Long-term Stability of Planets in the α Centauri System. II. Forced Eccentricities

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Abstract

We extend our study of the extent of the regions within the α Centauri AB star system where small planets are able to orbit for billion-year timescales to investigate the effects of minimizing the forced eccentricity of initial trajectories. We find that initially prograde, circumstellar orbits require a piecewise quadratic function to accurately approximate forced eccentricity as a function of semimajor axis, but retrograde orbits can be modeled using a linear function. Circumbinary orbits in the α Centauri AB system are less affected by the forced eccentricity. Planets on circumstellar orbits that begin with eccentricity vectors near their forced values are generally stable, up to \( \sim 10^3 \) years, out to a larger semimajor axis than are planets beginning on circular orbits. The amount by which the region of stability expands is much larger for retrograde orbits than it is for prograde orbits. The location of the stability boundary for two-planet systems on prograde, circular orbits is much more sensitive to the initial eccentricity state than it is for analogous single-planet systems.

Key words: binaries: general – methods: numerical – planets and satellites: dynamical evolution and stability

1. Introduction

The α Centauri star system contains the solar system’s nearest stellar neighbors. The primary, α Centauri A, is slightly more massive than the Sun, the secondary, α Centauri B, has slightly less than a solar mass, and the two stars orbit one another with a period of \( \sim 80 \) years and an eccentricity just over 0.5. If an Earth-like planet is present in the system, it could in another with a period of \( \sim 10^4 \) years, out to a larger semimajor axis than are planets beginning on circular orbits. The amount by which the region of stability expands is much larger for retrograde orbits than it is for prograde orbits. The location of the stability boundary for two-planet systems on prograde, circular orbits is much more sensitive to the initial eccentricity state than it is for analogous single-planet systems.

Because the binary companion induces a forced eccentricity upon the orbits of planets in orbit around either star, planets initially on circular orbits begin with nonzero free eccentricities (Michtchenko & Ferraz-Mello 2001; Michtchenko & Malhotra 2004). The total eccentricities of such planets oscillate on timescales of the order of \( \sim 10^4 \) years, reaching peak values approximately twice as large as their forced eccentricity. Planets on circumstellar orbits in the eccentric binary star system γ Cephei that have initial eccentricities equal to their forced eccentricity would experience far smaller oscillations than planets at the same semimajor axis beginning on circular orbits, and thus would not reach as high values of eccentricity (Giuppone et al. 2011). Therefore, we expect that planets on circumstellar orbits in the α Centauri AB system with appropriately phased initial eccentricities can be stable at a somewhat larger semimajor axis than are planets with initially circular orbits.

Our study uses updated values of the stellar masses and the configuration of the binary orbit given in the observational ephemeris derived by Pourbaix & Boffin (2016), which we list in Table 1. We include a brief comparison of the stability limits of particles on circular orbits using these new values to compare with the limits from our study in Paper I, which used stellar parameters from Pourbaix et al. (2002). Note that the current uncertainties in stellar parameters are comparable in magnitude to the differences between the 2002 values and those from 2016.

Some studies of planetary stability in binary star systems have been performed starting the planets on circular orbits (Wiegert & Holman 1997; Popova & Shevchenko 2012; Paper I). Other works (Giuppone et al. 2011; Andrade-Ines & Michtchenko 2014; Rafikov & Silsbee 2015; Silsbee & Rafikov 2015; Andrade-Ines et al. 2016; Andrade-Ines & Eggl 2017) have identified that choosing the planetary orbits relative to the architecture of the binary orbit may play a larger role in the formation and stability of planets within these systems. Additionally, the first simulations that we performed in our study of the stability of multi-planet systems orbits α Cen A or α Cen B showed that initially circular orbits lead to far less stable configurations than around single stars (Quarles & Lissauer 2018). As a result, we were inspired to investigate these effects on the stability of small (Earth-mass) planets within α Centauri AB.

