Birth environment of circumbinary planets: are there CBPs on the inclined orbits?

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ABSTRACT

The inclination distribution of circumbinary planets (CBPs) is an important scientific issue. It is of great significance in estimating the occurrence rate of CBPs and studying their formation and evolution. Although the CBPs currently discovered by the transit method are nearly coplanar, the true inclination distribution of CBPs is still unknown. Previous researches on CBPs mostly regarded them as an isolated binary-planet system, without considering the birth environment of their host binaries. It is generally believed that almost all stars are born in clusters. Therefore, it is necessary to consider the impact of the close encounters of stars on the CBP systems. This article discusses how the close encounters of fly-by stars affect the inclination of CBP. Based on extensive numerical simulations, we found that CBPs in close binary with a spacing of \(\sim 0.2\) au are almost unaffected by star fly-bys. Their orbits remain coplanar. However, when the spacing of the binary stars is greater than 1 au, the 2-3 fly-bys of the intruding star can excite a considerable inclination even for the CBP near the unstable boundary of the binary. For the planets in the outer region, a single star fly-by can excite an inclination to more than 5 degrees. Especially, CBPs in near polar or retrograde orbits can naturally form through binary-star encounters. If close binaries are born in open clusters, our simulations suggest that there may be high-inclination CBPs in binaries with spacing \(> 1\) au.

Key words: celestial mechanics – planetary systems – stars: binary.

1 INTRODUCTION

Circumbinary planet (CBP) is one of the miraculous discoveries of exoplanet exploration. And up to now, more than 20 CBPs have been found \cite{Schwarz2016}. The most influential subset of them is the 11 planets detected by Kepler, which constitute a small research sample. One remarkable feature of the orbits of Kepler’s CBP is coplanarity, that is, the planes and their host binary are nearly in a same plane. The inclination angle \(I\) between the two orbits is less than 2.5° \cite{Kostov2014}. This feature is partly due to the observational selection effect because that planets orbiting in the binary plane are more easily to be detected by the transit method. A very interesting question is: are there CBPs on the inclined orbits hidden in the universe? The inclination distribution of CBPs is an important scientific issue. For example, occurrence rates of CBP depend critically on the inclination distribution \cite{Armstrong2014}. If the underlying planetary inclination distribution is isotropic, the occurrence rate of CBP is significantly greater than analogous rates for single stars. The prospects of finding planets transiting non-eclipsing binaries have been investigated by \cite{Martin2014}. They find there are potentially many of them lurking in the Kepler photometric data. \cite{Zhang2019} provided a new tool for discovering potential polar CBPs, or misaligned CBPs of milder inclinations, from the existing ETV dataset of the Kepler. Maybe CBPs on the inclined orbits will be detected in the near future.

Although no CBPs are found on the high-inclination orbits \((I > 5°)\), some circumbinary disks (CBDs) on high inclination orbits have been discovered in recent years. For example, CBD in the IRS 43 system has an inclination \(I > 40°\) \cite{Brinch2016, Czekala2019}. The CBD 99 Herculis and a planet-forming CBD in the young HD 98800 system are thought to have a polar configuration \(I \sim 90°\) \cite{Kennedy2012, Kennedy2019}. Theoretical researches show that the evolution of a circumbinary disc tends to two extreme cases \cite{Brinch2016, Martin2017, Martin2018, Zanazzi2018, Lubow2018}. If the
initial inclination angle of the disk is small, the result of the evolution is that the disk tends to be coplanar with the binary star. If the initial inclination angle of the disc is large (> 40°, in Martin & Lubow (2017)) and the eccentricity of the binary star is nonnegligible, the disc will evolve into a polar orbit. The presence of high-inclination discs indicates high-inclination CBPs may exist. However, above conclusions are based on the evolution of the isolated CBD systems themselves. Besides, only in the specific initial configurations can they evolve to the high-inclination orbits, such as a high initial inclination and a large eccentricity for the binary. Why the CBD initially has a large inclination still requires other mechanisms to explain. A noteworthy phenomenon is that the semi-major axis (SMA) of the binaries with high-inclination disks found now are relatively large (several tens of au), while the discs around close binaries are nearly coplanar (Kennedy et al. 2012; Czekala et al. 2011). For the Kepler CBPs the SMA of their host binaries is small, about 0.1 – 0.2 au. One possibility is that the discs around well-spaced binaries are susceptible to the surrounding environment, such as the close encounters with fly-by stars.

