TERRESTRIAL PLANET FORMATION AROUND THE CIRCUMBINARY HABITABLE ZONE: INWARD MIGRATION IN THE PLANETESIMAL SWARM

YAN-XIANG GONG1,2, JI-LIN ZHOU1, and JI-WEI XIE1,3

1 Department of Astronomy & Key Laboratory of Modern Astronomy and Astrophysics in Ministry of Education, Nanjing University, Nanjing 210093, China; yxgong@nju.edu.cn, zhoulj@nju.edu.cn
2 College of Physics and Electronic Engineering, Taishan University, Taian 271021, China
3 Department of Astronomy and Astrophysics, University of Toronto, Toronto, ON M5S 3H4, Canada

Received 2012 October 21; accepted 2012 November 28; published 2012 December 28

ABSTRACT

According to the core accretion theory, circumbinary embryos can form only beyond a critical semimajor axis (CSMA). However, due to the relatively high density of solid materials in the inner disk, a significant amount of small planetesimals must exist in the inner zone when embryos form outside this CSMA. Thus, embryo migration induced by the planetesimal swarm is possible after gas disk depletion. Through numerical simulations, we found that (1) the scattering-driven inward migration of embryos is robust and planets can form in the habitable zone if we adopt a mass distribution of an MMSN-like disk; (2) the total mass of the planetesimals in the inner region and continuous embryo–embryo scattering are two key factors that cause significant embryo migrations; and (3) the scattering-driven migration of embryos is a natural water-delivery mechanism. We propose that planet detections should focus on the close binary with its habitable zone near CSMA.

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

Online-only material: color figures

1. INTRODUCTION

Circumbinary planets—planets that encircle both members of a binary—are interesting celestial bodies discovered by exoplanet-hunting missions. So far, six exoplanets circling main-sequence binary stars have been found by the Kepler mission. They are Kepler-16b (Doyle et al. 2011), Kepler-34b, Kepler-35b (Welsh et al. 2012), Kepler-38b (Orosz et al. 2012a), Kepler-47b, and Kepler-47c (Orosz et al. 2012b). Though exoplanet-hunting plans selectively avoid close binaries, circumbinary planets may be common. Studies have found that more than 1% of close binary stars have giant planets in nearly coplanar orbits, yielding a Galactic population of at least several million (Welsh et al. 2012). All of the six circumbinary planets hitherto discovered by Kepler are Saturn-like or Neptune-like planets, and are not suitable for the existence of extraterrestrial life. We know the ultimate aim of Kepler is to find Earth-like exoplanets and to search for extrasolar life. It is natural to ask whether terrestrial planets can form in the circumbinary case. This Letter intends to explore some aspects of this topic.

In this Letter, the semimajor axis (SMA), eccentricity, and mass ratio of a binary are designated $a_B$, $e_B$, and $\mu = M_B/(M_A + M_B)$ (where $M_A$ is the bigger one), respectively. According to Holman & Wiegert (1999), there is a critical SMA ($a_1$) within which test particles are unstable (besides some specific initial configurations). Based on the core accretion model, there is another critical SMA ($a_2$, usually outside $a_1$) within which planetesimal accretion is impossible due to the strong perturbation of the binary. In this Letter, we propose a mechanism for the formation of terrestrial planets in the habitable zone (HZ) through inward migration of embryos outside $a_2$. This Letter is organized as follows: A summary of past works and our ideas are presented in Section 2. Sections 3 and 4 show our model and simulation results. The conclusions are summarized in Section 5.

2. SYNOPSIS OF PAST WORKS AND OUR IDEAS

From planetesimals to embryos. In the circumbinary case, the perturbations of the companion star can stimulate the eccentricities of the planetesimals, which lead to high impact velocities between planetesimals. By ignoring the effect of gas, Moriwa & Nakagawa (2004) concluded that planetesimal accretion cannot occur within 13 AU ($\mu = 0.2$, $a_B = 1$, $e_B = 0.1$). The coupled effects of companion perturbations and gas friction lead to strong size-dependent orbital phasing, which reduces the planetesimal impact velocities and makes accretion more optimistic (Scholl et al. 2007). However, when the disk evolution is included, pericenters of planetesimals are less collimated than that in the stationary and axisymmetric disk model, which again inhibits planetesimal accretion (Marzari et al. 2008).