We present herein the results of simulations that analyze planets starting near their forced eccentricities to quantify the effects on orbital stability. Our methods and the initial conditions for our simulations are summarized in Section 2. In Section 3, we compare the stability of particles on initially prograde orbits about α Centauri B using the model setup from Paper I with updated system parameters and methods in this work. We discuss forced eccentricities within the α Centauri AB system in Section 4. The results of our study for single-planet systems are presented in Section 5. Results for an
as one of the following: a collision with either star, a body is ejected from the system, or a specified time interval elapses. We consider planets initially on circumstellar orbits to be ejected if they reach radial distances larger than 50 au from their host star and those on circumbinary orbits to be ejected if their distance from the center of mass of the system exceeds 200 au.

Our simulations model the planets as fully interacting (massive) bodies with mass equal to that of the Earth. Treating each planet individually (rather than as a large group of test particles) and using the hybrid symplectic method for integration with mercury6 allows us to appropriately scale the choice of the starting time step in terms of the Keplerian period (relative to the hosting star) while maintaining a tight control on the errors in energy and angular momentum.

All of our simulations use the nominal values for the stellar masses and the configuration of the binary orbit given in the observational ephemeris derived by Pourbaix & Boffin (2016), which we list in Table 1. We also report the uncertainties given in Pourbaix & Boffin (2016) for completeness. Our simulations begin the stellar orbit at a mean anomaly of 209°.6901, which corresponds to an epoch of JD 2452276.

| Element | Value |
|---------|-------|
| $a$ (au) | 17.66 ± 0.026 |
| $a$ | 23.78 ± 0.04 |
| $i_1$ (°) | 79.32 ± 0.044 |
| $i_2$ (°) | 232.3 ± 0.11 |
| $\Omega$ (°) | 32.78 ± 0.04 |
| $e$ | 0.524 ± 0.0011 |
| $P$ (years) | 79.91 ± 0.013 |
| $M_a (M_\odot)$ | 1.133 ± 0.0050 |
| $M_b (M_\odot)$ | 0.972 ± 0.0045 |

Note. Orbital ephemeris assumed for the binary orbit taken from Pourbaix & Boffin (2016). The smallness of the uncertainties in the parameters illustrate the high accuracy of the orbital solution.

The semimajor axis has been derived from other relevant quantities via Kepler’s third law.

2. Methodology

The numerical simulations in this paper use the same custom version of the mercury6 integration package designed to efficiently integrate orbits within a binary star system (Chambers et al. 2002) that we employed in Paper I to evaluate the long-term stability of planetary orbits within the α Centauri system. Similarly to Paper I, the simulations assume standard Newtonian gravity and integrate each trajectory until a termination event occurs. We define our termination events as one of the following: a collision with either star, a body is ejected from the system, or a specified time interval elapses. We consider planets initially on circumstellar orbits to be ejected if they reach radial distances larger than 50 au from their host star and those on circumbinary orbits to be ejected if their distance from the center of mass of the system exceeds 200 au.

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The planets reside within the binary plane in either prograde (inclination, $i_1 = 0°$) or retrograde ($i_2 = 180°$) motion relative to the binary orbit, where the planet’s forced eccentricity is expected to be similar to or larger than those of analogous planets whose orbits are inclined to the binary plane (Andrade-Ines et al. 2016). In our prograde runs, we begin the planet(s) with a longitude of periastron relative to the binary plane (Michtchenko & Ferraz-Mello 2001) defined by:

$$\Delta \omega \equiv \omega_1 - \omega_{\text{bin}},$$

the longitude of ascending node $\Omega$ is zero due to the near coplanarity, and the mean anomaly $M$ is determined for each planet using the relation with the golden ratio given in Smith & Lissauer (2009), where $M_1 = 222.492$ and $M_2 = 84.984$ for the first and second planet, respectively. We also determine $\Delta \omega$ numerically (See Section 4.1), as the previous works (Andrade-Ines et al. 2016) make certain assumptions that would influence the value of $\Delta \omega$ and find that its value varies with the orbital direction of the particle. The conditions for the retrograde simulations are almost identical to the prograde simulations, except that their longitude of periastron is misaligned with the binary orbit such that $\Delta \omega = -154°$ with respect to the plane of the sky, which corresponds to $\Delta \omega = 180°$ when measuring relative to the binary orbital plane.

