Planet-mediated precision reconstruction of the evolution of the cataclysmic variable HU Aquarii

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ABSTRACT
Cataclysmic variables (CVs) are binaries in which a compact white dwarf accretes material from a low-mass companion star. The discovery of two planets in orbit around the CV HU Aquarii (HU Aqr) opens unusual opportunities for understanding the formation and evolution of this system. In particular, the orbital parameters of the planets constrain the past and enable us to reconstruct the evolution of the system through the common-envelope phase. During this dramatic event, the entire hydrogen envelope of the primary star is ejected, passing the two planets on the way. The observed eccentricities and orbital separations of the planets in HU Aqr enable us to limit the common-envelope parameter $\alpha = 0.45 \pm 0.17$ or $\gamma = 1.77 \pm 0.02$ and measure the rate at which the common envelope is ejected, which turns out to be copious. The mass in the common envelope is ejected from the binary system at a rate of $\dot{m} = 1.9 \pm 0.3 \, M_\odot \, \text{yr}^{-1}$. The reconstruction of the initial conditions for HU Aqr indicates that the primary star had a mass of $M_{ZAMS} = 1.6 \pm 0.2 \, M_\odot$ and a companion in a $a = 25–160 \, R_\odot$ (best value $a = 97 \, R_\odot$) binary. The two planets were born with an orbital separation of $a_a = 541 \pm 44 \, R_\odot$ and $a_b = 750 \pm 72 \, R_\odot$, respectively. After the common envelope, the primary star turns into a $0.52 \pm 0.01 \, M_\odot$ helium white dwarf, which subsequently accretes $\sim 0.30 \, M_\odot$ from its Roche lobe filling companion star, grinding it down to its current observed mass of $0.18 \, M_\odot$.

Key words: methods: numerical – planets and satellites: dynamical evolution and stability – planets and satellites: formation – planet–star interactions – stars: evolution – stars: individual: HU Aquarii.

1 INTRODUCTION
The cataclysmic variable (CV) HU Aquarii (HU Aqr) currently consists of a $0.80 \, M_\odot$ white dwarf that accretes from a $0.18 \, M_\odot$ main-sequence companion star (Schwope et al. 2011). The transfer of mass in the tight $a = 0.82 \, R_\odot$ orbit is mediated by the emission of gravitational waves and the strong magnetic field of the accreting star (Verbunt & Zwaan 1981). Since its discovery (Schwope, Thomas & Beuermann 1993), irregularities of the observed variations have led to a range of explanations, including the presence of circumbinary planets (Schwarz et al. 2009; Goździewski et al. 2012; Horner et al. 2012b). Detailed timing analysis has eventually led to the conclusion that the CV is orbited by two planets (Hinse et al. 2012), a $5.7 M_{Jup}$ planet in an $\sim 1205 \, R_\odot$ orbit with an eccentricity of $e = 0.20$ and a somewhat more massive ($7.6 M_{Jup}$) planet in a wider $1785 \, R_\odot$ and eccentric $e = 0.38$ orbit (Horner et al. 2012b). Although the two-planet configuration turned out to be dynamically unstable on a $1000–10,000 \, \text{yr}$ timescale (Horner et al. 2012b, see also Section 4), a small fraction of the numerical simulations exhibit long-term dynamical stability (for model B2 in Wittenmyer et al. 2012, see Table 1 for the parameters).

It is peculiar to find a planet orbiting a binary, in particular around a CV. While planets may be a natural consequence of the formation of binaries (Pelupessy & Portegies Zwart 2012), planetary systems orbiting CVs could also be quite common. In particular because of recent timing residuals observed in NN Serpentis (Beuermann et al. 2010; Horner et al. 2012a), DP Leonis (Beuermann et al. 2011) and QS Virgo (Almeida & Jablonski 2011) which are also interpreted as being caused by circum-CV planets.

Although the verdict on the planets around HU Aqr (and the other CVs) remains debated (Tom Marsh, private communication, and Qian et al. 2010), we here demonstrate how a planet in orbit around a CV, and in particular two planets, can constrain the CV evolution and be used to reconstruct the history of the inner binary. We will use the planets to perform a precision reconstruction of the binary history, and for the remaining Letter, we assume the planets to be real.

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Because of their catastrophic evolutionary history, CVs seem to be the last place to find planets. The original binary lost probably more than half its mass in the common-envelope (CE) phase, which causes the reduction of the binary separation by more than an order of magnitude. It is hard to imagine how a planet (let alone two) can survive such turbulent past, but it could be a rather natural consequence of the evolution of CVs, and its survival offers unique diagnostics to constrain the origin and the evolution of the system.

