Tidal Decay of Circumbinary Planetary Systems

Ivan I. Shevchenko

1 Institute of Applied Astronomy, RAS, 191187 Saint Petersburg, Russia; ivan.i.shevchenko@gmail.com
2 Lebedev Physical Institute, RAS, 119991 Moscow, Russia

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Abstract

It is shown that circumbinary planetary systems are subject to universal tidal decay (shrinkage of orbits), caused by the forced orbital eccentricity inherent to them. Circumbinary planets (CBPs) are liberated from parent systems when, owing to the shrinkage, they enter the circumbinary chaotic zone. On shorter timescales (less than the current age of the universe), the effect may explain, at least partially, the observed lack of CBPs of close-enough (with periods <5 days) stellar binaries; on longer timescales (greater than the age of the universe but well within stellar lifetimes), it may provide massive liberation of chemically evolved CBPs. Observational signatures of the effect may comprise (1) a prevalence of large rocky planets (super-Earths) in the whole population of rogue planets (if this mechanism were the only source of rogue planets); (2) a mass-dependent paucity of CBPs in systems of low-mass binaries: the lower the stellar mass, the greater the paucity.

Key words: astrobiology – binaries: close – planetary systems – planets and satellites: general – stars: individual (EZ Aqr) – stars: low-mass

1. Introduction

Consider a planar three-body system of gravitating bodies: a central massive binary and a much less massive particle orbiting around the binary. Thus, the particle’s orbit is circumbinary. The orbital eccentricities of circumbinary particles are periodically forced on secular and local orbital timescales (Moriwaki & Nakagawa 2004; Paardekooper et al. 2012; Demidova & Shevchenko 2015; Andrade-Ines & Robutel 2018). Therefore, the circumbinary orbits cannot be permanently circular. This phenomenon provides a natural universal mechanism of internal tidal friction and heating in circumbinary planets (CBPs) (Shevchenko 2017). In this article, we describe and consider the planetary escape process that takes place as a result of this shrinkage. Indeed, a particle in the slowly shrinking circumbinary orbit eventually enters the chaotic zone around the central binary, and therefore escapes. Once in the zone, the particle escapes inevitably, being subject to chaotic diffusion along the “staircase” of overlapping integer mean-motion resonances (between the binary and the particle) until it crosses the separatrix between the bound and unbound dynamical states (Shevchenko 2015).

We show that the effect of tidal decay may explain, at least partially, the observed lack of CBPs of close-enough (with periods <5 days) stellar binaries. What is more, on longer timescales (greater than the age of the universe but well within stellar lifetimes), it may provide massive liberation of chemically evolved CBPs.

2. Tidal Heating and Orbital Decay

For brevity, we consider solely the case of equal-mass stellar binaries. It can be shown that moderate deviations from mass equality do not influence the derived timescales much. In the equal-mass case, the secular term in the time behavior of a CBP’s eccentricity vanishes; however, the eccentricity is still forced on a shorter timescale (Moriwaki & Nakagawa 2004; Paardekooper et al. 2012). By averaging the perturbing function on the orbital timescale of the central binary, and retaining terms up to the second order in the planetary eccentricity, Paardekooper et al. (2012) found that the eccentricity of a CBP (put initially in a circular orbit around the binary) oscillates around the forced non-zero value,

\[ e_{\text{eff}} = \frac{3}{4} \frac{m_1 m_2}{(m_1 + m_2)^2} \left( \frac{a_b}{a_p} \right)^2 \left( 1 + \frac{34}{3} e_b^2 \right)^{1/2}, \]  

where \( m_1 \) and \( m_2 \) are the masses of the binary components, \( a_b \) is the eccentricity of the binary, and \( a_b \ll a_p \) are the semimajor axes of the binary and the CBP, respectively. Equivalently, one has

\[ e_{\text{eff}} = \frac{3}{4} \mu (1 - \mu) \left( \frac{T_b}{T_p} \right)^{1/3} \left( 1 + \frac{34}{3} e_b^2 \right)^{1/2}, \]  

where \( \mu = m_2/(m_1 + m_2) \) is the mass parameter \((m_1 \geq m_2)\), and \( T_b \) and \( T_p \) are the orbital periods.

