Orbital stability of S-type circumbinary planets

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Abstract. Nowadays, more than 4,000 exoplanets have been discovered, including a hundred of circumbinary planets. In the following work, the orbital variations of 67 S-type circumbinary planets have been studied. Their orbital evolutions for a thousand years are simulated using the `REBOUND` package. The published physical and orbital parameters of the systems are used to computed the systems' orbital instability limits: Roche limit and Hill's sphere. From 67 systems, there are two unstable circumbinary systems: Kepler-420 and GJ 86. Kepler-420 Ab orbit passes into the system's Roche limit due to its high orbital eccentricity. For GJ 86 Ab, the planet orbits outside its Hill's sphere. The instability of GJ 86 Ab might be caused by an inaccurate measurement of GJ 86 A physical parameters. Using the GJ 86 A mass obtained from Farihi et al., the planet orbits in the stable orbit zone.

1. Introduction

To date, a hundred of circumbinary planets, which are planets orbiting in the binary star systems, have been discovered. Circumbinary planet orbit is classified as a three-body problem, which is an exceptional case that the orbit cannot be solved precisely and remains a significant problem in astrophysics research. Although, the orbit cannot be precisely predicted, the systems can have long-term orbital stability. However, in the systems which the planets have high eccentricity orbits, the instability of planetary orbits might be detected [1].

From the Catalogue of Exoplanets in Binary Star Systems, the data of 88 circumbinary systems can be obtained. The systems can be classified into two categories: S-type (planet orbiting a single star) and P-type (planet orbiting two stars), totaling 67 and 21 systems, respectively. In this work, only S-type circumbinary system is focused. The orbital stability of S-type circumbinary planet is constrained by two limits: Roche limit and Hill's sphere. The inner orbital limit is Roche limit, the minimum distance where the planet is not ripped to pieces by its host's tidal forces. The Roche limit can be written as,

$$d = R_p \sqrt[3]{\frac{2M_h}{M_p}} \ , \tag{1}$$

where d is the distance of Roche limit, R_p is the planetary radius, M_h and M_p are masses of the host star and the planet, respectively. The maximum orbital radius is limited by the Hill sphere, r_H, which is given by

$$r_H = a(1-e)\sqrt[3]{\frac{M_h}{3M_c}} \ , \tag{2}$$

where a is the orbital separation between the binary, e is an eccentricity of the binary system and M_c is the binary companion mass.

In this work, 1,000 years orbit of 67 known S-type circumbinary planetary systems are simulated with `REBOUND` package [2].

2. Orbital stability of known S-type circumbinary systems

The physical and orbital parameters of 67 S-type circumbinary systems are obtained from Catalogue of Exoplanets in Binary Star Systems (`https://www.univie.ac.at/adg/schwarz/bincat_binary.html`). The systems are simulated using `REBOUND` package [2]. In this work, the short term orbital stability is interested. In each system, a thousand years orbit with a step size of 1 year is simulated. The planetary Roche limit and Hill's sphere are assigned to be orbital stability limit.

From the 67 systems, only two systems: Kepler-420 Ab and GJ 86 Ab, show unstable orbits. For a comprehensive study, the orbits of these two systems are re-simulated with one day step size.

Kepler-420 Ab (also known as KOI-1257 b) is a transiting exoplanet with very high eccentricity orbit (e = 0.772). The planet has a mass of 1.45±0.35 M_{Jupiter}, and a radius of 0.94±0.12 R_{Jupiter} with 86.647661±0.000034 days orbital period. The planet has been discovered by *Kepler* and radial velocity follow-up with the SOPHIE spectrograph [3]. The simulation shows that the planet orbits around its planet-star centre of mass (Kepler-420 Ab and Kepler-420 A) with a distance between 1-3 AU. The planet wobbles around its orbit with period of ~3 days (figure 1). Due to the wobbling, the planet passes inside the circumbinary Roche limit after 142 days (figure 1, 2 and 3). The orbital instability might be caused by the very high eccentricity planetary orbit.