As a result, Meschiari (2012a) concluded that planetesimal accretion might be effectively inhibited within 4 AU in Kepler-16(AB). Meschiari (2012b) considered the turbulence driven by the magnetorotational instability. He found that planetesimal accretion can be inhibited even in the 4–10 AU region in Kepler-16(AB). Paardekooper et al. (2012) confirmed that in situ growth starting from planetesimals smaller than ~10 km is difficult for Kepler-16b, Kepler-34b, and Kepler-35b.

From the embryos to the terrestrial planets. Quintana & Lissauer (2006) found that the apastron distance $Q_B = a_B(1 + e_B)$ is a critical parameter for the formation of circumbinary terrestrial planets. When $Q_B < 0.2$ AU (for 0.05 AU < $a_B$ < 0.4 AU), the formed planetary systems are very similar to those around single stars, whereas those with larger $Q_B$ tend to harbor fewer planets, especially inside 1 AU. However, they did not consider the origin of the initial embryos.

Since circumbinary embryos can only form at large distances (beyond the ice line in the Kepler-16 system, Meschiari 2012a),
embryos’ inward migration is the only path to form terrestrial planets in the inner zone. There are two kinds of migration: type I migration driven by the gas disk (Goldreich & Tremaine 1979; Ward 1997) and the migration of embryos driven by the planetesimal disk (Ida et al. 2000). Pierens & Nelson (2007, 2008) have shown that planets with terrestrial to Saturn mass always migrate inward until they reach the inner border of the disk truncated by the tidal force of the binary. However, from the viewpoint of planet formation, there are some inevitable problems for the formation of the circumbinary embryos or protoplanets.

1. Long accretion timescales of distant embryos. Outside \( a_{2} \), planetesimal accretion will be slower than that in single-star systems due to the perturbations of the companion star with the so-called type II runaway growth (Kortenkamp et al. 2001). On the other hand, \( a_{2} \) is a function of time (Thébault 2006). Over longer timescales, the impact velocities in the outer region will also increase, which makes accretion slower.

2. Rapid dissipation of the circumbinary gas disk. Simulations of Artymowicz (1994) and Frager & Nelson (2010) have shown that the disk will be truncated, distorted, and torn quickly, so the lifetime of the circumbinary gas disk will be shorter. Some evidence for the reduced lifetimes (~0.1–1 Myr) of the primordial circumstellar disk in the binary system has been confirmed by observations (Cieza et al. 2009).

3. Uncertainty of type I migration. Recent studies show that the orientation and migration rate of type I migration is very uncertain (Kley & Nelson 2012; Ormel 2012). Inward migration cannot be guaranteed in all kinds of disk environments. A notable example is the solar system, where planets might not have obvious gas-driven migration.4 On the other hand, type I migration is unimportant for terrestrial planets (Bromley & Kenyon 2011) because the building blocks of solid planets are packed too closely to migrate.

Long accretion timescales of embryos and the reduced lifetime of gas disks indicate that significant gas-disk migration of a circumbinary planet may be less significant than in single-star systems. However, due to the relatively high density of solid materials in the inner disk, a significant amount of small planetesimals must exist in the inner region when small embryos form outside \( a_{2} \). Thus, planetesimal-driven migration of embryos may work. In this Letter, we consider the migration and accretion of embryos in a planetesimal disk—a “gas-free” case in which the influence of the residual gas disk can be ignored. Our work can be thought of as complementary to the work of Pierens & Nelson (2007, 2008)—a case in which the gas disk dissipates when the embryos form outside of \( a_{2} \). The aim is to determine whether or not the terrestrial planets can form in the inner region such as the HZ under “gas-free” circumstances. Payne et al. (2009) have discussed the migration of S-type embryos in a planetesimal disk; we apply a similar scattering-driven migration mechanism in the circular case.