If \( m_2 \sim m_1 \), the term with \( e_{\text{eff}} \) in the perturbing function dominates. In the alternative case, when \( m_2 \ll m_1 \), the dominating term is a secular one and the forced eccentricity is

\[ e_t = \frac{5}{4} (1 - 2 \mu) \frac{a_b}{a_p} e_b = \frac{5}{4} (1 - 2 \mu) \left( \frac{T_b}{T_p} \right)^{2/3} e_b, \]  

(Moriwaki & Nakagawa 2004; Demidova & Shevchenko 2015).

As shown in Demidova & Shevchenko (2015), the secular time variation of the planetary eccentricity, excited by the central binary, follows the law \( e_p = 2e_t \sin \omega t \), where \( \omega \) is the variation frequency and \( t \) is time. Therefore, for the effective tidal eccentricity one can take the time-averaged value \( \langle e_p \rangle = \frac{2}{3} e_t \) in the case of secular variations; analogously, \( \langle e_p \rangle = \frac{2}{3} e_{\text{eff}} \) in the case of local time variations.

From formula (2), for the effective tidally excited eccentricity of a CBP of a twin \((m_1 = m_2)\) and circular \((e_b = 0)\)
binary one has

\[ (e_p) = \frac{3}{4\pi} \left( \frac{a_0}{a_p} \right)^2 = \frac{3}{4\pi} \left( \frac{T_b}{T_p} \right)^{4/3}. \]  

(4)

Whichever the origin of the planetary eccentricity may be, the tidal heating flux through the planetary surface is given by

\[ h_p = \frac{63}{16\pi} G^{3/2} M_s^{5/2} R_p^{3} Q_p^{-1} a_p^{-15/2} e_p^2. \]  

(5)

(Jackson et al. 2008; Barnes et al. 2009), where \( G \) is the gravitational constant, \( M_s \) is the stellar mass, \( a_p \) and \( e_p \) are the semimajor axis and eccentricity of the planetary orbit, \( R_p \) is the planet’s radius, and \( Q_p = 3Q_{p} / (2k_s) \), where \( Q_p \) and \( k_s \) are the planetary tidal dissipation parameter and Love number, respectively. In our hierarchical model of a planet orbiting around a close twin \((m_1 = m_2)\) binary, one can set \( M_c = m_1 + m_2 = 2m_1 = 2m_2 \). Combining Equation (5) with Equation (4), one has

\[ h_p = \frac{567}{256\pi^2} \zeta G^{3/2} M_s^{5/2} R_p^3 Q_p^{-1} a_p^4 a_p^{-23/2}, \]  

(6)

where \( \zeta \) is the unitless constant responsible for the choice of a tidal model, as specified below.

The radius \( a_{cr} \) of the chaotic zone around a circular twin binary can be estimated, using a numerical-fitting relation derived in Holman & Wiegert (1999), as

\[ a_{cr} \approx 2.4a_0. \]  

(7)

Assuming (as justified in Shevchenko 2017; see also discussion below) that the planet initially moves in a resonant cell just at the edge of the central chaotic zone, one can express \( h_p \) through the binary period \( T_b \):

\[ h_p = A_h G^{-1} R_p^3 Q_p^{-1} T_b^{-5}, \]  

(8)

where the unitless constant \( A_h \approx \frac{567}{8} 2.4^{-23/2} \pi^2 \zeta \approx 0.0297\zeta. \)

3. The Escape Process

Both single-star and binary-star populations can lose their planets by a number of dynamical and physical mechanisms: stellar flybys, planet–planet scattering, supernova explosions, etc.; see Rasio & Ford (1996), Veras & Tout (2012), Veras et al. (2014), and Kostov et al. (2016). No comparative planetary escape statistics are available up to now, due to the complex and multifaceted nature of the phenomenon. Concerning circumbinary systems, Sutherland & Fabrycky (2016) found, based on massive numerical simulations, that planetary escape from such systems may efficiently fill the Galaxy with rogue planets. According to Sutherland & Fabrycky (2016) and Smullen et al. (2016), most CBPs are ejected rather than destroyed via planet–planet or planet–star collisions. Note that a major difference of our tidal mechanism from the planet–planet scattering is that it acts permanently, while planet–planet scattering is efficient only in young planetary systems.