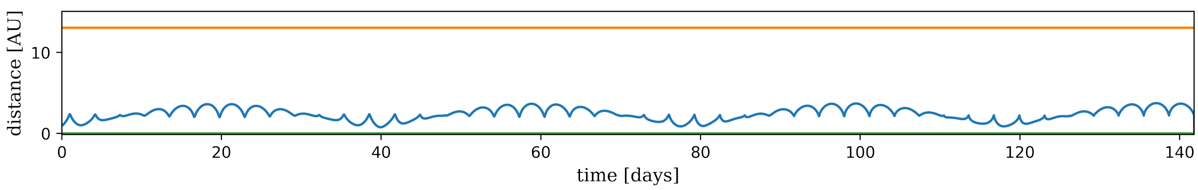


Figure 1. Distance between planet and planet-star center of mass of Kepler-420 Ab (Blue) with its Roche limit (Green) and Hill sphere (Orange). The simulation shows that Kepler-420 passes inside the Roche limit after 142 days.

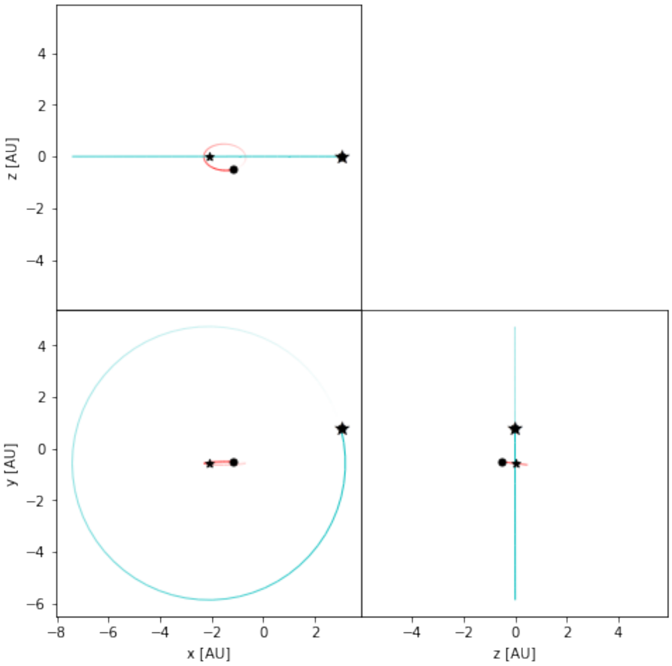
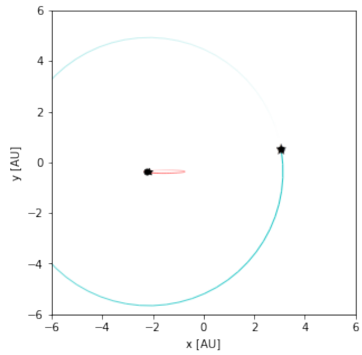
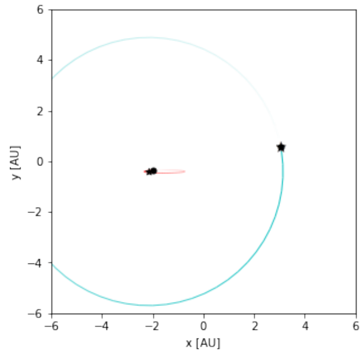


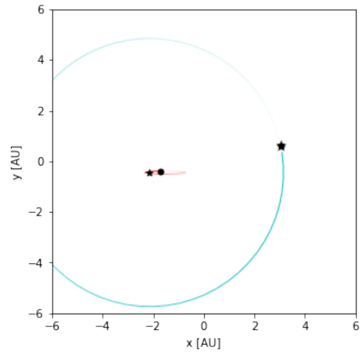
Figure 2. Top and side views of Kepler-420 system at 142nd day.