It is generally believed that most stars, and therefore most planetary systems, were born in clusters or associations (Clarke, Bonnell, & Hillenbrand 2000; Lada & Lada 2003; Pfalzner 2013; Hao, Kouwenhoven, & Spurzem 2013; Cai et al. 2017). Some open clusters later dissolved, forming the current field stars. A notable example is that our own solar system may have formed in an open cluster. According to the theory of star formation, it is impossible for some unstable islands) (Holman & Wiegert 1999). The planet is initially on a coplanar and circular orbit. Its mass is 1 Saturn mass. The SMAs of the binaries in Kepler CBP sample is about $a_B \sim 0.2$ au. We take 0.2 au as the lower limit of $a_B$. According to Trilling et al. (2007), the CBD around the close binaries with a SMA of 3 au is ubiquitous. 3 au is set as the upper limit of $a_B$. The mass ratio of the binary $m_2/m_1$ is 0.5. Here $m_1$ and $m_2$ are the mass of the primary and the secondary star, respectively. The eccentricity of the binary is $e_B = 0.3$.

There is a stable boundary $(a_c)$ around the binary beyond which the orbit of the planet is long-term stable (except for some unstable islands) (Holman & Wiegert 1999). Kepler-1647b has the longest-period in the small-family of CBPs (∼ 1100 days, $a_p = 7.4$ au) (Kostov et al. 2010), it may not have undergone significant migration. In this work we explore $a_p = 1.1, 4.1$ and 7.1 au. Their values in au are shown in Table 1. The orbital phase angles of the planets and the intruding star are randomly and uniformly distributed between 0 and 360°. Like most Kepler CBP systems, we only consider single-planet system.

We focus on stellar perturbers on parabolic orbits, which is common even for ONC-like clusters (Okazaki et al. 2010; Pfalzner 2013; Xiang-Gruess 2016). It should be noted that in more dense clusters most stellar flybys are hyperbolic (Spurzem et al. 2009; Cai et al. 2017). We don’t consider the hyperbolic orbit at present work for simplicity. The orbit of the stellar perturber is described by five parameters. They are the pericenter distance $q$, the inclination $i$, the longitude of ascending node $\Omega$, the argument of pericentre $\omega$, the true anomaly $f$, respectively (Murray & Dermott 1999). All the parameters are relative to the barycenter of the binary.

We use MERCURY _RAS (Smullen, Kratter & Shannon 2010) for numerical integration. It is a modified version of MERCURY (Chambers 1999) that can be used to simulate a CBP system. The code has been well tested in our former work (Gong & Ji 2018). We added a flyby star in the system. The parabolic orbits of the fly-by stars had been checked before the simulations. We found that although there is a negligible pulse in the eccentricity $e_B$ of the fly-by star near the pericenter, the intruding star is still in the near parabolic orbit $e_B \approx 1$ after

### Table 1.
The semi-major axis (in au) of CBP that we considered. The results come from Equation (1). The eccentricity $e_B$ and mass ratio $\mu$ of binaries are 0.3 and 1/3, respectively.

| $a_B$ (au) | $a_p = 1.1$ | $a_p = 4.1$ | $a_p = 7.1$ |
|-----------|------------|------------|------------|
| 0.2       | 0.74       | 2.8        | 4.8        |
| 1.0       | 3.7        | 13.8       | 24         |
| 3.0       | 11         | 41         | 71         |

**2 MODEL AND METHOD**

We consider the effect of star fly-by on the inclination of CBP. The CBP family found by *Kepler* is used as the reference to set the parameters of the binary star and the planet.
passing it. It means that the quadrupole moment of the binary has little effect on the orbit of the fly-by star in the cases we explored. In Figure 1, an example is shown. In our model, the fly-by star flies over the binary-planet system at an initial distance of 10,000 au from the barycenter of binary. When the star passes its pericenter and the distance between it and the binary exceeds 1000 au again, we record the orbital parameters of the planet.