3. NUMERICAL MODEL AND INITIAL CONDITIONS

The parameter space of the binary systems is relatively large. Here, we select Kepler-16(AB) as the fiducial binary configuration. The fitting formula found in Holman & Wiegert

\[ a_{c1} = \left[ 1.60 + 5.1 e_{B} - 2.22 e^{0.5} + 4.12 \mu \right. \]
\[ \left. - 4.27 e_{B} \mu - 5.09 \mu^{2} + 4.61 e^{2} \mu^{2} \right] a_{B}. \]

(1)

Using the parameter of Kepler-16(AB) (see Table 1), we obtain \( a_{c1} \approx 0.66 \) AU. The \( a_{c2} \) is 4 AU derived by Meschiari (2012a) is used to define the boundary inside which the embryo formation is effectively inhibited. We call \( a_{c1} \) to \( a_{c2} \) the inner region and \( a_{2} \) the outer region. According to the “minimum-mass solar nebula” (MMSN) disk (Hayashi 1981), the mass of solids within the inner region is about 6–8 \( M_{\oplus} \) of \( M_{\oplus} \).

| Binary | Kepler-16(AB) | Kepler-34(AB) | Kepler-35(AB) |
|--------|--------------|--------------|--------------|
| \( M_{A} (M_{\odot}) \) | 0.8697 | 1.0479 | 0.8877 |
| \( M_{B} (M_{\odot}) \) | 0.2026 | 1.0208 | 0.8094 |
| \( a_{B} (AU) \) | 0.2245 | 0.2288 | 0.1761 |
| \( e_{B} \) | 0.15944 | 0.52087 | 0.1421 |
| \( L_{A} + L_{B} (L_{\odot}) \) | 0.66 | 0.52 | 0.65 |
| \( a_{c1} (AU) \) | 4.00\( \Sigma \) | 2.67\( \Sigma \) | 2.70\( \Sigma \) |
| \( a_{c2} (AU) \) | 2.3 | 10.0 | 7.8 |
| \( HZ (AU) \) | 0.36–1.02\( \Sigma \) | 1.58–3.33 \( \Sigma \) | 1.10–2.32 \( \Sigma \) |
| \( \eta \) | \( \sim 0.05 \) | \( \sim 0.04 \) | \( \sim 0.07 \) |
| \( M_{2} (M_{B}) \) | 0.98\( \Sigma \) | 1.19\( \Sigma \) | 1.18\( \Sigma \) |
| \( a_{min} (AU) \) | 0.95 | 1.33 | 1.09 |
| EHZ (fraction) | 10% | 35% | 20% |

Notes. \( a_{min} \) is the minimum final SMA of the embryos in 20 runs. EHZ means the fraction of the innermost planet in the habitable zone.

\( a_{B} \) is a function of time (Thébault, 763:L8 (5pp), 2013 January 20).

Gong, Zhou, & Xie

4 A new point can be found in Walsh et al. (2012).
Figure 1. Time evolution of the circumbinary planetesimals and embryos. The binary is the Kepler-16(AB) configuration (see Table 1). The embryos are represented by filled circles whose sizes are proportional to the physical sizes of the bodies (in a scale relative to Earth). The planetesimals are represented by open circles but not on a scale relative to Earth. The dashed red line denotes $a_{1}$ and the dashed blue line denotes $a_{2}$. The green region is the habitable zone ($0.36 \text{ AU} \leq a_{p}(1 - e_{p})$ and $a_{p}(1 + e_{p}) \leq 1.02 \text{ AU}$).

A (color version of this figure is available in the online journal.)

Figure 1. Time evolution of the circumbinary planetesimals and embryos. The binary is the Kepler-16(AB) configuration (see Table 1). The embryos are represented by filled circles whose sizes are proportional to the physical sizes of the bodies (in a scale relative to Earth). The planetesimals are represented by open circles but not on a scale relative to Earth. The dashed red line denotes $a_{1}$ and the dashed blue line denotes $a_{2}$. The green region is the habitable zone ($0.36 \text{ AU} \leq a_{p}(1 - e_{p})$ and $a_{p}(1 + e_{p}) \leq 1.02 \text{ AU}$).

