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Secular Resonances and Terrestrial Planet Formation in Planetary Systems with Multiple Stars

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Abstract. We present the results of a study of secular resonances in a binary star system and their effects on the formation of terrestrial planets. The systems of our interest are binaries with moderate separations (i.e., smaller than 40 AU) where planets revolve around one of the stars. Using numerical simulations, we demonstrate the appearance and evolution of secular resonances in systems with two giant planets. Results indicate that the perturbation of the binary companion suppresses secular resonances and they do not play a significant role on the formation and orbital architecture of terrestrial planets. Unlike in our solar system where the secular resonance of Saturn confines the formation of terrestrial planets to regions interior to its location, in a binary star, terrestrial planets can form interior and exterior to this resonance. We present details of our simulations and discuss the implications of their results.

Keywords. Secular resonances, Binary systems, Terrestrial planet formation

1. Introduction

The mean-motion and secular resonances of giant planets, especially Jupiter and Saturn, have played crucial roles in the formation, dynamical evolution, and orbital architecture of the inner solar system. While the mean-motion resonances of Jupiter have created the Kirkwood gaps, the secular resonance of Saturn has confined the eccentricities and inclinations of asteroids, and has created an inner edge for the asteroid belt (Milani & Knežević 1992, 1994). Collectively, these resonances are the reason that no planet exists between Jupiter and Mars, and instead, the solar system has an asteroid belt.

In addition to the post-formation evolution of the inner solar systems, secular resonances affect the formation of the terrestrial planets as well (Levison & Agnor 2003; Haghighipour & Winter 2016). In a comprehensive study, Haghighipour & Winter (2016) examined the appearance and intensity of the secular resonances of Jupiter and Saturn for different distribution of protoplanetary bodies and different orbital eccentricities of Jupiter and Saturn. These authors demonstrated that while the intensities of the secular resonances stay unaffected by the surface density of the protoplanetary disk and the orbital eccentricities of Jupiter and Saturn, the mass, orbital assembly and water contents of the final terrestrial planets are strongly influenced by the two secular resonances.

The discovery of circumstellar giant planets in binary stars with separations smaller than 40 AU motivated us to extend the above studies to these systems as well. We, therefore, simulated terrestrial planet formation in binary systems with two circumstellar giant planets and used the general theory recently developed by Haghighipour (2023) to determine the locations of their secular resonances. Our goal was to determine how these secular resonances affect the formation of terrestrial planets around the planet-hosting star, and how the results would compare with those in single-star systems. We studied the dynamical evolution of these resonances and investigate their effects on the formation of the final system.

1.1. *The Model and Initial Set up*

We considered a four-body system consisting of the planet-hosting star (primary), two giant planets, and the secondary star. The semimajor axis of the binary was taken from a range of 20 AU to 40 AU, and its eccentricity was varied between 0 and 0.5. The planet-hosting star was considered to be solar-mass and the mass of the secondary star was taken to be between 0.4 and 1.3 times the mass of the Sun. The inner and outer planets were taken to be Jupiter- and Saturn-mass with semimajor axes of 1.6 AU and 2.94 AU, respectively. These semimajor axes were chosen to ensure that for all choices of the orbital parameters of the binary and the mass of the secondary star, the two giant planets would always stay within the stable zone around the primary. They also resemble the near 5:2 communicability between Jupiter and Saturn in our solar system. All other orbital parameters of the two planets were taken to be equal to those of Jupiter and Saturn. We also distributed 120 moon- to Mars-mass planetary embryos and 2000 planetesimals from 0.5 AU to 4.5 AU. The surface density of the disk was taken to follow an $r^{-1.5}$ radial profile. The choice of the radial extent of the disk was made to ensure the truncation effect of the secondary star.

