Implications of the TTV-detection of close-in terrestrial planets around M stars for their origin and dynamical evolution

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Abstract.   It has been shown that an Earth-size planet or a super-Earth, in resonance with a transiting Jupiter-like body around an M star, can create detectable TTV signals (Kirste & Haghighipour, 2011). Given the low masses of M stars and their circumstellar disks, it is expected that the transiting giant planet to have formed at large distances and migrated to its close-in orbit. That implies, the terrestrial planet has to form during the migration of the giant planet, be captured in resonances, and migrate with the giant body to short-period orbits. To determine the possibility of this scenario, we have studied the dynamics of a disk of protoplanetary embryos and the formation of terrestrial planets during the migration of a Jupiter-like planet around an M star. Results suggest that unless the terrestrial planet was also formed at large distances and carried to its close-in resonant orbit by the giant planet, it is unlikely for this object to form in small orbits. We present the details of our simulations and discuss the implication of the results for the origin of the terrestrial planet.

1. Introduction

In searching for potentially habitable planets, M stars present the most promising targets. Because of their small masses, these stars have the greatest reflex acceleration due to an orbiting planet. The low surface temperatures of these stars place their (liquid water) habitable zones at distances of approximately 0.1 to 0.2 AU (corresponding to orbital periods of $\sim$ 20 to 50 days) where the precision radial velocity surveys are normally at their optimal sensitivity. Given that within the Sun's immediate neighborhood, more 70% of stars are of spectral type M, it is not surprising that for more than a decade, these stars have been the subject of research by many authors (Joshi et al. 1997; Segura et al. 2005; Boss 2006; Scalo et al. 2007; Grenfell et al. 2007; Tarter et al. 2007).

In the past few years, such research has resulted in the detection of 25 extrasolar planets around 17 M stars. Slightly more than half of these planets are Neptune-mass or smaller, consistent with the fact that M stars have smaller circumstellar disks and their planets are less massive compared to those of G stars. Among these planets are the first Neptune-mass object around the star GJ 436 (Butler et al. 2004), the first Earth-size planet around the star GJ 876 (Rivera et al. 2005), and the recently discovered Earth-like planet in the habitable zone of the star GL 581 (Vogt et al. 2010).

Although majority of currently known planets around M stars have been detected using the radial velocity technique, these stars have also been targets of transit photometry searches. The MEarth project, a robotically controlled set of eight 40 cm telescopes at Whipple observatory on Mt. Hopkins in Arizona, is a transit photometry survey that is dedicated to detecting M stars. This program has been successful in discovering a 6.6 Earth-mass planet around M star GJ 1214 (Charbonneau et al. 2009).

The transit timing variation method has also been considered as a mechanism for detecting small planets around M stars. As shown by Kirste & Haghighipour (2009, 2011), the variations in the transit timing of a transiting giant planet due to the perturbation of an Earth-size body or a super-Earth can be large enough to match the temporal sensitivity of *Kepler* space telescope. Figures 1 and 2 show samples of the results by these authors. As shown in figure 1, an Earth-size planet in a 10-day orbit around a 0.32 solar-mass star produces strong TTVs on a transiting Jupiter-mass planet when the two objects are in (1:2), (2:3), (5:2), and (2:1) mean-motion resonances. Figure 2 shows the mean-motion resonances for which an Earth-like planet in the habitable zone of an M star will produce TTVs of the order of 10 s or larger on a transiting Jupiter-like body.
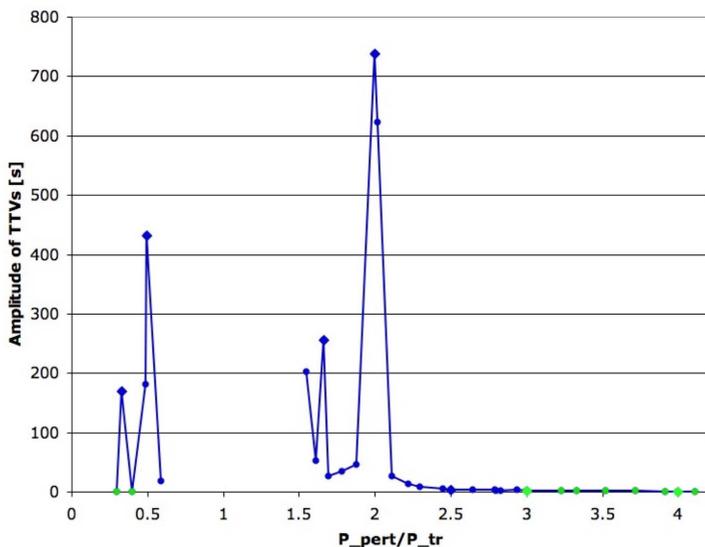

