion

paign. Besides, the other active group from OGLE project have detected several transiting planets (http://sirius.astrouw.edu.pl/~ogle/) in the observations.
resonance and secular resonance for a given system. Moreover, the formation of the terrestrial planets in the HZ is difficult in the planetary systems that contain a giant planet with a moderate-size eccentric orbit (Veras & Armitage 2005), because most of the initial material within HZ was depleted by orbital crossings; in addition, the accretion simulations (Paper II) show that the massive planetary embryos in the HZ should be created prior to the formation of giant gaseous planets. Hence, more efforts should also be directed to the understanding of the formation of habitable terrestrial planets.

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Table 1. The orbital parameters of 47 UMa planetary system (adopted from Fischer et al. [2003]). The stellar mass is $1.03 M_\odot$.

| Parameter                  | Companion B | Companion C |
|----------------------------|-------------|-------------|
| $M\sin i(M_{Jup})$         | 2.86        | 1.09        |
| Orbital period $P$(days)   | 1079.2      | 2845.0      |
| $a$(AU)                    | 2.077       | 3.968       |
| Eccentricity $e$           | 0.05        | 0.00        |
| $\omega$(deg)             | 124.3       | 170.89      |
| Periastron Time (JD)       | 2452374.1   | 2448750.9   |

Table 2. The orbital elements for 4 terrestrial planets at JD 2448750.9 (From DE405).

| Planet   | a(AU) | ecc  | $I$  | $\Omega$ | $\omega$ | $M$  |
|----------|-------|------|------|----------|----------|------|
| Mercury  | .387  | .2056| 7.00 | 48.34    | 29.10    | 260.40|
| Venus    | .723  | .0067| 3.39 | 76.70    | 55.06    | 253.70|
| Earth    | 1.000 | .0163| 0.001| 255.71   | 207.06   | 123.84|
| Mars     | 1.523 | .0935| 1.850| 49.57    | 286.48   | 355.18|
Fig. 1.— The orbital evolution of 4 terrestrial planets. *Left*: chaotic case with $a$ from Table 2, Mars leaves its initial orbit at $t < 10^4$ yr, and Venus begins to cross the orbits of Earth and Mercury at $t > 2.0 \times 10^4$ yr. *Right*: with rescaled semi-major axes, 4T remain regular motions that $a$ and $e$ both perform slight vibrations for 20 Myr.
Fig. 2.— The contour of status of the final eccentricities for Earth-like planets, the vertical axis for the initial \( e \). Left: \( 0.05 \text{ AU} \leq a < 0.4 \text{ AU} \) for 1 Myr. Notice \( \nu_1 \) secular resonance at \( \sim 0.30 \text{ AU} \) pumps up the eccentricities. Right: \( 0.4 \text{ AU} \leq a < 1.0 \text{ AU} \) for 5 Myr. The \( e \) of the orbits with \( 0.70 \text{ AU} < a < 0.78 \text{ AU} \) can be excited and in the 2:9 MMR at \( \sim 0.76 \text{ AU} \), \( e \) can reach \( \sim 0.90 \).
Fig. 3.— The surviving time for Earth-like planets for the integration of 10 Myr, the vertical axis is the same as Fig. 2. Left: for $1.0 \text{ AU} \leq a < 1.3 \text{ AU}$, see the gap for the 5:2 MMR at $\sim 1.13 \text{ AU}$. Right: for $1.3 \text{ AU} \leq a \leq 1.6 \text{ AU}$, a population of the terrestrial planets is about 9:5 MMR at $\sim 1.40 \text{ AU}$ for low eccentricities (see texts for details).
Fig. 4.— The secular evolution for the low-mass planets moving about L4 (black line) and L5 (yellow line) points for 47 UMa, where $a$ and $e$ both perform small modulations for $10^7$ yr, and $\lambda - \lambda_{1,2}$ also librate about 60$^\circ$ and 300$^\circ$ with low amplitudes, respectively. Left: for inner planet. Right: for outer planet.