A (color version of this figure is available in the online journal.)
velocity, the growth of planetesimals, and other factors have great uncertainty in determining $a_{\alpha}$. Different models give different $a_{\alpha}$. For example, Marzari et al. (2012) show $a_{\alpha} \sim 3$ AU, while Paardekooper et al. (2012) find $a_{\alpha} \geq 4.4$ AU for Kepler 16(AB). Here, $a_{\alpha}$ is varied to determine its effect on the migration rate. We consider $a_{\alpha} = [3.0, 3.5, 4.0, 4.5, 5.0]$ AU. $\Sigma_{\text{ice}}$ is adjusted to keep the total mass of embryos and planetesimals unchanged (equal to the fiducial case). The results are shown in Figure 3(a), and we find no significant changes in the migration rate and the masses of the innermost planets that formed.

**Density profile ($\alpha$).** The material distribution of a circumbinary disk is unclear. We consider five other kinds of density profiles: $\alpha = 0.0, 0.5, 1.0, 2.0$, and $2.5$. The results are shown in Figure 3(b). Again, there is no significant change in the migration rate and mass, which indicates that the inward migration of embryos is generally robust.

**Total mass of planetesimals.** Here we only consider two extreme cases: (1) no planetesimals in the inner region and (2) the total mass of planetesimals is double that of the fiducial case (the ice line is in the inner region). The other parameters are unchanged. We find that in the absence of planetesimals, the migration of the embryos is severely suppressed, generally with $a_{\alpha,m,f} > 3$ AU. For example, if we remove the planetesimals to the fiducial case, the SMA of innermost planet is $\sim 3.5$ AU. It shows that significant (inward) migration is caused not only by the scattering between embryos, but also by the planetesimals disk. If the mass of the planetesimals is doubled, we have $\eta = -0.76^{+0.07}_{-0.04}$, $a_{\alpha,m} = 0.90$ AU. Increasing the total mass of the planetesimals causes stronger inward migration (compared to the fiducial case). The probability of forming an HZ planet also increases (20%).

**The number of planetesimals ($N_{t}$).** In order to improve the computational efficiency, we model the planetesimals as test particles with associated mass. To validate that this is a reasonable approximation, we perform an additional two sets of runs with $N_{t} = 500$ and 1000, and the total mass of the planetesimals is unchanged. The results are $\eta = -0.74^{+0.03}_{-0.05}$ and $\eta = -0.73^{+0.08}_{-0.04}$, respectively. Obviously, using a larger number of planetesimals obtains similar results.

### 4.3. Other Systems

We explore the embryo migration in the other two binary configurations: Kepler-34(AB) and Kepler-35(AB). We use a sample formula to estimate the boundary of circumbinary HZ,

$$[\text{HZ}_{\text{in}}, \text{HZ}_{\text{out}}] = \sqrt{\frac{L_{A} + L_{B}}{L_{\odot}}} \cdot [0.95, 2.0] \text{ AU},$$



![Figure 2](image2.png)

**Figure 2.** Value of $\eta = (a_{\alpha,m,f} - a_{\alpha,m})/a_{\alpha,m}$ as a function of time, averaged over 20 runs. The median value is plotted, as well as the lower and upper quartile bounds. The inline image is a close-up view of the first 0.2 Myr.

(A color version of this figure is available in the online journal.)

![Table 2](image3.png)

**Table 2** Numerical Results of Changing the Number of Embryos

| $N_{t}$ | 200 | 150 | 100 | 50  | 25  | 1  |
|---------|-----|-----|-----|-----|-----|----|
| $M_{\text{tot}}$ (M$_{\oplus}$) | 14.72 | 9.81 | 5.87 | 2.65 | 1.27 | 0.05 |
| $\eta$ | $-0.76^{+0.15}_{-0.10}$ | $-0.75^{+0.10}_{-0.07}$ | $-0.75^{+0.05}_{-0.04}$ | $-0.62^{+0.06}_{-0.03}$ | $-0.50^{+0.07}_{-0.04}$ | $-0.06^{+0.06}_{-0.02}$ |
| $M_{\text{im}}$ (M$_{\oplus}$) | 1.06$^{+0.14}_{-0.12}$ | 1.65$^{+0.99}_{-0.65}$ | 0.98$^{+0.15}_{-0.20}$ | 0.91$^{+0.35}_{-0.07}$ | 1.14$^{+0.11}_{-0.11}$ | 0.45$^{+0.02}_{-0.10}$ |
| $a_{\alpha,m}$ (AU) | 0.93 | 0.94 | 0.95 | 1.39 | 1.57 | 3.36 |