Figure 1.: *Transit timing variations of a 1 Jupiter-mass planet around a 0.32 solar-mass M star. The perturber is an Earth-sized planet in a 10-day orbit. The graph shows the values of TTVs for different ratios of the orbital periods of the two planets. As shown here, when the two planets are in (1:2), (2:1), (5:3), and (2:3) resonances, the TTVs have values larger than 100 sec. Figure from Kirste & Haghighipour (2011).*

Although the calculations by Kirste & Haghighipour (2009, 2011) point to the detectability of terrestrial planets in systems studied by these authors, the low masses of circumstellar disks around M stars cast doubt in the existence of their assumed planetary configurations. Computational simulations have indicated that circumstellar disk around M stars are not massive enough to accommodate the formation of giant

planets, even in orbits as large as that of Jupiter around the Sun (Laughlin et al. 2004). The fact that observational surveys have been able to detected many Jovian-type planets around M dwarfs [e.g. GJ 876 with two Jupiter-like planets and a Uranus-mass body in approximately 30, 60, and 120 days orbits (Rivera et al. 2005, 2010), or HIP 57050 with a Saturn-mass planet in a 42 days orbit (Haghighipour et al. 2010)] suggests that these giant planets were probably formed at larger distances, where the disk contained more material, and migrated to their current short-period orbits. It would therefore be necessary to study how such a migration affects the formation of terrestrial planets around M stars and their final orbital configuration as the giant planet approaches short-period orbits.
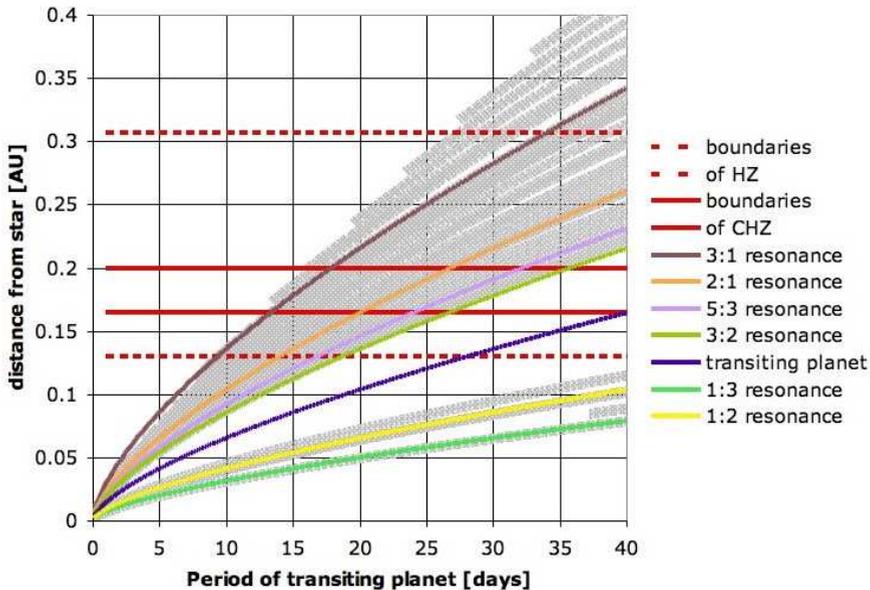