1.2. *Numerical Simulations and Results*

We integrated our systems for 100 Myr using a version of the N-body integration package MERCURY that has been designed to integrate circumstellar bodies in binary star systems (Chambers et al. 2002). The appearance of both mean-motion and secular resonances can be seen in all simulations. Figure 1 shows two examples of the results. The binary separation in both systems is 40 AU. The secondary star in the left panel is a 0.4 solar-mass M star and in the right panel, it is a 1.3 solar-mass F star. The two top panels show the initial locations of the secular resonances of the inner and outer planets (g_1 and g_2, respectively) based on the general theory of Haghighipour (2023). The two bottom panels show the evolution of the protoplanetary disk for the first 0.5 Myr of integrations. They also show the appearance of the mean-motion resonances of the inner planet (dashed lines) and the secular resonance of the outer planet (g_2). As shown here, the secular resonance of the outer planet appears very close to its theoretical value. A comparison with the simulations of disk evolution in Haghighipour & Winter (2016) demonstrates that the secular resonance of the outer planet has been severely suppressed (see also figure 2). We note that in the above two cases, the location of the secular resonance of the inner planet falls interior to the inner edge of the disk. As a result, this resonance does not appear in the simulations. However, we do expect this resonance to have been suppressed too.

Figure 2 shows another important characteristic of secular resonances, namely, their inward migration. As demonstrated by Ward (1981), in a system with giant planets, when a small object such as a planetesimal or planetary embryo is embedded in a massive disk, the response of the disk to the perturbation of the giant planets acts as another

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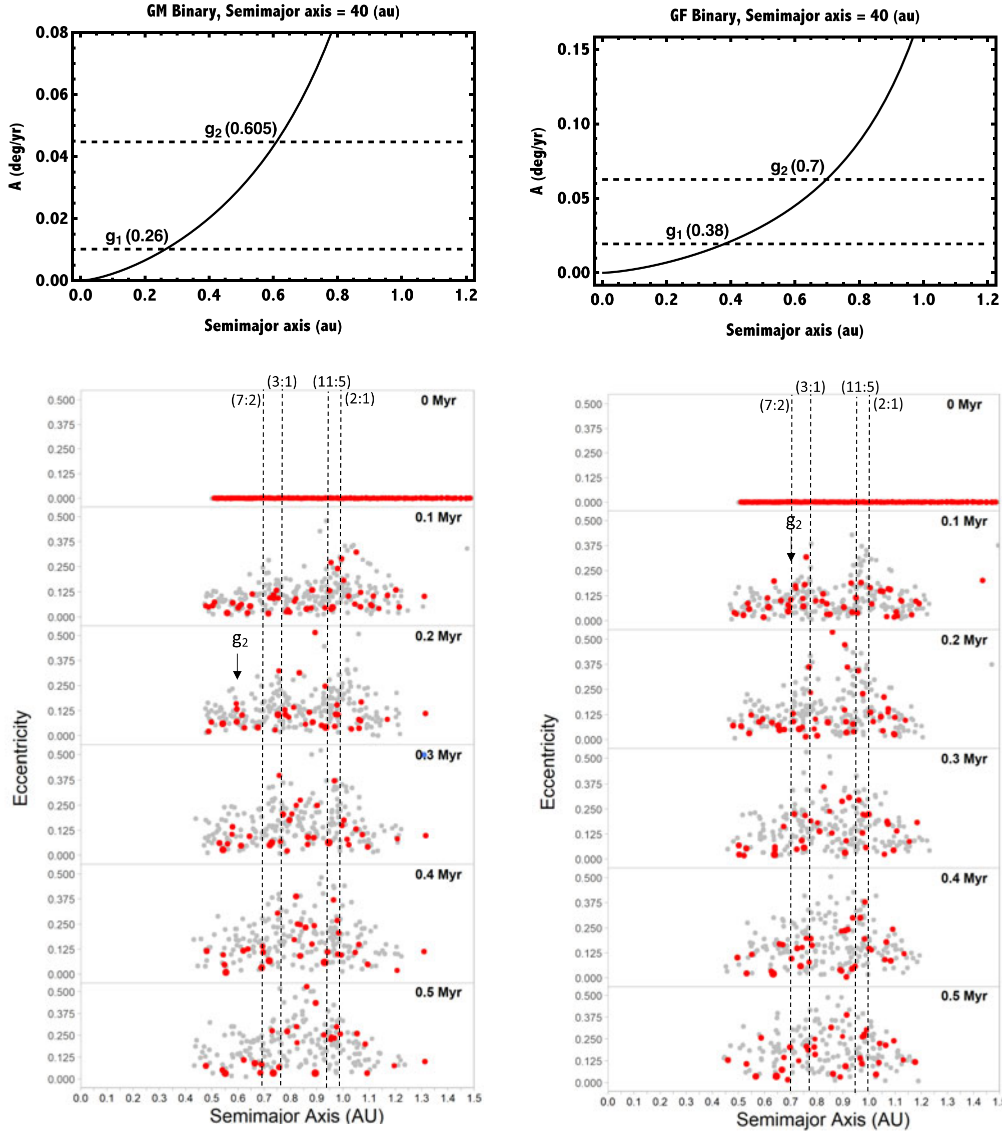