We study planets in circumstellar orbits over a range of initial semimajor axes $a_1$ starting at 0.5 au around either stellar component and extending to 4 au (prograde) and 5.6 au (retrograde). Particles in circumbinary orbits cover a larger range of initial semimajor axes $a_1$ (40–90 au), as motivated from the results of Paper I.

Dynamical effects, such as a mean motion resonances, are expected to have their largest effects on system lifetime over small intervals in the planet semimajor axis near the stability limit. Therefore, we take small steps (0.02) in the initial period ratio ($T_{\text{bin}}/T_i$) between the outermost planetary body and the companion star in order to resolve these small details. Our other runs that investigate the full range of semimajor axes use a constant increment in semimajor axis ($\Delta a_1 = 0.005$ au). Resonant effects can occur over a broader range in semimajor axes in the circumbinary runs, where larger steps ($\Delta a_1 = 0.1$ au) are taken in the planet’s semimajor axis.

3. Comparison with Paper I

In Paper I, we investigated the α Cen AB system using the best known parameters of the binary at the time (e.g., Pourbaix et al. 2002) and used standard assumptions on the planetary orbit (i.e., $\omega = \Omega = M = 0°$). We perform intermediate simulations with the initial planetary semimajor axis from 2.4 to 3.2 au and only update the binary orbit. We find that this change shifts the instability regions near mean motion resonances outwards in planetary semimajor axis, but occur near the appropriate mean motion resonance. In this work, we have updated our methodology in choosing a different planetary longitude and a slightly different binary orbit (See Section 2). We illustrate the effects of these changes by comparing the lifetimes of planets on prograde, planar, initially circular orbits around α Cen B. We determine the bulk stability of the ensemble of planets in this region as 27.2%, 21.6%, and 26.9% for the simulations from Paper I, our intermediate runs, and our new simulations presented in Figure 1, respectively.

Note that while the differences in these values are useful for comparing the effective limits of the stability zones for these three cases, they would all go up or down depending on the assumed window of planetary semimajor axis values considered.

Figure 1 shows the contrast between the methodology from Paper I and our current one that updates the binary orbit and
uses a different initial planetary longitude. The locations of the mean motion resonances are displaced due to the updated masses of the stars, so we compare the lifetimes of planets at a similar semimajor axis in Figure 1(a), and those at similar period ratio in Figure 1(b). The stability limit is slightly farther out (∼2.59 au) compared to the previously determined value (2.54 au) as shown in Figure 1(a), where in both cases the stability limit is near the 19:1 mean motion resonance. This is partly due to the shift of the N:1 mean motion resonances (Figure 1(b)), where particles were typically stable at period ratios larger than 19. Also some “lucky” orbits may not appear anymore due to a different initial phase of the planet. Figure 1(c) shows that only a small fraction of initial conditions lead to substantially different outcomes (i.e., larger than an order of magnitude), indicating that the two works are in rough agreement in the region close to the stability limit.

