Formation, Detection, and Characterization of Extrasolar Habitable Planets
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Formation of Habitable Planets in Inclined Planetary Systems

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Abstract. We extensively investigate the terrestrial planetary formation for the inclined planetary systems (considering the OGLE-2006-BLG-109L system as example) in the late stage. In the simulations, we show that the occurrence of terrestrial planets appears to be common in the final assembly stage. Moreover, we find that a lot of runs finally occupy at least one planet in the habitable zone (HZ). On the other hand, the numerical results also indicate that the inner region of the planetesimal disk, ranging from ~ 0.1 to 0.3 AU, plays an important role in building up terrestrial planets. The outcomes suggest that it may exist moderate possibility for the inclined systems to harbor terrestrial planets in the HZ.

Keywords. planets and satellites: formation - star: individual: OGLE-2006-BLG-109L

1. Introduction

To date, over 800 exoplanets have been discovered (http://exoplanet.eu), which is indicative of a diversity and complexity of planetary systems. Observations show that there are many of close-in planets orbiting the host stars, i.e., so-called hot Jupiters, hot Neptunes and Super-Earths. However, there still exists one category of exoplanetary systems which is featured by highly-inclined configuration, rather than a planar disk perpendicular to the stellar spin axis (McArthur *et al.* 2010 and Narita *et al.* 2008). Chatterjee *et al.* (2008) and Barnes *et al.* (2010) show that planet-planet scattering could be a plausible mechanism to explain the observed highly-inclined orbits.

Planetary formation in such highly-inclined systems would be very interesting, and the investigations may play a significant role in fully understanding complicated building scenarios for the planetary systems. We have performed an extensive series of simulations to explore the late-stage planetary formation for inclined systems. In these simulations, the initial conditions were set to emulate an environment of the early chaotic phase for terrestrial planet formation, where Moon-sized planetesimals and Mars-sized planetary embryos were distributed in the disk in company with two non-coplanar giant planets (say the OGLE-2006-109Lb,c analogues). All the simulation runs were carried out using a hybrid symplectic algorithm by the MERCURY package (Chambers (1999)).

2. Result

From the results, we show that it is quite common to form terrestrial planets, as shown in Fig. 1, where potential habitable planets, residing from 0.25 to 0.36 AU, are supposed to be in the HZ for the system. For example, in those runs that the outer giant planet

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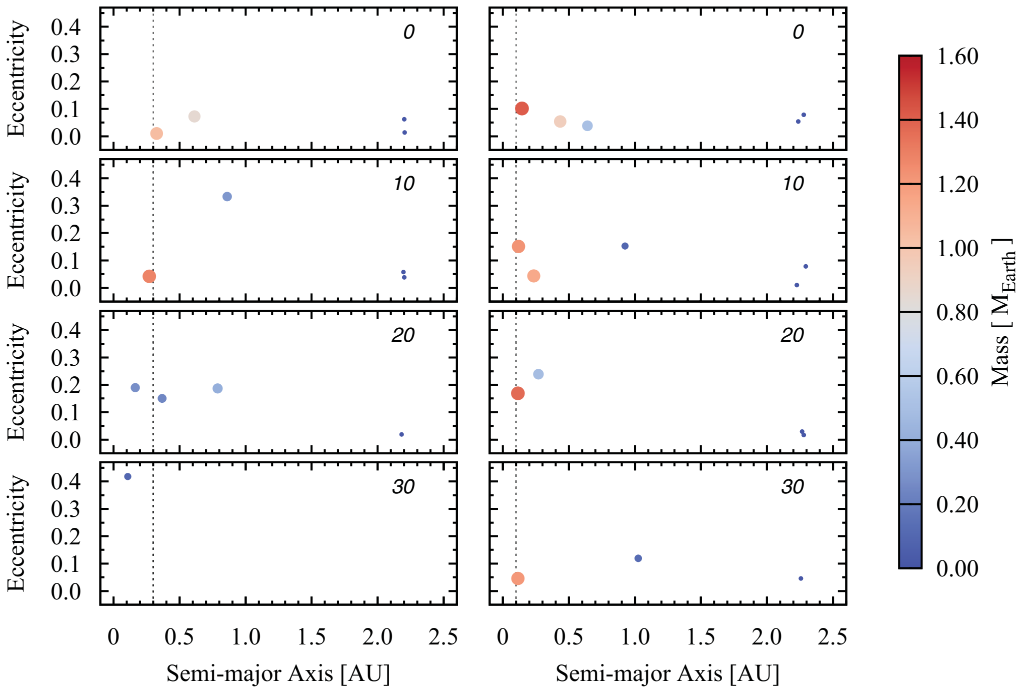

Figure 1. Final configurations of one simulation group

has a lower inclination $i \leqslant 10°$, 16 of the total 22 runs have formed a terrestrial planet in the HZ. The outcomes imply that it would be likely for the inclined systems to have terrestrial planets in the HZ.