Figure 1. Location of the secular resonance of the inner planet (g_1) and the outer planet (g_2) in a GM (left) and a GF binary with a separation of 40 AU. The top panels show the theoretical locations of these resonances obtained from the general theory of planetary secular resonances in multiple star system (Haghighipour 2023). The solid line shows the variation of the rate of the precession of the longitude of perihelion (A) of a small body with semimajor axes. The dashed lines correspond the the same quantity for the inner and outer planets shown by indeces 1 and 2, respectively. The bottom panels show the appearance of secular resonances during the evolution of the protoplanetary disk interior to the inner giant planet. The planet-hosting star (primary) is at the origin. The secondary star and the two giant planets are not shown. The red circles represent planetary embryos and the gray dots are the background planetesimals. The dashed lines in the bottom panels correspond to the locations of mean-motion resonances with the inner planet.

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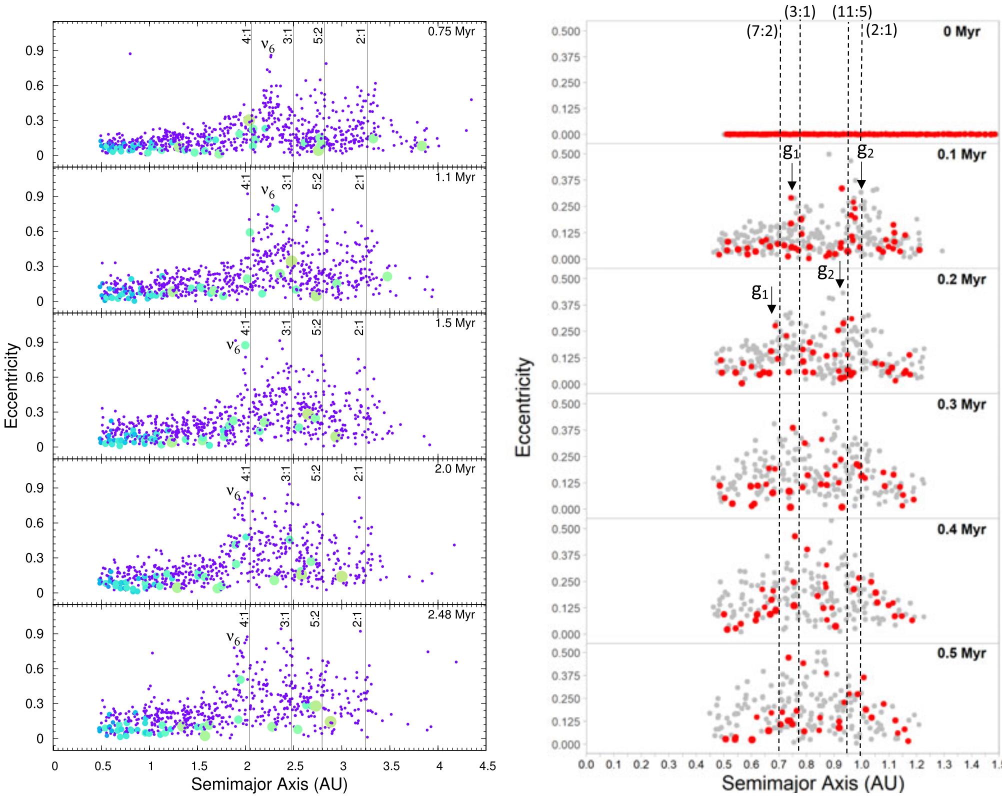

Figure 2. The inward displacement of secular resonances. The panel on the left (from figure 9 of Haghighipour & Winter 2016) shows the inward displacement of the secular resonance of Saturn (ν_6) in our solar system. The circles in cyan and light green represent planetary embryos and purple dots are the background planetesimals. The panel on the right shows the inward motion of the secular resonances of the inner planet (g_1) and outer planet (g_2) in a 20 AU GG binary in our simulations. Color coding in this panel is similar to that in figure 1.