The long-term stability of the surviving planet is judged by the condition \( q_p = a_p(1 - e_p) > a_c \) (the periastron of the planet is larger than \( a_c \)). Although the \( a_c \) in Holman & Wiegert (1999) was derived from the coplanar configuration, it still can applies to the non-coplanar configuration as shown in Pilat-Lohinger (2003). They found that the inclination of the CBP has little effect on the stable boundary. Therefore, we still use the criterion in Holman & Wiegert (1999) to check the orbital stability of the surviving CBPs.

As done in Malmberg, Davies, & Heggie (2011), we divided fly-bys into two different regimes, depending on \( q \): the strong regime (\( q < 100 \) au) and the weak regime (\( 100 \) au < \( q < 1000 \) au). When the \( q \) is very small, the binary may be disrupted. We discarded these cases when they occurred in the simulation. In other words, the criterion for us to judge whether a simulation is successful is that the close binary is still intact after star fly-bys.

The mass of the intruder star also has an effect on the simulation results. In the most simulations, we take \( m_3 = 1 \) \( M_\odot \). In principle, a wide variety of stars with masses ranging from 0.08 \( M_\odot \) up to 100 \( M_\odot \) might act as a fly-by star in a cluster (Pfalzner et al. 2018). For example, it is generally believed that the solar system can closely encounter with a star with a mass of 25 \( M_\odot \) (Adams 2010). However, the more massive the stars, the fewer they are in a cluster. We just take \( m_3 = 20 \) \( M_\odot \) as a representative of a high-mass perturber. The inclination of the fly-by star (relative to the binary plane) is randomly distributed between 0° and 180°. All initial phase angles of the planets and the intruding star were assigned randomly and uniformly from 0 to 2π.

3 NUMERICAL RESULTS

3.1 A single fly-by

3.1.1 \( q < 100 \) au

This close fly-by may occur in dense star clusters or in the inner part of an open cluster. Pfalzner et al. (2018) showed that a close fly-by with 50 au < \( q < 100 \) au of a neighboring star can reproduce the properties of the solar system. Numerical simulations showed in typical open clusters in the Solar neighbourhood containing hundreds or thousands of member stars, 10% to 20% of stars with mass \( \geq 1 \) \( M_\odot \) witness a fly-by < 100 au (Malmberg et al. 2005, Li, Mustill, & Davies 2013). In our simulation, the \( q \) of the fly-by star is evenly and randomly distributed between 0 and 100 au, and the inclination angle is randomly between 0° and 180°. The percentage of planets with an inclination greater than 5 degrees (PGT5) after a single star fly-by are shown in Table 2. Each statistical datum in Table 2 is based on 1000 realizations. The total number of the realizations is 72,000 in this work.

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| \( m_3 (M_\odot) \) | \( a_B \) (au) | \( a_p = 1.1 \) \( a_c \) | \( a_p = 4.1 \) \( a_c \) | \( a_p = 7.1 \) \( a_c \) |
|-----------------|-------------|-----------------|-----------------|-----------------|
| 1               | 0.2         | 0.3%, 18°       | 2.0%, 80°       | 3.6%, 75°       |
| 1.0             | 1.1%, 49°   | 10.6%, 119°     | 21.5%, 159°     |                 |
| 3.0             | 2.7%, 35°   | 39%, 163°       | 46%, 173°       |                 |
| 20              | 0.2         | 0.2%, 13°       | 2.1%, 52°       | 2.9%, 125°      |
| 1.0             | 0.7%, 86°   | 13%, 164°       | 26.8%, 128°     |                 |
| 3.0             | 4.3%, 84°   | 32.7%, 175°     | 39.4%, 177°     |                 |

To clearly show the trend of PGT5 we plot them in Figure 2. It can be seen from Figure 2 that the percentage of planets with an inclination greater than 5° (PGT5) is gradually increasing as \( a_p \) increases (or see the same column in Table 2). The maximum inclination of CBPs is also gradually increasing, albeit with some statistical randomness. In the same binary system, the further the planet is, the easier the inclination is to be excited. That is, PGT5 also gradually increasing, albeit with some statistical randomness. In the same binary system, the further the planet is, the easier the inclination is to be excited. That is, PGT5 also gradually increasing, albeit with some statistical randomness.
When the $q$ of a fly-by star is greater than 100 au and less than 1000 au, a solar-mass intruder has little effect on the inclination of CBP (see Table 3 and Figure 4). Only planets with $a_p \geq 4.1 \, a_c = 41$ au in the binaries of $a_B = 3$ au can be excited to an inclination of more than 5°. In other cases, PGT5 is 0.