Let us concentrate on circumbinary systems. A gravitating binary with components of comparable masses possesses a circumbinary zone of dynamical chaos if the mass ratio exceeds some threshold; this zone of instability is formed by the overlap of the integer mean-motion resonances (accumulating to the separatrix corresponding to the parabolic motion) between the central binary and the planet (Shevchenko 2015). As follows from the orbital data on the recently discovered CBPs of main-sequence stars (Kepler-16b, 34b, 35b, and others), most of them move in orbits closely encircling the central chaotic zone (Doyle et al. 2011; Welsh et al. 2012; Popova & Shevchenko 2013). In Shevchenko (2015), the extent of the chaotic zone around a system of two gravitationally bound bodies was estimated analytically, based on Chirikov’s (1979) resonance overlap criterion. The binary’s mass ratio, above which such a chaotic zone is universally present, was also estimated as equal to \( \approx 0.05 \). Note that central cavities of analogous origin are observed in protoplanetary disks, which contain planetesimals, dust, and gas; the gas is present at the initial stages of the disk evolution. The existence and properties of the central cavities in gaseous circumbinary disks were first considered analytically in Artymowicz & Lubow (1994). When CBPs are formed, they migrate towards the central stellar binary, and stall at the outer border of the chaotic zone around the binary, because there is no more matter to cause the migration (Pierens & Nelson 2007; Meschiari 2012; Paardekooper et al. 2012).

After completing this relatively fast migration and being stalled in a resonance cell just at the chaos border, is it possible for a planet to complete the remaining part of the journey and to enter the zone of chaos by any mechanism? As noted in Shevchenko (2017), one such mechanism may be provided by the slow stellar evolution of a parent binary star. Various outcomes of the evolution are possible; however, final supernova explosions may indeed free any planetary material (Kostov et al. 2016).

As proposed in the introduction, here we consider a different mechanism of planetary escape—that of the tidal decay of circumbinary orbits. Let us assess its efficiency. At a given eccentricity \( e_p \), the size of a planetary orbit tidally decays at the rate

\[ \frac{1}{a_p} \frac{da_p}{dt} = -\frac{63}{4} G^{3/2} M_s^{5/2} m_p^{-1} R_p^3 Q_p^{-1} a_p^{-15/2} e_p^2, \]  

(9)

(as may be derived from Equations (1) and (2) in Van Laerhoven et al. 2014).

Comparing Equations (5) and (9), one has

\[ \frac{1}{a_p} \frac{da_p}{dt} = -\frac{4\pi R_p^2 a_p h_p}{GM_m m_p}. \]  

(10)

The formal characteristic timescale for the decay of a planet’s circumbinary orbit from its initial size \( a_p \) to zero (i.e., the variation in orbital radius \( da_p \sim a_p \)) is given by

\[ \tau_0 = \frac{GM_m m_p}{4\pi R_p^2 a_p h_p^2} = \frac{GM_m \rho_p R_p}{3a_p h_p}, \]  

(11)

where \( \rho_p \) is the density of the planet.

The time needed to traverse a half of an integer mean-motion resonance cell at the border of the circumbinary chaotic zone is an order of magnitude shorter. To prove this, let us consider two neighboring integer and half-integer mean-motion resonances \( m:1 \) and \((2m + 1):2 \) between the binary and the planet; then, the relative radial distance between the resonances is \( \frac{a}{a_p} \approx \frac{2}{3(2m + 1)} \), for \( m \gg 1 \). Therefore, in the range of interest \((m = 4, 5, 6)\) one has \( \frac{a}{a_p} \approx 0.07–0.05 \). However, the chaotic layers formed at the integer resonances near the chaos border are broad, and this serves to diminish the distance that must be traversed. (Recall that the measures of the chaotic and regular
components of phase space of the standard map at the critical value of the stochasticity parameter are approximately equal; see Shevchenko 2004.) Therefore, we set \( \xi = \frac{2 \pi}{\tau} \approx 0.05 \), noting that this estimate is approximate and may even be an upper bound. This estimate is graphically confirmed, e.g., by the stability diagram for Kepler-16 in Figure 3 of Popova & Shevchenko (2013), where the planet Kepler-16b is located just at the given distance from the nearest inner chaotic layer.

Thus, for the upper bound of the timescale of traversing a half of an integer mean-motion resonance cell at the border we adopt

\[
\tau = \xi \tau_b, \quad (12)
\]

where \( \xi = 0.05 \).

Again, we assume that the planet, after it has been formed and has completed primordial migration, is stalled at the edge of the circumbinary chaotic zone; therefore, \( a_p = a_{cr} \approx 2.4a_h \) (see Equation (7)). Then, combining Equations (8), (11), and (12), one can express \( \tau \) through the binary period \( \tau_b \):

\[
\tau = B_s G_5^{5/3} M_s^{1/3} \rho_p^{1/2} R_p^{7/3} Q_p^{13/3} T_h^{1/3}, \quad (13)
\]

where \( M_s = 2m_1 = 2m_2 \) \( (m_1 = m_2) \), and the unitless constant \( B_s = \frac{3.34}{2/5} \approx 15.9 \).