perturbation that affects the precession of the orbit of the small body. This author showed that as the disk loses mass due to the effect of secular resonances, its response weakens which causes the locations of these resonances to vary in time. Levison & Agnor (2003) noticed that in their simulations of the formation of terrestrial planets in our solar system, when the disk is considerably massive, the locations of the secular resonances of Jupiter and Saturn move outward. Haghighipour & Winter (2016) showed that as the perturbation of these planets causes the disk to lose mass in its outer regions, the outward migration of secular resonances stop. These authors also showed that the growing embryos in the disk's inner regions create their own perturbing effects which causes smaller embryos in their vicinity to be captured in temporary secular resonances with these growing bodies. As the latter raises the eccentricity of smaller objects to higher values causing them to be scattered out of their orbits, the transfer of angular momentum to the bodies in the inner regions where the disk maintains more mass, causes the secular resonances to naturally move toward these regions. The left panel in figure 2 shows this for the secular resonance of Saturn in our solar system (shown by ν_6, Haghighipour & Winter 2016). As shown here, Saturn's secular resonance moves inward sweeping the region between 2.4 AU and 1.9 AU. The right panel of figure 2 shows the inward migration of the secular resonance of the outer planet for a 20 AU binary with two solar-mass stars. As shown here, within 100,000 years, g_2 moves slightly inward. Because in our

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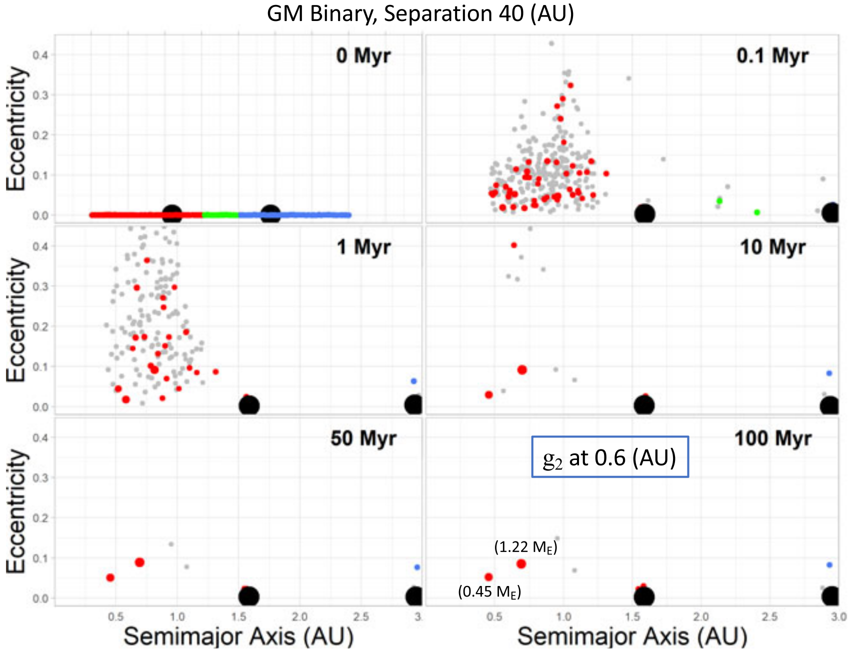

