

On secular resonances of small bodies in the planetary systems

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Abstract. We investigate the secular resonances for massless small bodies and Earth-like planets in several planetary systems. We further compare the results with those of Solar System. For example, in the GJ 876 planetary system, we show that the secular resonances ν_1 and ν_2 (respectively, resulting from the inner and outer giant planets) can excite the eccentricities of the Earth-like planets with orbits $0.21 \leq a < 0.50$ AU and eject them out of the system in a short timescale. However, in a dynamical sense, the potential zones for the existence of Earth-like planets are in the area $0.50 \leq a \leq 1.00$ AU, and there exist all stable orbits last up to 10^5 yr with low eccentricities. For other systems, e.g., 47 Uma, we also show that the Habitable Zones for Earth-like planets are related to both secular resonances and mean motion resonances in the systems.

Keywords. n-body simulations, planetary systems, habitable zone

1. Introduction

Since the discovery of the first Jupiter-mass planet orbiting the solar-type star 51 Peg (Mayor & Queloz 1995), it has been more than a decade. The breakthrough of scientific finding not only arouses great interests to search for other habitable planets or alien civilization worlds outside our own solar system, but also explicitly confirms that the planets can be at birth anywhere about their parent stars in the circumstellar disks, because these flat disks enshrouding young stars are considered to be a common feature of stellar evolution and of planetary system formation (Beichman *et al.* 2006). Primordial protoplanetary disks contain gas and dust and supply the raw ingredients from which the new planetary systems can form. To date, over 160 planetary systems (see also <http://www.exoplanets.org> and <http://exoplanet.eu/>) have been discovered by the measurements of Doppler radial velocity and other observational methods (Butler *et al.* 2006). More than 200 extrasolar planets have been detected about solar-type stars. Currently, amongst the detected systems, there are 20 multiple-planet systems, e.g., two-planet systems (e.g., 47 Uma etc.), three-planet systems (e.g., Upsilon And etc.) and a four-planet system, 55 Cancri. Then, the studies of the dynamics or formation of these systems are essential to understand how two (or more) planets originate from and evolve therein. In recent years, many authors have investigated the dynamical evolution of a planetary system and intended to reveal the possible mechanisms that stabilize a system, especially for those involved in the mean motion resonances (MMR), e.g., 2:1 MMR (GJ 876, HD 82943, HD 128311, HD 73651), and explored the secular interactions in the

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multiple systems (e.g., Hadjidemetriou 2002, 2006; Goździewski 2002, 2003; Ji *et al.* 2002, 2003; Lee & Peale 2002, 2003). Herein, we investigate the secular resonances for massless small bodies and Earth-like planets in several planetary systems, which is extremely important to make clear what dynamical structure of the newly-discovered systems may hold and how the secular resonances would have influence on the motions of the potential Earth-like planets and the location of the Habitable Zones (HZ). The HZs are generally believed as suitable locations where the biological evolution of life is able to develop on planetary surfaces in environment of liquid-water, subtle temperature and atmosphere components of CO₂, H₂O and N₂ (Kasting *et al.* 1993). In the meantime, the planetary habitability is also relevant to the stellar luminosity and the age of the star-planet system (Cuntz *et al.* 2003). However in Solar System, it is believed that the asteroids in the main belt can undergo secular resonances with respect to Jupiter (or Saturn), and their eccentricities can be greatly excited. The bodies can cross and approach Earth in million years, as a near-Earth object (NEO). Hence, the present study is mainly focusing on the issue that such secular resonances make a difference in other planetary systems.

Moreover, the scientific objectives of several space missions (e.g., SIM, TPF[†]) will be in part contributed to be hunting for the Earth-like planets, although this may come true after a significant improvement of precision of ground observations. Then, we also start such studies in the planetary systems advancing these projects. At first, we will quickly review the secular resonances taking place for the asteroids in the main belt.