Finally in this section, let us discuss in more detail the choice of the initial relative radial location of a CBP at the chaos border. Note, first of all, that the fitting function (a polynomial fit), obtained in Holman & Wiegert (1999), is in fact a severely smoothed version of the reality. The real border between chaotic and regular domains in the phase space of motion is fractal; and this manifests itself most clearly in charts of global dynamics, e.g., in the diagrams of eccentricity versus pericentric distance or eccentricity versus semimajor axis (initial values are implied; see Popova & Shevchenko (2013) and Mudryk & Wu (2006)) for the circumbinary and the circumincomponent cases of such diagrams, respectively. In particular, Kepler-16b appears to be literally “immersed” in the fractal border, formed by the Farey tree of the mean-motion resonances between the central binary and the planet; see Figures 2 and 3 of Popova & Shevchenko (2013). Therefore, the real distance from the close-to-border planet to the nearest instability layers can be much smaller than the distance to the smoothed border, and thus one may even assess the assumed 5% limit as an upper bound.

Regarding the physical grounds for initially placing a CBP so closely to the chaos border, it is important to note the following.

Circumbinary gaseous protoplanetary disks are tidally truncated on the inside (Artymowicz & Lubow 1994); in modern numerical simulations the radius of truncation \( a_d \) of a disk around a binary with \( \mu = 1/2 \) and \( e_h \sim 0 \) is estimated to be in the range from \( \approx 2a_h \) (Silsbee & Rafikov 2015) to \( \approx 3a_h \) (Pelupessy & Portegies Zwart 2013); i.e., it is taken to be either somewhat smaller or somewhat greater than the radius of the averaged (over the fractal structure, as discussed below) border of the circumbinary chaotic zone \( a_c \approx 2.4a_h \), given by Equation (7) at \( e_h = 0 \). Therefore, at present it does not seem possible to derive expected radii of the initial CBP pile-up with a high enough precision, based only on estimates of the radii of central cavities in protoplanetary disks.

As initially hypothesized in Shevchenko (2017), the escape process of a CBP may be eventually due to the orbital evolution of the host stellar binary (due to stellar mass loss and mutual tides), and not a CBP itself. In particular, at an early stage of a close binary’s evolution, due to the tidal transfer of angular momentum from the stellar rotation, the binary’s orbit may widen until the tidally locked state (spin–orbit resonance 1:1) is achieved. (At this moment, the size of the circumbinary chaotic zone is maximum, as revealed in Fleming et al. (2018); see a note in Section 8.) The pre-main-sequence (pre-MS) dwarf binaries with periods less than 7–8 days are effectively circularized by the stellar tidal interaction between companions, and most of the circularization takes place on a rather short timescale, at the beginning of the Hayashi contraction stage (Zahn & Bouchet 1989). The Hayashi stage typically takes \( \sim 1–10 \) Myr (Equation (6) of Zahn & Bouchet 1989), and the binary components reach the tidally locked state on a timescale much shorter than the circularization timescale, as also revealed in Zahn & Bouchet (1989). On the other hand, the lifetimes of circumbinary protoplanetary disks are typically \( \sim 1–10 \) Myr (Kraus et al. 2012; Pelupessy & Portegies Zwart 2013). The duration of the disk era in the history of the solar system was quite similar: \( \sim 10 \) Myr, see Montmerle et al. 2006.) Therefore, one may expect that the circumbinary chaotic zone is maximized already during the disk era, and the formation and the primary (migrational) orbital settlement of the CBP proceeds after (or marginally after) the basic settlement of the parent binary’s orbit. However, the timescales may overlap, and interplay of the processes is possible. In our study we just assume that the parent binary’s orbit is already settled and is circular, and that its size is constant.

4. The Lack of Close Binaries with CBPs

Now let us apply the developed theory and estimate numerically the timescales of the effect in various possible planetary and tidal heating models. Generally, close solar-type binaries with periods less than 10 days are believed to be a product of some dissipative evolution (most likely due to the Lidov–Kozai oscillations in triples, with tidal friction), because they cannot be born in such close pairs; see Moe & Kratter (2018) and references therein. On the other hand, the existing correlation of companion masses and the resemblance of the close-binary fractions for the pre-MS stars and for the MS field stars testify that the evolution to the close state is fast, taking \( \lesssim 5 \) Myr, most likely due to the dissipation in primordial gas (Moe & Kratter 2018). Therefore, one can consider the evolution of a circumbinary planetary system starting from an early state of the binary that is already close.