2.1. *Influence of the Planetesimal Distribution*

Fig. 1 shows the final configurations of two simulation groups that have various initial planetesimal distributions. The initial orbits of the planetesimals of the left panels are larger than 0.3 AU as shown by the vertical dotted lines, while those of the right panels bear the starting orbits beyond 0.1 AU. In each panel, the eccentricity versus semi-major axis is shown for the surviving bodies at the end of each run. The radii and colors of each object are related to planetary masses, with radius $\propto m^{1/3}$. The inclination of the outer giant planet is labeled at the top right corner.

For each row of Fig. 1, the right panel has more survived bodies or larger planets formed. The inner part of the disk have a great advantage in producing terrestrial planets, because of the relatively higher density of the planetesimal population and the more intense influence of the central star that may make them more difficult to be thrown out by the giant planets.

2.2. *Influence of the Inclined Giant Planet*

Fig. 1 also shows the trend that the masses of formed planets decrease along with the increasing inclination of the outer giant planet. This is because that a highly inclined giant planet may play a more efficient part in stirring the planetesimals, either by ejecting them out of the system or by inducing them to collide with the host star. Consequently, there are only a few planetesimals remaining in the planetary disk, leading to the difficulty of producing terrestrial planets. Fig. 2 shows the final locations of all planetesimals - **Hit the giants**, **Ejected**, or **Hit the star**, however the latter two cases actually made no

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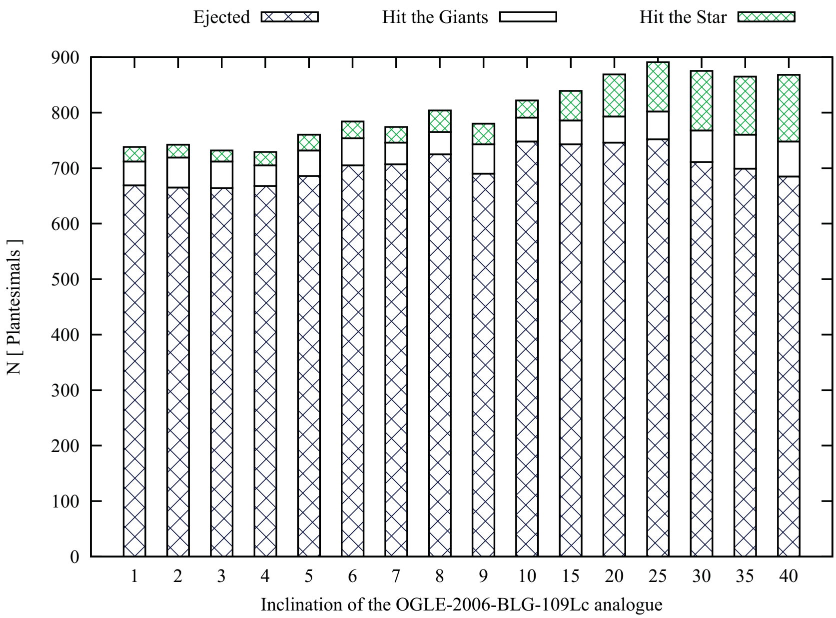

Figure 2. Destination of planetesimals in one simulation group

contribution to the growth of mass for terrestrial planets in the planetary formation (Jin & Ji (2011)) based on the results of one simulation group.

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References

Barnes R., Greenberg R., Quinn T. R., *et al.* 2010, *ApJ*, 726, 71
Chambers J. E. 1999, *MNRAS*, 304, 793
Chatterjee S., Ford E. B., Matsumura S., & Rasio F. A. 2008, r *ApJ*, 686, 580
Jin, S. & Ji, J. 2011, *MNRAS*, 418, 1335
McArthur B., Benedict G. F., Barnes R., *et al.* 2010, *ApJ*, 715, 1203
Narita N., Sato B., Ohshima O., & Winn J. N. 2008, *PASJ*, 60, L1

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