2. Secular Resonances for Main Belt Asteroids in Solar System

It is well-known that the concentration or depletion for the asteroids in the main belt are associated with the mean motion resonances (MMR) with Jupiter's orbit and secular resonances (Williams 1969; Milani & Knežević 1992; Morbidelli & Moons 1993). The main belt asteroids are populated at the 3:2, 4:3 and 1:1 MMR with Jupiter, but rarely resided in the 2:1, 3:1, 5:2 and 7:3 resonant regions, which are called the Kirkwood gaps. Moreover, the secular resonances are responsible for the long-term dynamical evolution for small bodies. In general, secular resonances occur when the longitude of the perihelion or that of the ascending node of the small body shares the same precession rate as that of the massive giant planet (e.g. Jupiter and Saturn). There are three governing secular resonances in the asteroidal belt, known as the ν_5 , ν_6 and ν_{16} resonances. The formed two are called apsidal secular resonances with respect to Jupiter and Saturn, respectively and can pump up the eccentricity of a small object; the latter one is the nodal secular resonance with respect to Saturn, which can enhance the inclination of the body. At present, it is believed that the NEOs are principally considered to be objects ejected from the main belt through a complicated dynamical process, where mean motion resonances as well as secular resonances play a vital role in their dynamical transportation (Morbidelli & Moons 1993; Froeschlé 1997; Morbidelli *et al.* 2002), indicating that the overlapping of mean motion resonances and secular resonances (Morbidelli & Moons 1993; Moons & Morbidelli 1995) can lead to large chaotic zones for the relevant asteroids.

For example, the small bodies trapped in a 3:1 orbital resonance with Jupiter (occupying the semi-major axes ~ 2.5 AU) are rarely distributed, involved in Kirkwood gaps. Wisdom (1983) pointed out that the chaotic motion for the asteroids in 3:1 MMR can increase the eccentricities and then make them approach and intersect the orbit of Mars (even Earth). Herein, Figure 1 shows that the orbital evolution for a massless test particle, however, over the time span of (0.65 Myr, 0.80 Myr) due to ν_5 and 3:1 resonance,

† <http://planetquest.jpl.nasa.gov/SIM>, and <http://planetquest.jpl.nasa.gov/TPF>

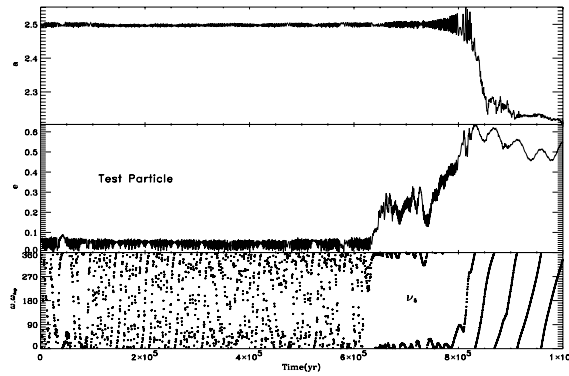


Figure 1. The time behavior of the semi-major axis a , the eccentricity e and $\varpi - \varpi_J$ for the test particle. a slightly oscillates about 2.50 AU within 0.6 Myr, over the time span of (0.65 Myr, 0.80 Myr) due to ν_5 resonance (see bottom and middle panels), and e is excited above 0.60, while a goes down to 2.20 AU. Eventually, the test body becomes a NEO candidate.