More than half of all (\( \sim 2000 \)) eclipsing binaries in the first two quarters of the Kepler data have periods less than 7 days (Figure 8 in Slawson et al. 2011), whereas all discovered Kepler CBPs (10 objects) have periods greater than 7 days. The dearth of CBPs of the binaries with \( P \lesssim 5 \) days was established as statistically significant in Armstrong et al. (2014) and Martin & Triaud (2014). This lack can be interpreted as being due to the stellar Lidov–Kozai effect with tidal friction, in the presence of an outer tertiary star (Armstrong et al. 2014; Martin et al. 2015; Muñoz & Lai 2015; Hamers et al. 2016). Conversely, the mechanism studied here does not need a tertiary, although the process can be slower.

To represent the effect graphically, we construct diagrams of mass versus orbital period for twin stellar binaries (Figure 1). The mass is counted for a companion, i.e., it is equal to a twin’s half-mass. The depicted curves are the tidal escape isochrones in several planetary models. The curves are defined by

\[
M = F(t) \quad (\text{in the case of a CBP})
\]

and

\[
M = F(t) \quad (\text{in the case of a CBP itself})
\]

where \( F(t) \) is the tidal escape function for a CBP and a CBP itself, respectively. The two curves are denoted by the appropriate name. In particular, if the binary is not a CBP, the tidal escape isochrones in the planet–stellar models are given by \( m_2 = F(t) \).
Equation (13) with the escape time $\tau$ fixed to $10^9$ (1 billion) yr (in the left panel) and $10^{10}$ yr (in the right panel). The curves for Earth-like rocky planets are drawn in blue, those for super-Earths in green. In the first case, we set $R_p = R_{\text{Earth}}$, $\rho_p = \rho_{\text{Earth}}$, $Q_p = 100$, as adopted in Van Laerhoven et al. (2014). In the second case, the parameters are the same except $R_p = 2R_{\text{Earth}}$.

The curves in the diagrams are olive for Saturn-like giants, orange for Jupiter-like giants, and red for Kepler-35b-like giants. For Saturns, we set $R_p = 9.07R_{\text{Earth}}$, $\rho_p = 0.71\text{ g cm}^{-3}$; for Jupiters, $R_p = 11.0R_{\text{Earth}}$, $\rho_p = 1.33\text{ g cm}^{-3}$; and for Kepler-35b-like giants, $R_p = 0.728R_{\text{Jupiter}}$, $\rho_p = 0.41\text{ g cm}^{-3}$ (as determined in Welsh et al. 2012). For all giants we set $Q_p = 10^5$, as a typical value, according to Goldreich & Soter (1966).

There exists a variety of models of planetary tidal heating. According to Renaud & Henning (2018), in the Andrade and Sundberg–Cooper rheologies the tidal heating can be 10 times or even more greater than in the traditional Maxwell model. To compare graphically the role of the choice of tidal model, the curves for $\zeta = 1$ in both panels of Figure 1 are dashed, and the curves for $\zeta = 10$ are drawn solid. We see that the solid isochrones are somewhat to the right of the dashed ones, thus permitting more planets to escape.

Any planet located on the left of a curve in the diagrams in Figure 1 would be liberated on a timescale that is less than that corresponding to the curve. In total, we see that, on timescales less than the current age of the universe, the proposed mechanism may explain, at least partially, the observed lack of CBPs of close-enough (with periods of several days) stellar binaries. As follows from the diagrams, the mechanism is especially effective for low-mass binaries and for super-Earths.

The increase in the tidal efficiency in the models of Renaud & Henning (2018) can be assessed now only qualitatively, by the order of magnitude; in fact, the efficiency can be more than 10 times greater than in the traditional models. Therefore, an increase of 35 times that is needed to make the described process relevant for 10 Gyr old solar-type binaries with periods of 5 days can be well within reach of the new tidal models. In this framework, the fact that many Kepler CBPs are not orbiting right at the chaos border, but some 10% or further away, can be interpreted as a result of the already-accomplished removal of closer planets, because the tidal decay accelerates (being sharply dependent on the radial distance) as the orbit shrinks.