4. Forced Eccentricities

4.1. Identifying the Forced Eccentricity

We present example simulations in Figure 2 to demonstrate how the maximum eccentricity varies for an Earth-mass planet of semimajor axis $a_1 = 1.5$ au within the phase space of its initial eccentricity, $e_1$, and longitude of periastron relative to the binary orbit, $\Delta \varpi$ (see Section 2). Each panel in Figure 2 uses results from a uniform grid of simulations in $e_1 - \Delta \varpi$ space resulting in a resolution of 101 × 180 initial conditions (0 ≤ $e_1$ ≤ 0.2 in steps of 0.002 and 2° increments in $\Delta \varpi$) over a timescale of 100,000 years. The contours are drawn using the maximum eccentricity achieved over a given simulation, where we include contour levels only up to $e_{\text{max}} = 0.2$ in steps of 0.005. In this way, we can define numerically the forced eccentricity vector as the initial conditions that produces the lowest maximum eccentricity measured, which is similar to the definition used by Andrade-ines et al. (2016, see their Section 3.1).

Figure 2(a) shows that a minimum occurs for $e_1 = 0.05$ and $\Delta \varpi = 0°$ for a prograde orbit, and Figure 2(b) reveals that the minimum for a retrograde orbit occurs when $e_1 = 0.065$ and $\Delta \varpi = -154°$. If we perform similar integrations at larger and smaller semimajor axes of the planet, the minimum value of $e$ moves up or down in response to a greater or lower perturbation, respectively. However, the value of $\Delta \varpi$ remains unchanged as it is set by the binary orbit, which we keep fixed among all of our simulations.

We perform a similar analysis for circumbinary orbits, where we chose $a_1 = 85$ au, informed by Paper I. Figure 3 illustrates these results, with prograde orbits in Figure 3(a) and retrograde
orbits in Figure 3(b). There is a stark contrast between Figures 2 and 3, where the latter indicates initially circular orbits to have the lowest value in maximum eccentricity.

4.2. Eccentricity Variations

Figure 4 displays the evolution of the total eccentricity vector of planets on prograde orbits with $a_1 = 1.5$ au and initial eccentricity either equal to zero or near the forced eccentricity over 20,000 years (a few secular cycles). Panels 4(b) and (d) show the time series evolution of the osculating eccentricity of the planet. The blue dashed horizontal line in these figures marks the magnitude of the forced eccentricity, and the red solid horizontal line marks the maximum value of eccentricity encountered within the first 5000 years. The difference between the maximum eccentricity in Figures 4(b) and (d) is non-trivial. Moreover, starting the planet at a semimajor axis near the stability limit increases this difference in eccentricity variation.

We perform a similar set of simulations for retrograde orbits using the appropriate components of the forced eccentricity vector derived from Figure 2(b). These retrograde simulations,
whose results are shown in Figure 5, exhibit a similar trend in lowering the maximum eccentricity when starting the planet with an appropriately phased eccentricity.

4.3. Formulas for Forced Eccentricity

Recently, Andrade-Ines et al. (2016) and Andrade-Ines & Eggl (2017) investigated how the forced eccentricity varies within the context of a restricted three-body problem using first- and second-order perturbation theories. We are exploring a similar problem with planets in α Centauri AB, specifically with two circumstellar configurations. Their numerical procedure for determining the forced eccentricity makes use of techniques based upon frequency analysis on numerical integration (Laskar 1990; Michtchenko et al. 2002), where a time averaged component of the eccentricity vector is determined iteratively. We follow a similar iterative process using our values for $\Delta \omega$ determined in Section 4.1 in a series of numerical simulations (Noyelles et al. 2008; Couetdic et al. 2010).
Figure 4. Components of the eccentricity vectors (a) and (c) and the magnitude of eccentricity for 20000 years of evolution for a prograde planet initially orbiting $\alpha$ Cen B with a semimajor axis of 1.5 au. The planet represented on the top row (a) and (b) begins on a circular orbit, and the planet represented on the bottom row (c) and (d) begins near the forced eccentricity due to $\alpha$ Cen A. The blue arrows and blue dashed lines correspond to the forced components of eccentricity. The red horizontal lines mark the maximum eccentricity reached in the first 5000 years of evolution.