Planet	$M_{star}(M_{\odot})$	$M \sin i(M_{Jup})$	Period P (d)	a (AU)	e
GJ 876 b	0.32	3.39	62.09	0.211	0.05
GJ 876 c	0.32	1.06	30.00	0.129	0.31
47 UMa b	1.03	2.86	1079.2	2.077	0.05
47 UMa c	1.03	1.09	2845.0	3.968	0.00

Table 1. Properties of 2 multiple planet systems (data adopted from Laughlin & Chambers 2001; Fischer *et al.* 2003)

the eccentricity e of the small body is excited up to 0.60 and meanwhile the semi-major axis a drops down to 2.20 AU, being an Earth-crossing body. In other numerical investigations for the dynamical evolution of the minor bodies over millions of years, we also find that several NEOs can be temporarily locked a 3:1 orbital resonance and also experience secular resonance ν_5 (or ν_6) with Jupiter (or Saturn), then confirm that the 3:1 orbital resonance and secular resonances play an important role in the origin for NEOs by previous studies (e.g., Morbidelli *et al.* 2002 and references therein).

3. Secular Resonances in Extrasolar Systems

In order to investigate the dynamical structure or Habitable Zones in the planetary systems, we also performed extensive numerical simulations for the planetary configurations of two giant planets with one fictitious low-mass body for several systems (e.g., 47 UMa, GJ 876, etc). We also show that the secular resonances can affect the motions of the small bodies in these systems, and shape the dynamical architecture in the debris disk as mean motion resonances. As for the methodology, we use a N-body code (Ji *et al.* 2002) of direct numerical simulations with the RKF7(8) (Fehlberg 1968) and symplectic integrators (Wisdom & Holman 1991). We always take the stellar mass and the minimum planetary masses from Table 1, while the mass of an assumed terrestrial planet is adopted to be in the range from $0.1 M_{\oplus}$ to $10 M_{\oplus}$. The used time stepsize is usually $\sim 1\%$ - 2.5% of the orbital period of the innermost planet. In addition, the numerical errors were effectively controlled over the integration timescale. The typical integration timescale for the simulation is 10^5 yr. The main results now follow.

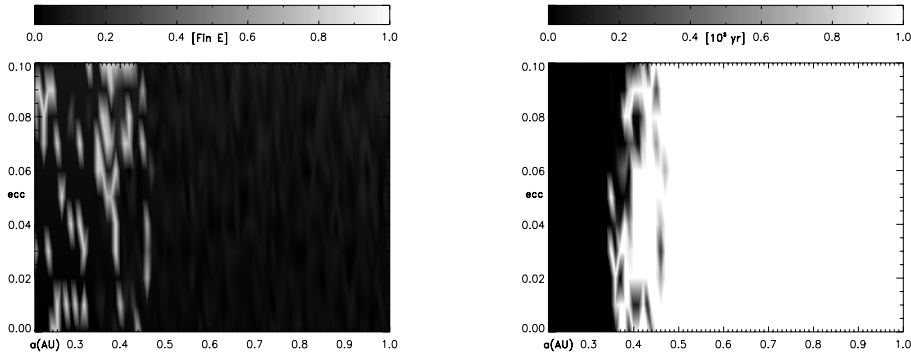


Figure 2. *Left panel:* Contour of the final eccentricities for the Earth-like planets in the GJ 876 system. Horizontal and vertical axes are the initial values of a and e . In the region $0.21 \leq a < 0.50$ AU, the eccentricities can be pumped up to high values ~ 1 or these bodies are directly ejected from the system due to the starting dynamical instability. Hence, in this region, the Earth-like planets are strongly chaotic and cannot survive in the system. *Right panel:* Surviving time for Earth-like planets in the system. The Earth-like planets evolve with short dynamical time before they end their destinies in the area $0.21 \leq a < 0.30$ AU, indicating that these orbits are completely unstable, for the initial conditions. The chaotic behaviors of the Earth-like planets in $0.21 \leq a < 0.50$ AU are, somewhat related to two secular resonances (ν_1 and ν_2).