Figure 2.: *Graph of transit timing variation for different resonances between an Earth--size perturber and a Jupiter-mass transiting planet. The central star is a 0.36 Solar–mass M star. The habitable zone (HZ) and continuous habitable zone (CHZ) of the star are shown. The shaded area corresponds to TTVs larger than 10 sec. A shown here, (1:3), (1:2), and (3:5) resonances produce large TTVs when the perturber is in the continuous habitable zone.*

2. Giant Planet Migration and the Accretion of Embryos

Terrestrial planet formation in the presence of a migrating giant planet has been studied by many authors. Examples can be found in the works of Zhou et al. (2005), Fog & Nelson (2005, 2007a&b, 2009), Raymond et al. (2006), Mandell et al. (2007), and Kennedy & Kenyon (2008). As shown by these authors, a migrating giant planet may capture protoplanetary objects in mean-motion resonances and increase their orbital eccentricities to high values. The latter prevents the accretion of these bodies to larger sizes by either scattering them to outer distances, or increasing their impact velocities to values beyond their fragmentation limits.

If during the migration of the giant planet, substantial amount of gas still exists, the combination of gas drag and dynamical friction may prevent the eccentricities of planetary embryos to reach high values and may facilitate their growth to larger objects. Simulations by these authors have shown that, an Earth-size planet can form around a Sun-like star while a Jupiter-mass body migrates through the disk of planetary embryos and the system is subject to gas drag. At times, the final terrestrial planet was even captured in a mean-motion resonance with the giant body and migrated to close-in orbits (Zhou et al. 2005).

In order to assess the possibility of the existence of planetary systems studied by Kirste & Haghighipour (2009, 2011), similar simulations have to be carried out for a migrating giant planet and a protoplanetary disk around an M stars. We note that in the above-mentioned simulations, the migration of the giant planet was stopped before it reached to very short-period (e.g., 3-day or 4-day) orbits. Such a termination of the migration was necessary to ensure that the terrestrial planets would in fact form, and would not be scattered out or crash into the central star. In the system studied by Kirste & Haghighipour (2009, 2011), the giant planet revolves around the central star in 3-5 day orbits. That suggests, in order to examine the viability of the scenario presented by these authors, simulations of terrestrial planet formation have to be carried out for a migrating giant planet in a disk of planetary embryos while allowing the giant planet to migrate to very close-in orbits.

3. Numerical Simulations and the Results

To simulated the formation of terrestrial planets during the migration of a Jupiter-like body around an M star, we considered a model consisting of a star, a protoplanetary disk, and a Jupiter-size planet. We assumed the central star to be similar to GJ 876 and have a mass of 0.32 solar-masses. The protoplanetary disk was considered to be of two types. Once, similar to Zhou et al. (2005), we randomly distributed 30 planetary embryos, with masses ranging from 0.1 to 0.5 Earth-masses, in a region between 0.05 AU (Terquem & Papaloizou 2007) and 0.5 AU. The mutual separations of embryos were chosen to be no smaller than 10 Hill's radii. Their eccentricities and inclinations were set to 0.001 and 0.001 deg, respectively. In the second model, we changed the number of protoplanets to 40 and distributed them randomly between 0.1 AU and 0.8 AU. The outer edge of the disk in this model was chosen to be equal to 2.7 times the mass of the central star as suggested by Kennedy & Kenyon (2008). In both disk models, the disk surface density followed an $r^{-1.5}$ profile.