Of course, the enhanced tidal efficiency is still debatable, but what one can say for sure is that for binaries with orbital periods of 2–3 days or less the tidal decay can compete with any other possible mechanism of CBP removal, even for solar-type binaries and even without any enhancement in the tidal efficiency, as directly follows from the diagram in the right panel of Figure 1. What may be even more important, in the future, is that it may remove more and more planets, as directly follows from the same diagram.

5. Post-CBP Population of Rogue Planets

The main-sequence binary stellar population in the Galaxy has a rather broad distribution of periods (Duquennoy & Mayor 1991), with a median value at $\approx 180$ yr. However, this distribution includes a physically distinct stellar subpopulation, that of the so-called “twin binaries,” i.e. those with almost equal mass (with mass ratios of the companions ranging from $\sim 0.8$ to 1), which form a statistical excess at short orbital periods (Halbwachs et al. 2003; Lucy 2006; Simon & Obbie 2009). For the twins, the median period is $\sim 7$ days, and the upper cut-off of the period distribution is at $\approx 43$ days (Lucy 2006; Simon & Obbie 2009). Note that M dwarfs comprise the majority of stars in the Galaxy, whereas binaries dominate in number over single stars; M dwarfs comprise more than 70% of the Galactic stellar population, and more than 50% of the stellar population are in binaries (Duquennoy & Mayor 1991; Bochanski et al. 2010). Therefore, M-dwarf twin
6. Massive Liberation of CBPs

Now let us consider longer timescales, which may permit massive production of complex chemicals on Earth-like planets. In Figure 2, diagrams of mass versus orbital period are constructed for a rocky Earth-like planet, with insolation and tidal habitability zones (HZs) superimposed, to demonstrate how they overlap with planetary escape isochrones. We adopt the parameters for the standard Earth-like planet, as specified above. To illustrate graphically the role of the choice of tidal model, the diagram in the left panel of Figure 2 is constructed with \( \zeta = 1 \), and that in the right panel with \( \zeta = 10 \). It should be emphasized that the parameters for rocky planets used to construct both diagrams in Figure 2 are standard and the same. The difference is in the choice of the tidal dissipation model.

According to heuristic estimates in Barnes et al. (2009), heating rates of less than 0.04 W m\(^{-2}\) and greater than 2 W m\(^{-2}\) imply non-habitability. Thus, no biogenic chemicals are produced if a planet does not fit this range. We assume that most of complex planetogenic (not only biogenic) chemicals are produced on planets that fit this range; heating rates somewhat higher than the given upper bound can also be plausible, because they allow for active tectonics, and thus a planet can be regarded as an active chemical reactor.

The green-shaded vertical band in the diagrams in Figure 2 is the tidal HZ for a CBP orbiting at the edge of the circumbinary chaotic zone. Its vertical borders are specified by formula (8) with \( h_p = 0.04 \) W m\(^{-2}\) and 2 W m\(^{-2}\), as referenced above. The red and cyan curves are the “hot” and “cold” borders of the insolation HZ, drawn according to the theory of Kopparapu et al. (2013). The blue curves (both dashed and solid) are the escape isochrones corresponding (from left to right in each panel) to escape times of \( 10^5 \), \( 10^6 \), and \( 10^{11} \) yr. The horizontal and vertical dotted lines correspond to the median values of masses and orbital periods for the twin-binary subpopulation. The asterisk marks the location of EZ Aqr A–C. Left: the habitable zones and escape isochrones are for a standard Earth-like rocky planet and \( \zeta = 1 \). Right: the same except \( \zeta = 10 \).
The proposed mechanism provides the liberation timescales in any range, depending on the closeness of the parent binary, and this is an advantage. Indeed, other possible mechanisms act either in young planetary systems (e.g., liberation due to planet–planet scattering, see Rasio & Ford 1996) or in very old planetary systems (e.g., liberation due to post-main-sequence loss of mass of parent stars, see Veras et al. 2014; or liberation due to supernova explosions of parent stars, see Kostov et al. 2016). Thus, the proposed mechanism is able to liberate planets that are on the one hand chemically evolved, and on the other hand not ruined by processes of late stellar evolution.

In massive numerical simulations of the long-term dynamics of CBPs subject to slow inward migration, Sutherland & Fabrycky (2016) found that a migrating planet entering a chaotic layer corresponding to an integer mean-motion resonance (in the vicinity of the circumbinary chaotic zone) with the central binary is liberated virtually always without collision with any component of the parent binary. Even if the initial conditions are chosen arbitrarily inside the central chaotic zone, the collisionless outcome exceeds 80%. Therefore, whichever the mechanism of inward migration might be, the process of liberation of a planet entering the circumbinary chaotic zone is effectively non-nuious for the planet.