![Figure 3](image4.png)

**Figure 3.** Variation of the final $\eta = (a_{\alpha,m,f} - a_{\alpha,m})/a_{\alpha,m}$ and the mass of the innermost embryos due to changes of the location of $a_{\alpha}$ (a) or the surface density profile $\Sigma \propto a^{-\alpha}$ (b). The median values at 1 Myr (20 runs for each point) are plotted, and the error bars are the upper and lower quartiles.

(A color version of this figure is available in the online journal.)
where \([0.95, \ 2.0]\) AU is the extended HZ of the Sun (Kasting et al. 1993; Mischna et al. 2000; Quarles et al. 2012). \(L_A + L_B\) and \(L_\odot\) are luminosities of the binary and the Sun. By including planetesimal formation and dust accretion, Paardekooper et al. (2012) find \(a_{\text{ice}} = 2.76\) AU for Kepler-34(AB) and \(a_{\text{ice}} = 2.7\) AU for Kepler-35(AB). The location of the ice line for an irradiated disk can be estimated from the scaling \(2.7 \left[ (M_A + M_B)/M_\odot \right]^2\) AU (Meschiari 2012a). We get 10 AU for Kepler-34(AB), and 7.8 AU for Kepler-35(AB), so we can ignore the material enhancement caused by the ice line in the initial distribution of embryos due to \(a_{\text{ice}} > a_{\text{2}}\). Other initial conditions are analogous to the fiducial case of Kepler-16(AB).

The results are summarized in Table 1. Again, we find that the formation of planets in the HZ is possible.

4.4. The Effects of a Pre-existing Giant Planet

Three giant planets discovered in Kepler-16(AB), Kepler-34(AB), and Kepler-35(AB) lie just outside the stability boundaries of the binaries (Meschiari 2012a). In order to check how a pre-existing planet might affect the previous migration scenario, we performed several additional simulations by initially placing a planet in orbits similar to Kepler-16b, Kepler-34b, and Kepler-35b. None of the innermost planets always remain in the HZ (with \(a_p(1 + e_p) > \text{HZ}_{\text{out}}\)). But in Kepler-34(AB), we get \(a_p(1 + e_p) = 3.AU\) in the fiducial case. We find \(a_{\text{2}} = 0.70^{+0.07}_{-0.08}\) and \(a_{\text{min}} = 1.15\) AU in the HZ of Kepler-16(AB). None of the innermost planets always remain in the HZ (with \(a_p(1 + e_p) > \text{HZ}_{\text{out}}\)). However, in Kepler-34(AB), we get \(a_{\text{2}} = 0.44^{+0.06}_{-0.03}\) and \(a_{\text{min}} = 1.57\) AU, and 75% of the innermost planets are located in the HZ. Kepler-35(AB) has about 90% of its innermost planets in the HZ. The giant planet and binary compose a three-body system, which has a new stable boundary \(a_{\text{3}}\) (larger than \(a_{\text{2}}\)), and the planetesimal disk that we used in the fiducial case is truncated by this \(a_{\text{3}}\). As a result, the embryo migration is limited by \(a_{\text{3}}\). Actually, if no giant planets are included in Kepler-34(AB) and Kepler-35(AB), some of the innermost planets migrate over the HZ, so the fraction of the innermost planets in the HZ (Table 1) is smaller than in cases with a giant planet.

5. SUMMARY

In this Letter we discuss the inward migration of the circumbinary embryos driven by the planetesimal swarm. The main results and their implications are summarized as follows. (1) Scattering-driven inward migration of embryos is robust in the circumbinary case. In the three close binary configurations that we explored, planets can form in the HZ if we adopt mass distributions of an MMSN-like disk. (2) The total mass of the planetesimals in the inner region is the main factor that affects the migration (rate). Embryo–embryo scattering is another necessary factor that causes significant migration. The migration of a single embryo is limited because its increasing mass will reduce the migration rate; ultimately, it clears the adjacent planetesimals and migration stops. While in a multiple-embryo system, embryo–embryo scattering can continually push the smaller embryo inward. (3) We propose that planet detection should focus on close binaries with HZs near \(a_{\text{2}}\). (4) Scattering-driven migration of embryos is a natural water-delivery mechanism. In a close binary like Kepler-16(AB), embryos can only form outside the snow line \((a_{\text{ice}} < a_{\text{2}})\), so the planet found in the HZ should have water contents.