For fly-by stars with $m_3 = 20 \, M_\odot$, the PGT5 increases compared to $m_3 = M_\odot$ case. But for the binaries of $a_B \sim 0.2$ au, PGT5 is still zero. The fly-by stars have little effect
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Figure 3. Orbital evolution of a circumbinary planet. To show the details, we only simulate a piece of time before and after the fly-by. The time evolution of the SMA, eccentricity and inclination of the planet are shown in the first, second and third panel, respectively. The orbit of the intruding star is shown in the bottom panel. The parameters of the binary are: \( m_1 = M_\odot \), \( m_2 = 0.5 M_\odot \), \( a_B = 1 \) au, \( e_B = 0.3 \). The planet is initially on a circular and coplanar orbit. Its SMA is \( a_p = 7.1 a_c \approx 24 \) au. The intruding star is \( m_3 = 1 M_\odot \) with the pericenter distance \( q < 100 \) au. After star fly-by, the planet is excited to a high-inclination orbit \( (i_p \approx 60^\circ) \). Its orbit satisfies \( q_p > a_c \) where \( q_p = a_p(1-e_p) = 9.3 \) au, \( a_c = 3.4 \) au.

### Table 3. PGT5

| \( m_3 (M_\odot) \) | \( a_B (\text{au}) \) | \( a_p = 1.1 a_c \) | \( a_p = 4.1 a_c \) | \( a_p = 7.1 a_c \) |
|---------------------|---------------------|---------------------|---------------------|---------------------|
| 1                   | 0.2                 | 0%, 0.005\(^\circ\) | 0%, 0.1\(^\circ\)  | 0%, 0.25\(^\circ\)  |
| 1                   | 1.0                 | 0%, 0.15\(^\circ\)  | 0%, 1.3\(^\circ\)  | 0%, 3\(^\circ\)    |
| 3.0                 | 0%                  | 0.68\(^\circ\)      | 0.5\(^\circ\), 7.5\(^\circ\) | 4.0\(^\circ\), 35\(^\circ\) |
| 20                  | 0.2                 | 0%, 0.01\(^\circ\)  | 0%, 0.35\(^\circ\) | 0%, 0.8\(^\circ\) |
|                     | 1.0                 | 0%, 0.92\(^\circ\)  | 2.3\(^\circ\), 17.1\(^\circ\) | 9.5\(^\circ\), 65\(^\circ\) |
|                     | 3.0                 | 0.1\(^\circ\), 5.6\(^\circ\) | 18.1\(^\circ\), 59\(^\circ\) | 20.6\(^\circ\), 99\(^\circ\) |

The orbit of the intruding Star

The planet is initially on a circular and coplanar orbit. Its SMA is \( a_p = 7.1 a_c \approx 24 \) au. The intruding star is \( m_3 = 1 M_\odot \) with the pericenter distance \( q < 100 \) au. After star fly-by, the planet is excited to a high-inclination orbit \( (i_p \approx 60^\circ) \). Its orbit satisfies \( q_p > a_c \) where \( q_p = a_p(1-e_p) = 9.3 \) au, \( a_c = 3.4 \) au.

Table 3. PGT5. The pericenter distance of the fly-by star is uniformly and randomly distributed between 100 and 1000 au. Other parameters are the same as in Table 2.

