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Formation of S-type planets in close binaries: tidal capture of circumbinary planets

Jianghui Ji[1] **and Yan-Xiang Gong**[1,2]

[1]CAS Key Laboratory of Planetary Sciences, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China
email: jijh@pmo.ac.cn

[2]College of Physics and Electronic Engineering, Taishan University, Taian 271000, China
email: yxgong@pmo.ac.cn

Abstract. In this work, we proposed a possible mechanism for the formation S-type planet in close binaries (0.5 au $< a_B <$ 3 au). Numerical simulations showed that the maximum capture probability is $\sim 10\%$, which can be comparable to the tidal capture probability of hot Jupiters in single star systems. The capture probability is related to binary configurations. Furthermore, we find that S-type planets with retrograde orbits can be naturally produced via capture process. These planets on retrograde orbits can help us distinguish in situ formation and post-capture origin for S-type planet in close binaries. The forthcoming missions (PLATO or TESS) will provide the opportunity and feasibility to detect such planets.

Keywords. binaries (including multiple): close, planetary systems: formation, methods: n-body simulations.

1. Introduction

As of today, about 130 exoplanets were found in the binary star system. Over 100 of them are S-type planets, and others are P-type planets. S-type planets have not yet been found in the binaries with an orbital period P $<$ 1000 days. The space missions, e.g., PLATO or TESS, will offer the opportunity to discover them. However, according to the classical theories of planetary formation, in situ formation of S-type planets in close binaries is very challenging. Compared with the difficulty in formation of S-type planets in close binaries, it is comparatively easy to yield P-type planets around them. Observations provide evidence that P-type planets around close binaries would be common in the universe (Armstrong *et al.* 2014). Here we aim to explore the formation of S-type planets in close binaries by considering the scenario of scattering of P-type planets and tidal interactions from stars, thereby turning P-type orbit into S-type orbit. Convergent migration of two adjacent circumbinary planets in a multi-planet system will cause planetary scattering (Pierens & Nelson (2008), Kley & Haghighipour (2015)).

2. Tidal capture scenario

From the point of view of CRTBP, there exists a Jacobi constant satisfying the condition $C_J > C_J(L_2)$ for orbits to remain stable. It is impossible for the planet to penetrate the forbidden area around the binary and approach either of the stars. However, in a multiple CBP system, C_J of a planet is not perfectly conserved when one considers the gravitational perturbations of the other planets. Especially the change of C_J is significant during close encounters with other planets. Planet-planet scattering can bring about a sudden decrease in C_J, to make $C_J < C_J(L_2)$. When this condition is satisfied, the planet

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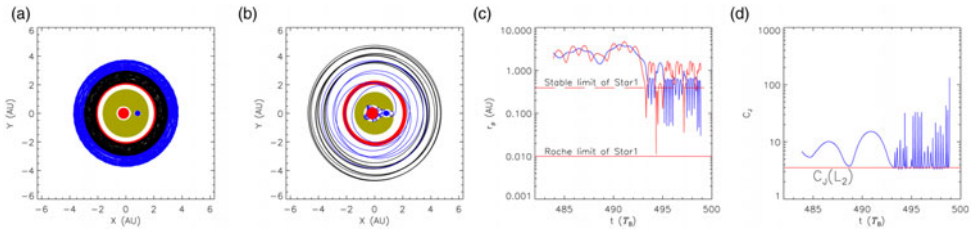

Figure 1. An example of scattering induced tidal capture of circumbinary planet. (a) Two circumbinary planets are modeled as test particles. The thick red line is the unstable boundary outside the binary. The brown regime is the zero velocity surface of $C_J = 4$ for reference. (b) The two planets have identical initial conditions as in Panel (a), but the scattering between two planets has been considered. (c) Red line is time varying distance between the captured planet and the secondary. The blue line shows the distance of the same planet from the primary. (d) The Panel shows the Jacobi constant of the captured planet varies with time.

can approach either of the binary. If the planet is scattered far enough away from the other planets, then its C_J might maintain a value on appreciable time-scales. Again, the motion of the scattered planet can be dictated by the CRTBP as long as the perturbations from the other planets are negligible. If we do not consider other dissipations such as tides, the scattering lead to a *temporary capture*. In most cases planets will be scattered out of the system or collide with two stars. However, tidal interaction from the star becomes more important when the periastron of the planet is very close to either of binary. Therefore, tidal effects between the planet and the star will further diminish the orbital energy of the planet, thereby producing $C_J > C_J(L_2)$ again. Under such circumstance, a *permanent capture* of the planet can form. Figure 1 shows an example of this scenario using an artificial two-planet system.

3. Conclusions

We study the scattering scenario of 3 circumbinary planets in the systems (see Gong & Ji (2018)). The major conclusions are summarized as follows: The scattering induced tidal capture mechanism can turn a P-type orbit into an S-type orbit. S-type planets in close binaries with SMA of $0.5 - 3$ au can be yielded through this capture scenario. The formation probability varies with the mass ratio and eccentricity of the binary. The maximum capture probability is more than 10%. Retrograde S-type planets can be produced via tidal capture mechanism. They can be adopted as an important indicator that distinguishes in situ formation and post-capture formation scenario.

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