Figure 5. Components of the eccentricity vectors (a) and (c) and the magnitude of eccentricity for 20000 years of evolution for a retrograde planet initially orbiting $\alpha$ Cen B with a semimajor axis of 1.5 au. The planet represented on the top row (a) and (b) begins on a circular orbit, and the planet represented on the bottom row (c) and (d) begins near the forced eccentricity due to $\alpha$ Cen A. The blue arrows and blue dashed lines correspond to the forced components of eccentricity. The red horizontal lines mark the maximum eccentricity reached in the first 5000 years of evolution.
Our simulations seek to identify the maximum eccentricity through a grid of initial conditions over a range of the planet’s initial eccentricity $e_1$ (0.0–0.20) in steps of 0.0005 and initial semimajor axis $a_1$ (0.5–3.5) in steps of 0.005 au and using the relative longitude of periastron values determined from Section 4.1. Following from Figure 2, we identify the forced eccentricity $e_F$ as the lowest magnitude of the maximum eccentricity at a given planet semimajor axis $a_1$. Figure 6 shows how the forced eccentricity varies with $a_1$ for circumstellar planets orbiting each star in both the prograde (blue) or retrograde (red) directions. Andrade-Ines et al. (2016) adopted an expansion to second order in perturbation theory, where we have implemented a hybrid approach between numerical and analytic methods. Andrade-Ines & Eggl (2017) developed a higher-order scheme to estimate the forced eccentricity of planets on prograde orbits, which is plotted as a dashed curve in Figure 6. While it matches our numerical results nicely at small semimajor axes, it tends to overestimate the forced eccentricity relative to our numerical simulations for $a_2 > a_1$.

We fit the blue curves in Figure 6 using a quadratic function of the form

$$e_F = C_1 a_1^2 + C_2 a_1 + C_3,$$

where $C_1$, $C_2$, and $C_3$ are our fitted coefficients. A single function can be fit for semimajor axes less than 2 au, but tend to overestimate the forced eccentricity at larger semimajor axes. Thus, we split the parameter space and fit coefficients piecewise using 2 au as a break point. The results of our fitting are given in Table 2. The forced eccentricity behaves much more linearly for the retrograde cases, so we implement the following equation that has a form similar to Andrade-Ines et al. (2016), which uses the disturbing function from Heppenheimer (1978):

$$e_F = C_1 \frac{a_1}{a_{bin}} \frac{e_{bin}}{1 - e_{bin}},$$

where $C_1$ is a fitted coefficient from our simulations, $a_{bin}$ denotes the binary semimajor axis, and $e_{bin}$ marks the...
eccentricity of the binary orbit. The results of our fitting are given in Table 3.

5. Regions Where a Single Planet Can Remain Stable

Having deduced an approximate value for the forced eccentricity vector (see Section 4.2), we investigate the differences in stability between planets initially on circular orbits and those starting with the forced eccentricity vector. We focus on the region near the stability boundary that we found in Paper I for nearly coplanar, circular orbits. As shown in Paper I, N:1 MMRs destabilize specific regions, and thus we proceed with steps of 0.02 in the initial period ratio between the secondary star and the planet.

By choosing our steps in the x-axis in this way, we can more uniformly sample regions where the N:1 MMRs would be active.

Figure 7 shows the results of our simulations for both initially prograde and retrograde planets around α Cen A, respectively. In Figure 7(a), we mark the lifetime of a prograde planet as a function of the starting semimajor axis. Stable (>1 Gyr lifetime) runs with initially circular (blue) or eccentric (red) orbits are filled, where unstable runs are open circles carrying the respective color-code. Runs that are stable for both circular and eccentric orbits are overplotted in purple. The vertical dashed lines and labels mark the locations of N:1 mean motion resonances with the binary orbit.

eccentricity of the binary orbit. The results of our fitting are given in Table 3.