3.2 Multiple fly-bys

Above we only discuss a single fly-by. Multiple fly-bys also may occur in an open cluster. For example, Malmberg, Davies, & Heggie (2011) showed the average number of fly-bys per sun-like star is 4 in the cluster with an initial number of stars of 700 and an initial half-mass radius of 0.38 pc. Besides, the more encounters a star undergoes, the smaller its fraction will be. For example, more than 60% of the stars that have undergone fly-bys in their reference cluster experience \( \leq 5 \) fly-bys. Close binaries \( (a_B \leq 3 \) au\) that we consider in this work are known as ‘hard binaries’ in cluster dynamics (Malmberg et al. 2005). They are more tightly bound and will not easily be broken up when they encounter another star. So the encounter rate of a close binary with a single star would be similar to the star-star encounter rate mentioned above. We explored the effect of 2-3 fly-bys on the orbits of CBP at present work. Certainly, during the dissolution of a long-lived cluster many more encounters exist. However, as mentioned above, their occurrence rate decreases significantly as the encounter number increases. On the other hand, with the dissolution of a cluster, the average encounter distance gets large. On average, despite the encounter number increases, the effects of fly-by stars on the planetary systems get weak. These issues complicate the problem and beyond the scope of our work.

We did the multiple fly-bys simulations as follows. After the first fly-by, we recorded the final position and velocity of the binary stars and planet. The data of the intruding star is discarded because it will have little effect on the orbit of the planet \( (r_3 \geq 1000 \) au\). We started a new run. These data above on the planetary systems. But for \( a_B = 3 \) au, the orbit of the outer planet is easily excited to a large inclination. For example, for \( a_p = 4.1 a_c = 41 \) au, about one-fifth of the planets are excited to an inclination of more than 5\(^\circ\). For \( a_p = 7.1 a_c = 71 \) au, PGT5 is \( \sim 21\% \) with a maximum inclination of 99\(^\circ\).
are used as the initial condition for binary and planet. In addition, we added a new random fly-by star in the system. As we done in the first fly-by, the new fly-by star flies over the binary-planet system at an initial distance of 10,000 au from the barycenter of binary. Similarly, the third fly-by was performed.

For the fly-by stars with $q < 100$ au, the results of the three fly-bys are shown in Table 4. F1, F2 and F3 represent the results of the first, second, and third fly-by, respectively. For the case of $a_B = 3.0$ au, after three fly-bys, most planets in the outer region are scattered out of the system. A few surviving planets can’t give a meaningful statistical results. So we discarded these data. The fractions of planets with an inclination greater than 5 degrees after the first, second and third fly-by are given in Figure 5. In general, as the number of fly-bys increases, the PGT5 gets larger. The larger the $a_B$ and $a_p$, the larger the PGT5.

For the planetary system similar to Kepler CBP, ie $a_B = 0.2$ au, $a_p = 1.1$ $a_c = 0.74$ au in the Table 4, PGT5 is still less than 1%. After three fly-bys, PGT5 is 0.6% and the maximum inclination is $19^\circ$. Only for the planets in the outer region ($a_p = 7.1$ $a_c = 4.8$ au), more than 10% of the planets are on the orbits greater than $5^\circ$ after three fly-bys.

Table 5 and Figure 6 give the results of 100 au < $q < 1000$ au. For the intruding stars of $1 M_\odot$, the effect of multiple fly-bys on the planetary system is still limited. For the binary of $a_B = 0.2$ au and 1 au, PGT5 is 0. Only for the systems with $a_B = 3$ au and $a_p = 7.1$ $a_c = 71$ au, a considerable PGT5 is obtained after three fly-bys. For three successive fly-by, the results of PGT5 are 4%, 10.4%, and 15.9%, respectively. The resulting maximum inclination is $39^\circ$.

4 SUMMARY

It is generally believed that most stars are born in a clusters. The nascent planetary system of these stars is vulnerable to the perturbations of other stars. This article considers the effects of star fly-by(s) on the inclination of CBP. Our main conclusions are as follows.