2 THE EVOLUTION OF A CV WITH PLANETS

After the birth of the binary, the primary star evolved until it overflowed its Roche lobe, which initiated a CE phase. The hydrogen envelope of the primary was ejected quite suddenly in this episode (Webbink 1984), and the white dwarf still bears the imprint of its progenitor: the mass and composition of the white dwarf limit the mass and evolutionary phase of its progenitor star at the moment of Roche lobe overflow (RLOF). For an isolated binary, the degeneracy between the donor mass at the moment of RLOF \((M_{\text{core}})\) for stars with zero-age main-sequence mass \(M_{\text{ZAMS}}\) cannot be broken.

The presence of the inner planet in orbit around HU Aqr (Hinse et al. 2012; Horner et al. 2012b; Goździewski et al. 2012) allows us to break this degeneracy and derive the rate of mass loss in the CE phase. The outer planet allows us to validate this calculation and in addition to determine the conditions under which the CV was born. The requirement that the initial binary must have been dynamically stable further constrains the masses of the two stars and their orbital separation.

2.1 Pre-CE evolution

During the CV phase little mass is lost from the binary system, \(M_{\text{CV}} \approx \text{constant}\) (but see Schenker & King 2002), and the current total binary mass \((M_{\text{comp}} = 0.98 M_{\odot})\) was not affected by the past (and current) CV evolution (Ritter 2010). The observed white dwarf mass then provides an upper limit to the mass of the core of the primary star at the moment of Roche lobe contact, and therefore also provides a minimum to the companion mass via \(m_{\text{comp}} \geq M_{\text{CV}} - M_{\text{core}}\).

With the mass of the companion not being affected by the CE phase, we constrain the orbital parameters at the moment of RLOF by calculating stellar evolution tracks to measure the core mass \(M_{\text{core}}\) and the corresponding radius \(R(M_{\text{core}})\) for stars with zero-age main-sequence mass \(M_{\text{ZAMS}}\). In Fig. 1, we present the evolution of the radius of a 3 \(M_{\odot}\) star as a function of \(M_{\text{core}}\), which is a measure of time.

We adopted the Henyey stellar evolution code MESA (Paxton et al. 2011) to calculate the evolutionary track of stars from \(M_{\text{ZAMS}} = 1\) to \(8 M_{\odot}\) using AMUSE\(^1\) (Portegies Zwart et al. 2009, 2012) to run MESA.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The orbital separation as a function of core mass for a primary star of \(M_{\text{ZAMS}} = 3 M_{\odot}\). The thin blue curve (bottom) gives the stellar radius \(R_{\text{ZAMS}}\) as a function of its core mass \(M_{\text{core}}\), and the curve directly above that (red) gives the initial orbital separation \(a_{\text{ZAMS}}\) for which RLOF of that binary occurs. Here we adopted a companion mass of \(m_{\text{comp}} = 0.98 M_{\odot} - M_{\text{core}}\) as in HU Aqr. The interruptions in the curves indicate the core masses for which RLOF cannot occur, because it would already have occurred in an earlier stage of the evolution, i.e. at a smaller core mass. The solid black curve (top) gives the minimal orbital separation of a planet born at \(a_0 = 3M_{\text{ZAMS}}\) for which the orbit was adiabatically expanded due to the mass loss in the CE \(M_{\text{ZAMS}} - M_{\text{core}}\). The horizontal dotted curve gives the separation at which the inner planet around HU Aqr was observed. For viable solutions, the solid black curve should remain below the horizontal dotted curve. The thick parts of the red curve indicate where the zero-age binary complies with the most favourable conditions for engaging RLOF, surviving the CE and producing a planet that can migrate to at least the observed separation for the inner planet in HU Aqr.

**Table 1.** Reconstructed and observationally constrained parameters for HU Aqr. The parameters at zero-age (columns 2 and 3) and directly after the CE phase (columns 4 and 5) are derived by means of reconstructing the CV evolution. The best comparison is achieved for a mass-loss rate in the CE from the binary system of \(m = 1.9 \pm 0.3 M_{\odot} \text{yr}^{-1}\) (or \(m = 0.15 \pm 0.01 M_{\odot} \text{yr}^{-1}\) from the orbit of the first planet). Parameters that we were unable to constrain are printed in slanted font; observed parameters are from Schwöpe et al. (2011), Hinse et al. (2012) and Goździewski et al. (2012) and are printed in boldface.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Zero age</th>
<th>After CE</th>
<th>Today</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M/M_{\odot})</td>
<td>1.6 ± 0.2</td>
<td>0.52 ± 0.01</td>
<td>0.80 ± 0.04</td>
</tr>
<tr>
<td>(m/M_{\odot})</td>
<td>0.47 ± 0.04</td>
<td>0.47 ± 0.04</td>
<td>0.18 ± 0.06</td>
</tr>
<tr>
<td>(a/R_{\odot})</td>
<td>25–160</td>
<td>0.867–2.0</td>
<td>0.8</td>
</tr>
<tr>
<td>(e)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