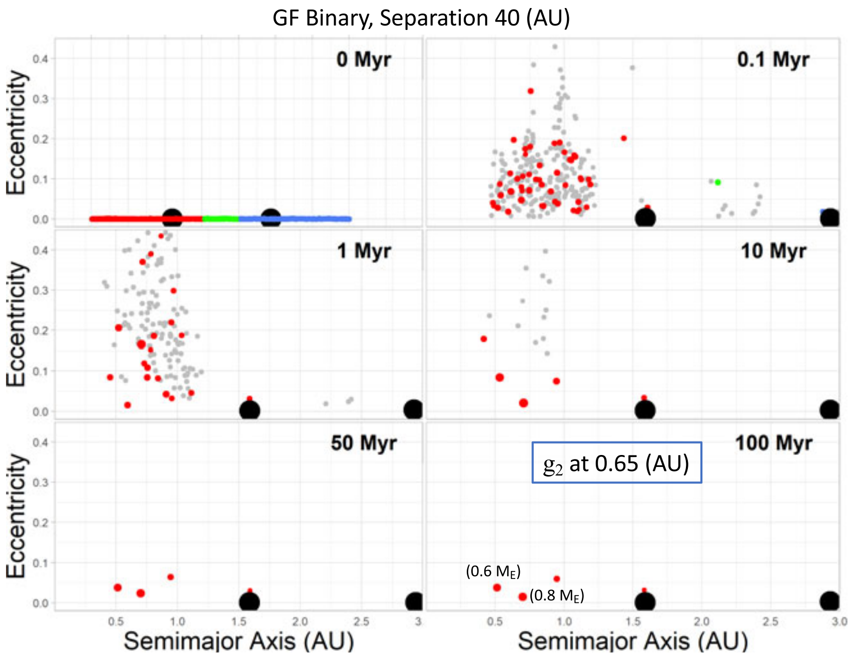

Figure 3. Snapshots of the formation of terrestrial planets interior to the inner planet in a GM (left) and a GF binary (right) with a separation of 40 AU. To show both planets at the start of the simulations, we have used smaller scales in the two $t = 0$ panels. In these two pnels, each scale on the semimajor axis corresponds to 0.25 AU. The planetary embryos are distributed between 0.5 AU and 4 AU with the color coding representing their water-mass ratio. Red corresponds to dry embryos, light green corresponds to embryos with 1% water content, and blue corresponds to embryos with 5% water-mass ratio. The last panel at 100 Myr shows the masses of the final terrestrial planets and the final location of the secular resonance of the outer giant body (g_2). As shown here, the final planets carry no water and unlike in our solar system, terrestrial planets can form interior and exterior to the location of g_2.

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binary systems, secular resonances are weaker than those in our solar system, the inward migration of g_2 does not result in as sever of a mass-loss as that caused by the secular resonance of Saturn. In fact, in our binaries, most of the mass-loss is due to the mean-motion resonance of the inner planet. For that reason, the rate and amount of the inward migration of the secular resonance of the outer planet is substantially small.

The fact that the secular resonance of the outer planet is not strong enough to scatter many objects out of the disk has an immediate implication for the formation of small planets interior to the inner giant planets. Unlike in our solar system where the secular resonance of Saturn confines the formation of terrestrial planet to inside 2.1 AU, in our binary systems, small planets can form both inside and outside the final location of the outer planet's secular resonance. Figure 3 shows the latter for the two systems of figure 1. In the top panel, corresponding to a 40 AU GM binary, the last location of the outer planet's secular resonance is at 0.6 AU. As show here, at the end of the simulations, a planet with a mass of 1.22 Earth-masses is formed at 0.7 AU. The bottom panel shows the situation for a 40 AU GF binary. In this system, the final location of the outer planet's secular resonance is at 0.65 AU while two planets with masses of 0.6 and 0.8 Earth-masses have formed at 0.51 AU and 0.7 AU, respectively.

2. Summary and Concluding Remarks

We have studied the occurrence of secular resonances and their effects on the formation of terrestrial planets around one star of a moderately closed binary. We considered a four-body system consisting of the primary star, two giant planets and the secondary star, and simulated the formation of terrestrial planets interior to the inner planet. Results demonstrated the appearance of secular resonances in very close proximity to their theoretical locations, and also showed that

• Unlike in single star systems where the secular resonances of giant planets are strong and play an important role in shaping the dynamical architecture of system, in binary stars, these resonances are severely suppressed. The perturbation of the secondary star in these systems weakens the strength and effect of secular resonances. For instance, our simulations demonstrated that the secular resonance of the outer planet was hardly able to increase the eccentricities of planetesimals and planetary embryos to values larger than 0.5, whereas in our solar system, the secular resonance of Saturn has had significant effect on depleting the inner part of the asteroid belt;

• Similar to the resonances in the solar system, secular resonances take longer to appear than mean-motion resonances. As a result, in binary star systems, mean-motion resonances of giant planets play a more effective role in removing material from interior regions;

• The above two results imply that unlike in our solar system where the secular resonance of Saturn confined the formation of terrestrial planets to the region interior to 2.1 AU, the weak nature of these resonances in binary star systems does not have significant effects on the formation of planets interior to their locations allowing terrestrial-class planets to form inside and outside the location of secular resonances.

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