The CBP systems with $a_B \sim 0.2$ au similar to those discovered by Kepler are almost unaffected by a single star. The result of multiple fly-bys. F1, F2, and F3 represent the results of the first, second, and third fly-by, respectively. For multiple fly-bys, we only consider the fly-by star of $1 M_\odot$ mass. The pericenter distance of the fly-by star is $q < 100$ au as in Table 2.

| $a_B$ (au) | Fly-by times | $a_p$ = 1.1 $a_c$ | $a_p$ = 4.1 $a_c$ | $a_p$ = 7.1 $a_c$ |
|---|---|---|---|---|
| 0.2 | F1 | 0.3%, 18° | 2%, 80° | 3.6%, 75° |
| | F2 | 0.3%, 29° | 6.1%, 160° | 9.7%, 169° |
| | F3 | 0.6%, 20.1° | 7.3%, 150° | 16.4%, 116° |
| 1.0 | F1 | 1.1%, 49° | 10.6%, 119° | 21.5%, 159° |
| | F2 | 0.9%, 26° | 23.6%, 131° | 39.6%, 171° |
| | F3 | 1.4%, 37° | 30.4%, 144° | 57.2%, 169° |
| 3.0 | F1 | 2.7%, 35° | 39%, 163° | 46%, 173° |
| | F2 | 4.5%, 18.2° | 36%, 165° |— |
| | F3 | 9.7%, 56° |— |— |

Table 5. The result of multiple fly-bys. The pericenter distance of the fly-by star is uniformly and randomly distributed between 100 au and 1000 au. Other parameters are the same as in Table 4.

| $a_B$ (au) | Fly-by times | $a_p$ = 1.1 $a_c$ | $a_p$ = 4.1 $a_c$ | $a_p$ = 7.1 $a_c$ |
|---|---|---|---|---|
| 0.2 | F1 | 0%, 0.005° | 0%, 0.105° | 0%, 0.25° |
| | F2 | 0%, 0.004° | 0%, 0.14° | 0%, 0.31° |
| | F3 | 0%, 0.005° | 0%, 0.15° | 0%, 0.32° |
| 1.0 | F1 | 0%, 0.15° | 0%, 1.22° | 0%, 3° |
| | F2 | 0%, 0.18° | 0%, 1.35° | 0%, 3.3° |
| | F3 | 0%, 0.19° | 0%, 1.31° | 0%, 2.9° |
| 3.0 | F1 | 0%, 0.68° | 0.5%, 7.5° | 4%, 35° |
| | F2 | 0%, 0.74° | 1%, 8.5° | 10%, 30° |
| | F3 | 0%, 0.93° | 2.2%, 7.7° | 16%, 39° |
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Figure 5. The fraction of planets with an inclination greater than 5 degrees after the first, second and third fly-by. Data are from Table 4. The squares, circles and triangles represent the results of $a_B = 0.2$ au, 1 au and 3 au, respectively. The results of the first, second and third fly-by are shown in red, green and blue, respectively. The pericenter distance of the fly-by star is $q < 100$ au.

Figure 6. Conventions are as in Figure 5. Data are from Table 5. The pericenter distance of the fly-by star is $100$ au $< q < 1000$ au.

fly-by. Their orbits remain coplanar. Even a relatively close flyby, or a massive intruder, has little effect on the inclination of the planet. Our simulations also showed that several successive fly-bys do not cause significant inclination change for CBP in tight binaries. These results imply that for planets similar to those discovered by Kepler, even if they were born in an open cluster, their orbits keep nearly coplanar.

However, for binaries with $a_B > 1$ au, the planets in the outer region ($a_p > 4.1a_c$) will be affected by the stellar fly-by(s). A single fly-by can excite the inclination of CBP to more than 5° (PGT5 > 10%). For planets close to the unstable boundary of the binary, the 2-3 close fly-bys cause significant inclination excitation. If, like most stars, close binaries are born in clusters, our simulations suggested that there may be high-inclination planets around binaries with $a_B > 1$ au. Besides, it is worth mentioning that CBPs in near polar or retrograde orbits can naturally form in clusters through this mechanism.

At present, CBDs with high inclination angles are found in binaries with a large $a_B$, while CBDs (and CBPs) found in close binaries are almost coplanar. Our research implies that the star fly-by may be one of the possible mechanisms accounting for this difference. If the nascent CBD and their host binaries are coplanar, this difference can be explained by the fact that the CBD in the binaries with a larger $a_B$ is more susceptible to stellar fly-bys. Generation of highly inclined protoplanetary discs in single star systems through a single stellar fly-by has been explored in Xiang-Gruess (2016). We will discuss how it works for CBD in the near future.