7. Discussion

CBPs can be mostly liberated and become rogue and then migrate freely, whereas planetary systems of single stars are generally expected to be stable (as the solar system is, where only Mercury can be ejected on a billion-year timescale, see Laskar 1994, 2008). As described in Shevchenko (2010), the typical mode of disruption of a hierarchical three-body system is a kind of “Lévy unfolding” of the system in both time and space: at the edge of the system’s disruption, the escaping body exhibits Lévy flights in its orbital period and semimajor axis, and in the course of this random process the orbital period and semimajor axis become arbitrarily large until the separatrix between the bound and unbound states of the motion is crossed and the body escapes. Therefore, any escaping particle eventually moves close to the “parabolic separatrix.” As the orbital velocity of a particle in a parabolic trajectory about the barycenter is proportional to \( r^{-1/2} \) (where \( r \) is the radial distance from the barycenter), “at infinity” the escaping particle would have an almost zero velocity with respect to the barycenter; a small surplus is provided by the “final kick” from the parent binary, which allows the planet to cross the separatrix. The diffusion of chemically evolved planets inside the Galaxy may serve to disseminate the planetogenic and biogenetic chemicals even outside the Galactic habitable zone. This annular concentric Galactic zone has a rather restricted radial size, as revealed in Lineweaver et al. (2004).

Why should one care about the chemically evolved status of ejected planets? It is plausible to assume that planetary chemicals are indeed necessary in some way for long-lasting galactic chemical evolution, as, analogously, stellar-born metals are necessary. Therefore, (1) the ejected planets must be chemically evolved in some sense (enriched by complex chemicals), (2) the ejection process must keep the produced matter safe. Both these conditions are obviously satisfied in the proposed scenario, because the process is slow enough and mostly collisionless. As we know from the sole example of Earth, the evolution to, e.g., the superhabitability stage (as defined in Heller & Armstrong 2014), associated with the maximum in biomass production, may take some billion years. Therefore, it may need gigayears for a planet to become chemically (or biochemically) evolved.

Similar massive processes in other galaxies may depend on their type. In 1969, an excess of flux (the so-called UV upturn) was discovered in the far-ultraviolet spectrum of elliptical galaxies, in the course of pioneering observations of the bulge of M31 from the Stargazer Orbiting Astronomical Observatory 2 (Code 1969). As later on suggested and argued in Han et al. (2007, 2009), the UV upturn is caused by an old population of hot helium-burning binary stars that lost their hydrogen-rich envelopes due to binary interactions. This reveals the presence of a large number of short-period binaries (and presumably circumbinary planetary systems) in elliptical galaxies. Taking into account that elliptical galaxies contain many more stars (by one or two orders of magnitude) than spiral ones, one comes to the conclusion that the described mechanism of production of chemically evolved rogue planets may occur on far greater scales in typical elliptic galaxies than in our Galaxy.

Habitability properties of CBPs are of especial interest. As argued in Shevchenko (2017), striking analogies exist between the habitability conditions on CBPs and on the Earth. In its habitability properties, the Earth seems to mimic a typical CB in certain classes of stellar binaries: according to Shevchenko (2017), a system consisting of a planet orbiting at the edge of the circumbinary chaotic zone around a typical M-dwarf twin binary is a photo-tidal equivalent of the Sun–Earth–Moon system. In this respect, of particular interest in the diagrams in Figure 2 is the quadrangle formed by the boundaries of the two intersecting bands corresponding to the tidal and insolation habitable zones. CBPs of any binaries in this quadrangle are favorable for the production of biogenetic chemicals. Tantalizingly, one can see that (1) this area tends to overlap with the maximum of the expected distribution of the twin-binary subpopulation (this maximum is at the intersection of the horizontal and vertical dotted lines, corresponding to the median values of masses and orbital periods for twin binaries); (2) it is located between the escape isochrones corresponding to escape times of \( 10^9 \) and \( 10^{11} \) yr, which are long enough for bio-evolution but shorter than stellar lifetimes. Indeed, the main-sequence lifetime of M dwarfs is up to \( 10^{11} \) yr (Laughlin et al. 1997).