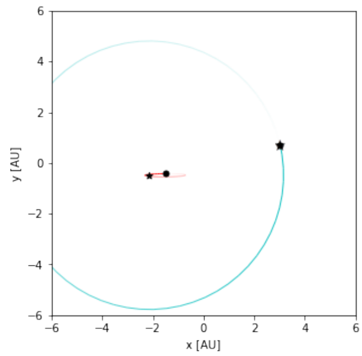
(a) 92nd day



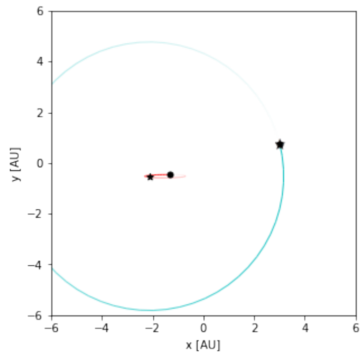
(b) 102nd day



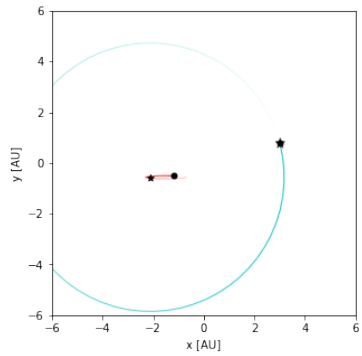
(c) 112nd day



(d) 122nd day



(e) 132nd day

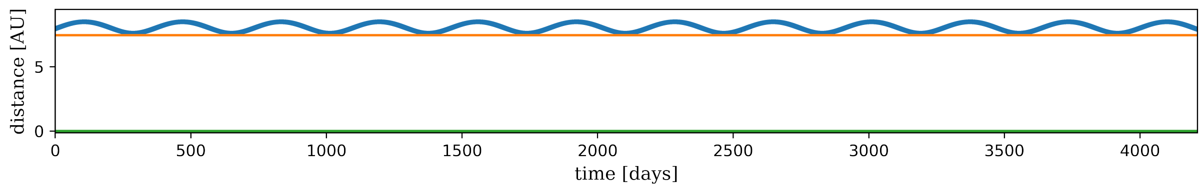


(f) 142nd day

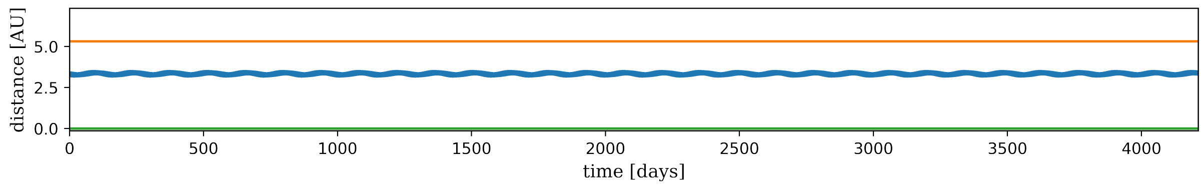
Figure 3. Top views of Kepler-420 system between 92nd and 142nd day.

GJ 86 Ab, a 4 M_{Jupiter} planet orbiting a nearby K main sequence star with orbital period of 15.8 days, was discovered by the CORALIE echelle spectrograph [4]. GJ 86 B, a 50 M_{Jupiter} companion orbiting GJ 86 at a distance of 18.75 AU, is discovered by Els. *et al.*, [5]. In 2005, Mugrauer and Neuhäuser proposed a model of faint T-dwarf companion with mass down to 35 M_{Jupiter} and separation between 1 and 23 AU [6]. From the Hubble Space Telescope observation, the mass of the binary is constrained to be 1.9 $M_\odot$ and 0.59 $M_\odot$ with orbital separation of >14 AU [7]. In this work, published mass 0.8 $M_\odot$ and 0.49 $M_\odot$ and separation of 21 AU from Catalogue of Exoplanets in Binary Star Systems are used.

GJ 86 Ab shows a stable orbit over a thousand years (figure 4). However, the planet orbits outside the Hill's sphere where the instability might be occurred. The instability of GJ 86 Ab cannot be confirmed due to the uncertainty of binary companion's mass and separation. The catalogue provides the binary with host star mass of 0.8 $M_\odot$ proposed by Queloz *et al.*, [4]. Using the update host star mass of 1.9 $M_\odot$ from Farihi *et al.* [7], the planet will orbit inside the Hill's sphere (figure 4).



(a)



(b)

Figure 4. Distance between planet and planet-star center of mass of of GJ 86 Ab (Blue) with its Roche limit (Green) and Hill sphere (Orange) with parameters from (a) the Catalogue of Exoplanets in Binary Star Systems and (b) the Hubble space telescope observations of Farihi *et al*. [7].

3. Conclusion

The orbit of 67 S-type circumbinary systems are simulated using `REBOUND` package. Most of them have stable orbits over a thousand years. There are only two systems that show unstable orbits, namely, Kepler-420 Ab and GJ 86 Ab. In our simulation, Kepler-420 Ab has an orbit which passes into the Roche limit within 142 days. The planet has very high eccentricity orbit which might cause the instability of the system. GJ 86 Ab has a stable orbital characteristic but orbits outside the Hill's sphere. The instability of GJ 86 Ab might be caused by the uncertainty of host star mass. GJ 86 A mass varies between 0.8 and 1.9 $M_\odot$ while GJ 86 B mass varies between 0.05 and 0.59 $M_\odot$. The orbit is inside the Hill's sphere with the parameters from the Hubble space telescope observations Farihi *et al*. [7]. In the future work, further studies of these two systems are required.

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