An in-depth exploration of Kepler’s existing data, as well as the ongoing PLATO and TESS mission, is expected to find more CBPs. The orbital inclination distribution of
CBP will be the key information to understand their formation and evolution.

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REFERENCES

Adams F. C., 2010, ARA&A, 48, 47
Armstrong D. J., Osborn H. P., Brown D. J. A., Faedi F., Gómez Maqueo Chew Y., Martin D. V., Pollacco D., Udry S., 2014, MNRAS, 444, 1873
Brinch C., Jørgensen J. K., Hogerheijde M. R., Nelson R. P., Gressel O., 2016, ApJ, 830, L16
Cai M. X., Kouwenhoven M. B. N., Portegies Zwart S. F., Spurzem R., 2017, MNRAS, 470, 4337
Clarke C. J., Bonnell I. A., Hillenbrand L. A., 2000, prpl.conf, 151
Chambers J. E., 1999, MNRAS, 304, 793
Czekala I., Chiang E., Andrews S. M., Jensen E. L. N., Torres G., Wilner D. J., Stassun K. G., Macintosh B., 2019, arXiv, arXiv:1906.03269
Dukes D., Krumholz M. R., 2012, ApJ, 754, 56
Gong Y.-X., Ji J., 2017, AJ, 154, 179
Gong Y.-X., Ji J., 2018, MNRAS, 478, 4565
Hao W., Kouwenhoven M. B. N., Spurzem R., 2013, MNRAS, 433, 867
Hamers A. S., Perets H. B., Portegies Zwart S. F., 2016, MNRAS, 455, 3180
Holman M. J., Wiegert P. A., 1999, AJ, 117, 621
Kennedy G. M., Wyatt M. C., Sibthorpe B., Phillips N. M., Matthews B. C., Greaves J. S., 2012, MNRAS, 426, 2115
Kennedy G. M., et al., 2019, NatAs, 3, 230
Kostov V. B., et al., 2014, ApJ, 784, 14
Kostov V. B., et al., 2016, ApJ, 827, 86
Lada C. J., Lada E. A., 2003, ARA&A, 41, 57
Li D., Mustill A. J., Davies M. B., 2019, MNRAS
Lubow S. H., Martin R. G., 2018, MNRAS, 473, 3733
Malmberg D., de Angeli F., Davies M. B., Church R. P., Mackey D., Wilkinson M. I., 2007, MNRAS, 378, 1207
Malmberg D., Davies M. B., Heggie D. C., 2011, MNRAS, 411, 859
Martin D. V., Triaud A. H. M. J., 2014, A&A, 570, A91
Martin D. V., Mazeh T., Fabrycky D. C., 2015, MNRAS, 453, 3554
Martin R. G., Lubow S. H., 2017, ApJ, 835, L28
Martin R. G., Lubow S. H., 2018, MNRAS, 479, 1297
Moe M., Kratter K. M., 2018, ApJ, 854, 44
Murray C. D., Dermott S. F., 1999, ssd..book
Olczak C., Pfalzner S., Eckart A., 2010, A&A, 509, A63
Pfalzner S., 2013, A&A, 549, A82
Pfalzner S., Bhandare A., Vincke K., Lacerda P., 2018, ApJ, 863, 45
Pillat-Lohinger E., Funk B., Dvorak R., 2003, A&A, 400, 1085
Schwarz R., Funk B., Zeche R., Bocz Á., 2016, MNRAS, 460, 3598
Sigurdsson S., Richer H. B., Hansen B. M., Stairs I. H., Thorsett S. E., 2003, Sci, 301, 193
Smullen R. A., Kratter K. M., Shannon A., 2016, MNRAS, 461, 1288
Spurzem R., Giersz M., Heggie D. C., Lin D. N. C., 2009, ApJ, 697, 458
Thun D., Kley W., 2018, A&A, 616, A47
Trilling D. E., et al., 2007, ApJ, 658, 1289
Xiang-Gruess M., 2016, MNRAS, 455, 3086
Zanazhi J. J., Lai D., 2018, MNRAS, 473, 603
Zhang Z., Fabrycky D. C., 2019, ApJ, 879, 92