Figure 7. Lifetime (panels (a) and (c)) and maximum eccentricity (panels (b) and (d)) of prograde and retrograde planets orbiting α Cen A as a function of the starting planetary semimajor axis. Stable (>1 Gyr lifetime) runs with initially circular (blue) or eccentric (red) orbits are filled, where unstable runs are open circles carrying the respective color-code. Runs that are stable for both circular and eccentric orbits are overplotted in purple. The vertical dashed lines and labels mark the locations of N:1 mean motion resonances with the binary orbit.
We plot the maximum eccentricity of the stable configurations attained over the 1 Gyr simulated in Figure 7(b). From this view, we see that the initially circular orbits typically rise to higher values of eccentricity. Moreover, the elevated eccentricities due to interactions with both the N:1 and N:2 MMRs with the binary are readily apparent.

For retrograde orbits, we examine much larger distances from the host star, ~3.4–6.0 au. Figure 7(c) illustrates that the lifetimes of the planets are strikingly different between our two cases, circular or eccentric, where retrograde planets starting near their forced eccentricities can remain stable on a 1 Gyr timescale at a semimajor axis of ~5 au. Elevated levels of the maximum eccentricity appear displaced from our marked locations for the N:1 MMRs (Figure 7(d)).

For completeness, we show results when the planet begins in a prograde and retrograde orbit around α Cen B in Figure 8. Due to the symmetry of the problem, we find the borders of stability (Figures 8(a) and (c)) appear at nearly similar MMRs and shift to smaller semimajor axis values.

Section 4.2 shows that circumbinary orbits are not affected strongly by the assumption on the initial eccentricity, but are dependent on the initial phase relative to the binary orbit (see Figure 3). Thus, we provide results of circumbinary planets in which the respective initial longitude is modified between the

Figure 8. Lifetime (panels (a) and (c)) and maximum eccentricity (panels (b) and (d)) of prograde and retrograde planets orbiting α Cen B as a function of the starting planetary semimajor axis. Stable (>1 Gyr lifetime) runs with initially circular (blue) or eccentric (red) orbits are filled, where unstable runs are open circles carrying the respective color-code. Runs that are stable for both circular and eccentric orbits are overplotted in purple. The vertical dashed lines and labels mark the locations of N:1 mean motion resonances with the binary orbit.
Figure 9. Lifetime (top) and maximum eccentricity (bottom) of planets in circumbinary orbits around $\alpha$ Cen AB as a function of the starting planetary semimajor axis. Stable (>1 Gyr lifetime) runs with initially prograde (blue) or retrograde (red) orbits are filled, where unstable runs are open circles carrying the respective color-code. Runs that are stable for both prograde and retrograde orbits are overplotted in purple. The vertical dashed lines and labels mark the locations of $N$:1 mean motion resonances with the binary orbit.

Figure 10. Lifetime (top) and maximum eccentricity (bottom) of prograde two-planet systems orbiting $\alpha$ Cen A as a function of the starting planetary semimajor axis of the outermost planet, where the planets are separated by $12R_{H_\text{m}}$ (see Equation (4)). Stable (>1 Gyr lifetime) runs with initially circular (blue) or eccentric (red) orbits are filled, where unstable runs are open circles carrying the respective color-code. We note that the termination event is usually a collision between the two planets and the maximum eccentricity does not have to be very large for our definition of instability to occur. The top $x$-axis labels and vertical dashed lines mark the locations of $N$:1 mean motion resonances of the outer planet with the binary orbit. Note that all of the stable systems have $e_{2,\text{max}} < 0.15$. 
prograde or retrograde simulations. Figure 9 (top panel) illustrates that retrograde planets can stably orbit ~20 au closer to the binary than in the case of prograde. These orbits are typically more eccentric than in the circumstellar case and likely allowed due to the initial phase difference with the binary orbit. The locations of stable particles are slightly displaced compared to our results in Paper I, which is mainly a result of the orbital solution of the binary used in this work.