We thank the anonymous referee for constructive comments and suggestions. This work is supported by the National Basic Research Program of China (973 Program 2013CB834900), NSFC (10925313, 10833001), the Fundamental Research Fund for Central Universities (1112020102), and funding from the Chinese Ministry of Education. Gong Yan-Xiang also acknowledges the support from the Shandong Provincial Natural Science Foundation, China (No. ZR2010AQ023, ZR2010AM024).

REFERENCES

Artyomowicz, P., & Lubow, S. H. 1994, ApJ, 421, 651
Bronley, B. C., & Kenyon, S. T. 2011, ApJ, 735, 29
Chambers, J. E. 1999, MNRAS, 304, 793
Cieza, L. A., Padgett, D. L., Allen, L. E., et al. 2009, ApJL, 696, 84
Doyle, L. R., Carter, J. A., Fabrycky, D. C., et al. 2011, Sci, 333, 1602
Fragner, M. M., & Nelson, R. P. 2010, A&A, 511, A77
Goldreich, P., & Tremaine, S. 1979, ApJ, 233, 857
Hayashi, C. 1981, PTIPS, 70, 35
Holman, M. J., & Wiegert, P. A. 1999, AJ, 117, 621
Ida, S., Bryden, G., Lin, D. N. C., & Tanaka, H. 2000, ApJ, 534, 428
Kasting, J. F., Whimire, D. P., & Reynolds, R. T. 1993, Icar, 101, 108
Kley, W., & Nelson, R. P. 2012, ARA&A, 50, 211
Kokubo, E., & Ida, S. 2011, ApJ, 781, 666
Kortenkamp, S. J., Wetherill, G. W., & Inaba, S. 2001, Sci, 293, 1127
Marzari, F., Picogna, G., Desidera, S., & Vanzani, V. 2012, Lunar and Planetary Institute Science Conference Abstracts (Vol. 43; Houston, TX: LPI), 1093
Marzari, F., Thebault, P., & Scholl, H. 2008, ApJ, 681, 1599
Meschiari, S. 2012a, ApJ, 752, 71
Meschiari, S. 2012b, ApJ, 761, 7
Mischna, M. A., Kasting, J. F., Pavlov, A., & Freedman, R. 2000, Icar, 145, 546
Moriwaki, K., & Nakagawa, Y. 2004, ApJ, 609, 1065
Ormel, C. W., Ida, S., & Tanaka, H. 2012, ApJ, 758, 80
Orosz, J. A., Welsh, W. F., Carter, J. A., et al. 2012a, ApJ, 758, 87
Orosz, J. A., Welsh, W. F., Carter, J. A., et al. 2012b, Sci, 337, 1511
Paardekooper, S.-J., Leinhardt, Z. M., Thebault, P., & Baruteau, C. 2012, ApJL, 754, 16
Payne, M. J., Wyatt, M. C., & Thebault, P. 2009, MNRAS, 400, 1936
Pierens, A., & Nelson, R. P. 2007, A&A, 472, 993
Pierens, A., & Nelson, R. P. 2008, A&A, 478, 939
Quarles, B., Musielak, Z. E., & Cuntz, M. 2012, ApJ, 750, 14
Quintana, E. V., & Lissauer, J. J. 2006, Icar, 185, 1
Scholl, H., Marzari, F., & Thebault, P. 2007, MNRAS, 380, 1119
Thébault, P., Marzari, F., & Scholl, H. 2006, Icar, 183, 193
Ward, W. R. 1997, Icar, 126, 261
Walsh, K. J., Morbidelli, A., Raymond, S. N., et al. 2012, Natur, 475, 206
Welsh, W. F., Orosz, J. A., Carter, J. A., et al. 2012, Natur, 481, 475

Gong, Zhou, & Xie