3.1. GJ 876

The M dwarf main-sequence star GJ 876 with an estimated mass of $0.32 M_{\odot}$ is the lowest mass star that hosts planets, and two Jupiter-like planets (Marcy *et al.* 2001) are revealed with minimum masses of $1.89 M_{Jup}$ and $0.56 M_{Jup}$ in this system. Moreover, the ratio of the orbital periods of two planets is close to a mean motion commensuration of 2:1. Being the first discovered 2:1 resonant planetary system, the GJ 876 has generated great interests and the long-term dynamics and planetary formation for two giant companions are extensively investigated (e.g., Hadjidemetriou 2002; Ji *et al.* 2002; Lee & Peale 2002; Beauge & Michtchenko 2003; Kley *et al.* 2005; Laughlin *et al.* 2005, and references therein). However, the planetary formation theory (Lissauer 1993) suggests that even low-mass planets (e.g., Earth-like planets) may exist about the most abundant M dwarf stars with mass of $0.08 - 0.8 M_{\odot}$, which covers 75% of the total stellar population in the galaxy. For instance, Butler *et al.* (2004) announced the discovery of a Neptune-mass planet ($\sim 18 M_{\oplus}$) about M dwarf star GJ 436, implying the potential existence of the terrestrial or Neptunian planet in other systems.

Thus, we exhaustively investigated the case of two coplanar-configuration giant companions with one terrestrial planet. The initial orbital parameters were adopted as follows: the low-mass terrestrial bodies were placed at an equal interval of 0.01 AU from 0.21 AU to 1.0 AU in a , the eccentricities e were taken every 0.01 from 0 to 0.1, the inclinations are $0^{\circ} < I < 5^{\circ}$, and the other angles were randomly distributed between 0° and 360° . Then each integration was carried out for 10^5 yr.

The numerical outcomes reveal that the two secular resonances ν_1 and ν_2 respectively arising from the inner and outer giant planets are responsible for the chaotic motions of the Earth-like planets. To understand the vital role of the secular resonances, we have carried out several computations. If a terrestrial planet has the mass of $1 M_{\oplus}$, the location for ν_2 secular resonance is ~ 0.4550 AU, where the two eigenfrequencies for the terrestrial body and the outer giant planet are provided by Laplace-Lagrange secular theory (Murray & Dermott 1999) are, respectively, $1^{\circ}.83 \text{ yr}^{-1}$ and $1^{\circ}.90 \text{ yr}^{-1}$. This is fairly in agreement with numerical results, where Figure 2 (*left panel*) shows the excitation of eccentricity

of the Earth-like planets at ~ 0.45 AU. In addition, the relevant location for ν_1 secular resonance is ~ 0.2930 AU, in this case the terrestrial planet almost shares the same eigenfrequency as the inner giant planet, the values are $21^\circ.30 \text{ yr}^{-1}$ and $20^\circ.94 \text{ yr}^{-1}$, respectively. The mutual Hill radius is $R_H = [(M_1 + M_2)/(3M_s)]^{1/3}(a_1 + a_2)/2$, where M_s , M_i are the masses of the host star and the planets (the subscript $i = 1, 2$, stands for the inner and outer planets, respectively), and a_1 , a_2 the semi-major axes. Using the data in Table 1, we obtain $3R_H = 0.084$ AU, where $a_2 = 0.211$ AU, then we have an exterior influence boundary ~ 0.295 AU, which is almost equal to ν_1 . Thus, the Earth-like planets with orbits ~ 0.30 AU are strongly affected by ν_1 , and this also confirms our numerical explorations. On the other hand, plenty of mean motion resonances exist and overlap within Hill radius. The dynamical lifetime of the bodies will decrease drastically.

In a dynamical sense, for GJ 876, the potential existence of the Earth-like planets[†] concerns the region $0.50 \leq a \leq 1.00$ AU. Stable orbits exist, up to 10^5 yr with low eccentricities (see *right panel* of Figure 2) in the resulting evolution. This is because the initial orbits of Earth-like planets are a bit far away from the two secular resonances, free from secular perturbation. Moreover, the dynamical stability beyond 0.50 AU also suggests that outer belts for unaccreted planetesimals may exist in this system.