The asterisk in the diagrams marks the location of the M-dwarf binary EZ Aqr A–C, as specified by the values of orbital period and mass taken from Delfosse et al. (1999). According to Popova & Shevchenko (2016), a CBP orbiting at the edge of the circumbinary chaotic zone of this binary (which is, by the way, a close neighbor of the Sun) can belong to the insolation HZ. Here we see that it can also belong to the tidal HZ; moreover, the timescale of escape of such a planet can be as short as \( 10^9 \) yr.

What are the general observable signatures of the considered effect? They can be basically twofold, comprising its manifestations in statistical and physical properties of (1) circumbinary planetary systems and (2) rogue planets. In the first case, the effect can provide the lack of observed CBPs belonging to close-enough binaries, as described above. In the second case, one should underline that the ejected planets interact with field stars (for a review on similar stellar interactions, see Section 3.1 of Yu & Tremaine 2003), and specifically with binaries. They can even be temporarily
captured by binaries, analogously to the process of capture of dark matter particles by binaries, considered in Rollin et al. (2015). Concerning observations of individual rogue planets, post-CBPs may indeed have specific physical properties that are potentially observable (Sutherland & Fabrycky 2016).

An inspection of Equation (13) and Figure 1 makes it clear that the shortest libration timescales are achieved, on the one hand, for large rocky planets (super-Earths), and on the other hand for CBPs in systems of low-mass binaries (the lower a binary’s mass, the shorter the timescale). This allows one to conclude that observational signatures of the effect may comprise: (1) a prevalence of super-Earths in the whole population of rogue planets (of course, if this mechanism were the only source of rogue planets); (2) a mass-dependent paucity of CBPs in systems of low-mass binaries: the lower the stellar mass, the greater the paucity. Note that there already exists observational evidence for a moderate abundance of rogue super-Earths; see Mróz et al. (2017).

An important distinctive property of the proposed mechanism is that it is not expected to fill interstellar space with small bodies, such as interstellar planetesimals. Indeed, according to Equation (13), the escape timescale is proportional to a circumbinary particle’s size to the power \(\frac{2}{3}\), and this cannot be balanced by any realistic correlation with \(\rho_\odot\) or \(q_\odot^\prime\). On the other hand, due to variations of the planetary Hill radius with distance from either of the two parent stars, an escaping giant planet can in parallel release dozens of its irregular satellites. Therefore, production of objects such as 1I/‘Oumuamua is not excluded.

It is worth noting that the tidal mechanism for escape of circumbinary material, described in this article, can also be relevant to astrophysical systems other than planetary ones. For example, relevant orbital configurations of circumbinary “satellites” may occur around binary asteroids or trans-Neptunian objects, around rotating contact binaries (such as cometary nuclei, many asteroids, and trans-Neptunian objects), and around binary black holes. Analysis of the efficiency of the mechanism in such different settings is beyond the scope of this paper, but it can be worth studying.

8. Conclusions

We have shown that circumbinary planetary systems are subject to universal tidal decay (shrinkage of orbits), caused by the forced orbital eccentricity inherent to them. CBPs are ejected from parent systems when they enter the circumbinary chaotic zone.

On shorter timescales (less than the current age of the universe), the proposed effect may explain, at least partially, the observed lack of CBPs of close-enough (with periods <5 days) stellar binaries. On longer timescales (greater than the age of the universe but well within stellar lifetimes), they may provide massive liberation of chemically evolved CBPs.

It should be underlined that the phenomenon of tidal decay of circumbinary systems is universal. Here we have considered planetary systems, but in fact it is present in any circumbinary system of gravitating bodies.

While this paper was in the reviewing process, a preprint was posted and an article published (Fleming et al. 2018), where the lack of close isolated binaries with CBPs was also explained by the destabilization of CBP orbits due to their entering the circumbinary chaotic zone. However, the mechanism of the entry is different from that considered above. In our scenario, the planetary orbit slowly shrinks, while the chaotic zone stays constant in size. In the tidal scenario of Fleming et al. (2018), in contrast, the chaotic zone swells (as the binary’s orbit widens, due to the tidal transfer of angular momentum from stellar rotation), while the planetary orbit stays constant in size. It should be noted that the tidal scenario of Fleming et al. (2018) is relevant to an early (pre-main-sequence) stage of evolution of the host star (see Section 3), whereas our scenario acts on much longer timescales, and is thus capable of providing the escape of chemically evolved planets.

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ORCID iDs

Ivan I. Shevchenko https://orcid.org/0000-0002-9706-0557

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