### 6. Stability of Two-planet Systems around α Cen A

We briefly investigate the lifetime and maximum eccentricity of the outermost planet in prograde two-planet systems orbiting α Cen A. Our simulations follow a similar approach as in Section 5 in terms of the steps in the semimajor axis $a_2$. The other planet is placed interior to $a_2$ using the formalism developed in Smith & Lissauer (2009). The difference between the initial semimajor axes of the two planets is taken to be $12R_{H,m}$, where the mutual Hill Radius of the two planets is given by (Chambers et al. 1996)

$$R_{H,m} = \frac{(a_1 + a_2)}{2} \left( \frac{m_1 + m_2}{3(M_1 + m_1)} \right)^{1/3}. \quad (4)$$

We explore a wider range of planet spacings in Quarles & Lissauer (2018). The planets either both have initially circular orbits or both begin with the appropriate forced eccentricity (Equation (1)).

Figure 10 (top panel) shows the systems' lifetimes, i.e., when a termination event (ejection or collision) occurs for either of the two planets. The growth of eccentricity when the planets begin on circular orbits typically leads to a collision between the planets on a short ($\lesssim 10$ Myr) timescale, although it is possible for collisions with the stars or ejection (radial distance $> 100$ au) from the system to occur. We continued our circular runs inward (decreasing $a_2$) and found that stable configurations were possible for $a_2 \sim 1$ au (Quarles & Lissauer 2018). The lifetimes of two planets starting near their forced eccentricities is strongly correlated with proximity to the binary N:1 MMRs, which act as a destabilizing force. Broad regions of stability are seen for values of $a_2 \lesssim 2.1$ au.

Figure 10 (bottom panel) shows the maximum eccentricity of the outermost planet, $e_{2,\text{max}}$, up to the termination event. This contrasts sharply with the figures in Section 5 because much smaller eccentricities are sufficient for a run to be stopped, where in the previous cases the unstable configurations typically grew to $e_1 \gtrsim 1$. The maximum eccentricity, $e_{2,\text{max}}$, did not increase much over the initial value ($e_{2,0} \sim 0.05$) for the stable cases.

### 7. Conclusions

The stability of Earth-mass planets in the α Centauri AB system depends more strongly on the planet’s initial eccentricity vector than was assumed in Paper I. This is evident when we measure the maximum value of eccentricity and vary the initial longitude for planets orbiting either stellar component. The binary orbit from Pourbaix & Boffin (2016) has shifted the dynamics slightly, where these changes largely reside within the chaotic regimes that are dependent on the starting semimajor axis $a_1$ and initial longitude of the planet.

We determine numerically a relation for α Cen where the forced eccentricity can be estimated in either a prograde or retrograde direction relative to the orbital motion of the binary. A piecewise quadratic formula of the forced eccentricity $e_F$ as a function of $a_1$ is appropriate for most practical applications of prograde planets, where retrograde planets are well approximated using a linear function in $a_1$.

Stable planets with lifetimes of 1 Gyr occur at larger values of $a_1$ when they begin at or near the corresponding forced eccentricity. This results in a slight difference (~0.1–0.3 au) in the largest stable semimajor axis when considering prograde orbits around either star, but more substantial differences (~1 au) occur for planets in retrograde orbits. Retrograde planets can occupy stable orbits with $a_1 \sim 5$ au for at least one billion years when $e_1 \approx e_F$.

The forced eccentricity of circumbinary planets in α Cen is small; thus, we simulated initially circular orbits in either a prograde or retrograde direction as in Paper I. The differences in our circumbinary results on stability as a function of $a_1$ stem from the updated orbit (e.g., stellar masses) by Pourbaix & Boffin (2016).

The existence of a pair of planets alters the prospects of stability, and the system lifetime becomes more sensitive to the assumed initial eccentricity vector for planets on prograde circumbinary orbits. When both planets begin near their forced eccentricities, the pair can survive up to much larger values of semimajor axis. We performed a very narrow investigation of multiple planets in α Cen for this work, but present a more intensive study in Quarles & Lissauer (2018).

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