The formation of two giant planets in the GJ 876 system has been recently modelled by Lee & Peale (2002) and Kley *et al.* (2005), and the planets were likely captured into the 2:1 resonance by converging differential migrations in the protoplanetary disk. In this sense, the motions of the Earth-like planets or the planetesimals in the disk may be influenced by the orbital migration of the two giant planets, and they may be swept out directly or captured into the resonance with the two larger planets of GJ 876. This should be re-examined in future studies.

3.2. 47 UMa

The main sequence star 47 UMa is of spectral type G0 V with a mass of $1.03M_\odot$. Butler & Marcy (1996) reported the discovery of the first planet in the 47 UMa system which has become one of the most amazing systems particularly after the subsequent release of an additional companion (Fischer *et al.* 2002, 2003). 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 ~ 2.62 (Table 1), as comparable to that of Jupiter-Saturn (JS) of 3.34; and the ratios of the two orbital periods are very similar. Hence, one may wonder whether there exists additional members in 47 UMa system (see Ji *et al.* 2005 for details).

Laughlin *et al.* (2002) 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 periape longitudes (Ji *et al.* 2003). Then the eccentricities avoid larger oscillations 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 Laughlin *et al.* (2002) 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

[†] Rivera *et al.* (2005) reported a ~ 7.5 Earth-Mass planet about GJ 876, with the orbital period of 1.938 d, and they also indicated that additional planets may be revealed in this system with more observational data.

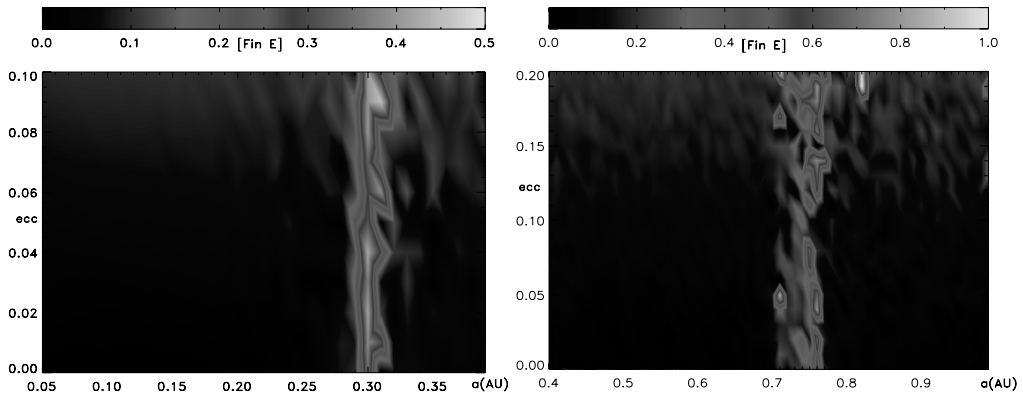


Figure 3. The contour of status of the final eccentricities for Earth-like planets, the vertical axis for the initial e . *Left panel*: $0.05 \leq a < 0.4$ AU for 1 Myr. Notice that the secular resonance at ~ 0.30 AU pumps up the eccentricities. *Right panel*: $0.4 \leq a < 1.0$ AU for 5 Myr. The eccentricity e of the orbits with $0.70 < a < 0.78$ AU is excited and in the 2:9 MMR at ~ 0.76 AU, e can reach ~ 0.90 .

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. Herein, we performed extensive simulations to examine the dynamical architecture in both the HZ and the 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 Fischer *et al.* (2003). 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, the discovery of the close-in Neptune-mass planets (Butler *et al.* 2004; McArthur *et al.* 2004; Santos *et al.* 2004) demonstrates that it may be possible for less massive planets ($\sim M_{\oplus}$) to move close to the star. Therefore, we also explored low-mass planets in the region $0.05 \leq a < 0.4$ AU and we found that the secular resonance arising from the inner giant planet render the eccentricity excitations for the Earth-like planets.