We integrated the motions of planetary embryos using the N-body integrator MER-CURY (Chambers 1999). We modified MERCURY to include planet migration (Lee & Peale 2002), gas drag (Raymond et al. 2006), tidal force (Mardeling & Lin 2002, 2004), eccentricity damping (Lee & Peale 2002), and general relativity (Saha & Tremaine 1992). Integration were carried out for both disk models and for different values of the rate of the migration of the giant planet. We assumed that the giant planet was initially at 1 AU and radially migrated with rates of 10^{-5}, 10^{-6}, and 10^{-7} AU/years. Figure 3 shows the results of one of such simulations. The protoplanetary disk in this simulation is of the second type and the rate of migration is 10^{-7} AU/year. As shown here, during the migration of the giant planet, planetary embryos collid ancollided form bigger objects. Collisions were considered to be perfectly inelastic and result in the prefect accretion of both bodies. The interaction between embryos and the giant planet caused many of these objects to be captured in resonance. However, the latter increased the orbital eccentricities of these bodies which eventually resulted in their
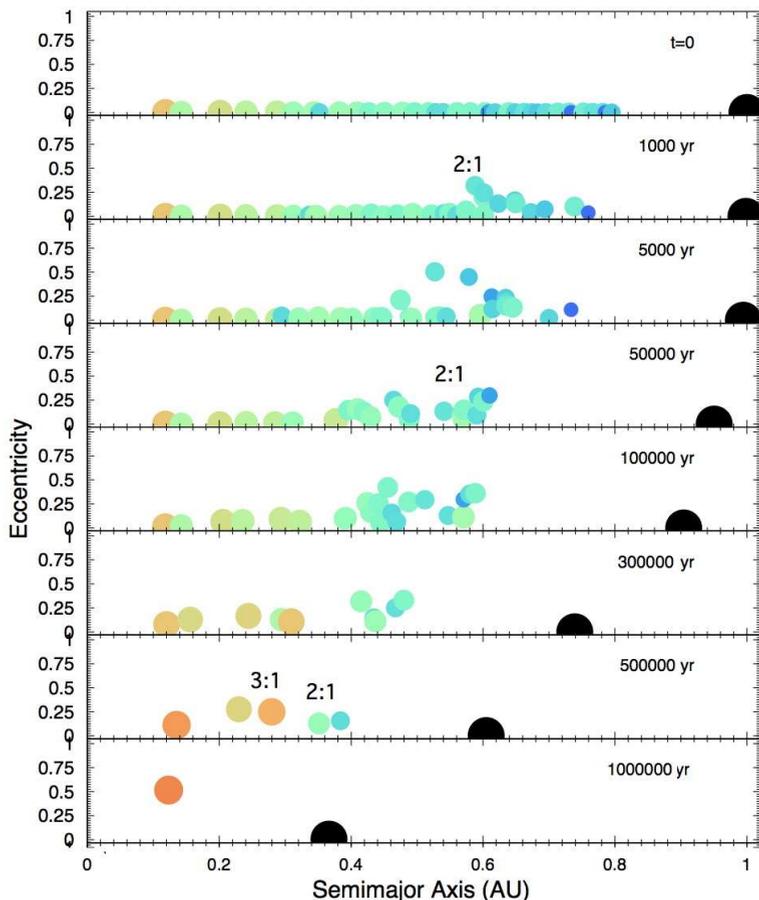
Figure 3.: *Terrestrial planet formation and resonance capture during the migration of a giant planet (black circle). The disk consists of 40 protoplanets with masses of 0.1 to 0.5 Earth-masses. The continuation of the simulation shows that no terrestrial planet survives when the giant planet reaches the 3-day orbit.*

scattering to large distance. We stopped the simulation when the giant planet reached the 3-day orbit. All our simulations showed that no terrestrial planet survived when the giant planet reached short-period orbits.

4. Conclusions

Simulations results indicate that although for both disks models and all migration rates, terrestrial planets were formed in the protoplanetary disk, they did not maintain stability and were ejected from the system. The time of the ejection is inversely proportional to the rate of giant planet migration. Our study suggests that if a terrestrial planet is detected in resonance with a transiting giant planet around an M star, 1) the terrestrial planet is unlikely to have formed in-situ, 2) formation at far distances followed by resonance capture and migration while in resonance seems to be more viable, 3) the

capture probability varies with the migration rate which itself depends on the mass of the protoplanetary disk. The latter suggests that slow migration rates and small proto-planetary disks may in fact facilitate the formation and subsequent resonance capture of a terrestrial planet with a close-in giant planet around M stars.

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