For $0.05 \leq a < 0.4$ AU, we explored the secular evolution of hundreds of “hot Earths” or “hot Neptunes” over timescale of 1 Myr. All the simulations are dynamically stable for 10^6 yr, and 96% of the orbits possess $e_{final} < 0.20$. However, Figure 3 (*left panel*) shows that the eccentricities for the bodies at ~ 0.30 AU are excited to ~ 0.40 , where the secular resonance ν_1 ($41''11 \text{ yr}^{-1}$) of the inner giant planet (similar to ν_5 for Jupiter) is responsible for excitation of the eccentricities. In addition, Malhotra (2004) also presented similar results, showing that the eccentricities of massless bodies are excited in the debris disk at ~ 0.30 AU, using nonlinear analytical theory.

In the region $0.4 \leq a < 1.0$ AU, more than one thousand of simulations were carried out for 5 Myr each (see *right panel* in Figure 3). Most of the Earth-like planets about 1:4 MMR at ~ 0.82 AU move stably in bounded motions with low-eccentricity trajectories, except for two cases where the eccentricities eventually grow to high values. The secular resonance ν_2 arising from the outer companion (similar to ν_6 for Saturn) can remove the test bodies. Herein ν_2 can also influence the Earth-like planets in this system. The terrestrial planets 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 location for ν_2 secular resonance is about ~ 0.70 AU, where the two eigenfrequencies for

the terrestrial body and outer giant planet given by the Laplace-Lagrange secular theory are, respectively, $211''37 \text{ yr}^{-1}$ and $225''48 \text{ yr}^{-1}$. This indicates that both planets have almost the same secular apsidal precession rates in their motion. Hence, the ν_2 resonance, together with the mean motion resonance, can work at clearing up the planetesimals in the disk (see Fig. 3) by the excitation of the eccentricity (see also Nagasawa *et al.* 2005).

We point out that the most likely candidate for habitable environment is terrestrial planets with orbits in the ranges $0.8 \leq a < 1.0 \text{ AU}$ 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, the 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 Fig. 3), 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 0.80 AU. But this should be carefully examined by forthcoming space measurements (e.g., SIM or GAIA) capable of detecting low-mass planets.

4. Summary and Discussion

In this work, we investigate the secular resonances for massless small bodies and Earth-like planets in several planetary systems with two giant planets (e.g., 47 UMa and GJ 876) by extensive numerical simulations, and further we have studied the potential existence of Earth-like planets in the related regions for these systems. In final, we summarize the following results:

(1) We can see that the 47 UMa planetary system may be a close analog of our solar system, and even it can also own several terrestrial members resembling the inner solar system (Ji *et al.* 2005). Besides, the two giant planets in the 47 UMa are similar to the Jupiter-Saturn pair in the solar system, and the corresponding secular resonances originating from them can stir the low-mass small bodies with low eccentricities in the initial “cold” disk. As to other systems, we also find that the Habitable Zones for Earth-like planets are related to both secular resonances and mean motion resonances in these systems, which may play an important role of shaping the asteroidal belts. A comparative study has been also performed in other planetary systems (see Érdi *et al.* 2004; Dvorak *et al.* 2004; Ji *et al.* 2006) with one or more giant planets to explore whether Earth-like planets can exist there, and further to locate less massive undetected planets or characterize the nature of the potential asteroidal structure in general planetary systems.

(2) The habitability for the development of biological evolution depends on many factors, such as the liquid water state, the temperature constraint, the atmosphere composition, the obliquity and rotation rate of a target terrestrial planet, the stellar luminosity, etc. However, in a dynamical viewpoint, it also requires that the habitable terrestrial planets have stable orbits in the HZ with low eccentricity at a nearly circular trajectory, herein we show that the secular resonances can excite some orbits residing in the HZ of a system, which may provide useful information or place some constraints on the observational strategy to discover such low-mass planets.

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