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\(^1\) The Astrophysics Multipurpose Software Environment, or AMUSE, is a component library with a homogeneous interface structure, and can be downloaded for free at amusecode.org. All the source codes and scripts for reproducing the calculations described in this Letter are available via the AMUSE website.
and determine the mass of the stellar core. The latter is measured by searching for the mass shell in the stellar evolution code for which the relative hydrogen fraction $< 10^{-9}$ (Tauris & Dewi 2001).

At the moment of RLOF the core mass is $M_{\text{core}}$ and the stellar radius $R_{\text{RLOF}} = R(M_{\text{core}})$. Via the relation for the Roche radius (Eggleton 1983), we can now calculate the orbital separation at the moment of RLOF $a_{\text{RLOF}}$ as a function of $M_{\text{RLOF}}$. This separation is slightly larger than the initial (zero-age) binary separation $a_{\text{ZAMS}}$ due to the mass lost by the primary star since its birth $M_{\text{RLOF}} = M_{\text{ZAMS}}$. The long (main-sequence) time-scale in which this mass is lost guarantees an adiabatic response to the orbital separation, i.e. $aM_\odot = \text{constant}$.

For each $M_{\text{ZAMS}}$ we now have a range of possible solutions for $a_{\text{RLOF}}$ as a function of $M_{\text{core}}$ and $m_{\text{comp}} = M_{\text{cv}} - M_{\text{core}}$. This reflects the assumption that the total mass $(m_{\text{comp}} + M_{\text{core}} = 0.98 M_\odot)$ in the observed binary with mass $M_{\text{cv}}$ is conserved throughout the evolution of the CV. In Fig. 1, we present the corresponding stellar radius $R_{\text{RLOF}}$ and $a_{\text{RLOF}}$ as a function of $M_{\text{core}}$ for $M_{\text{ZAMS}} = 3 M_\odot$. This curve for $a_{\text{RLOF}}$ is interrupted when RLOF would already have been initiated earlier for that particular orbital separation. We calculate this curve by first measuring the size of the donor for core mass $M_{\text{core}}$, and assuming that the primary fills its Roche lobe we calculate the orbital separation at which this happens.

### 2.2 The CE evolution

During the CE phase, the primary’s mantle is blown away beyond the orbit of the planets. The latter respond to this by migrating from the orbits in which they were born (semi-major axis $a_s$ and eccentricity $e_s$, the subscript ‘a’ indicating the inner planet; we adopt a ‘b’ to indicate the outer planet) to the currently observed orbits. Using first-order analysis, we recognize two regimes of mass loss: fast and slow. In the latter case, the orbit expands adiabatically without affecting the eccentricity: the minimum possible expansion of the planet’s orbit is achieved when the common envelope is lost adiabatically. Fast mass loss leads to an increase in the eccentricity as well and may even cause the planet to escape (Hills 1983; Fijloo, Caputo & Portegies Zwart 2012).

A planet born at the shortest possible orbital separation to be dynamically stable will have $a_s \sim 3a_{\text{ZAMS}}$ (Mardling & Aarseth 2001), which is slightly smaller than the distance at which circumbinary planets tend to form (Pelupessy & Portegies Zwart 2012). In Fig. 1, we present a minimum to the semi-major axis for a planet that was born at $a_s = 3a_{\text{ZAMS}}$ and migrated by the adiabatic loss of the hydrogen envelope from the primary star in the CE phase. The planet can have migrated to a wider orbit, but not to an orbit smaller than the solid black curve [indicated with min($a_s$)] in Fig. 1. For the $3 M_\odot$ star, presented in Fig. 1, RLOF can successfully result in the migration of the planet to the observed separation in HU Aqr for $M_{\text{core}} \lesssim 0.521 M_\odot$, which occurs for $a_{\text{ZAMS}} \lesssim 111 R_\odot$. A core mass $M_{\text{core}} > 0.521 R_\odot$ would, for a $3 M_\odot$ primary star, result in an orbital separation that exceeds that of the inner planet in HU Aqr; in this case, the core mass of the primary star must have been smaller than 0.521 $M_\odot$.

Another constraint on the initial binary orbit is provided by the requirement that the mass transfer in the post-CE binary should be stable when the companion starts to overfill its Roche lobe. To guarantee stable mass transfer, we require that $m_{\text{comp}} \gtrsim M_{\text{core}}$. The thick part of the red curve in Fig. 1 indicates the valid range for the initial orbital separation and core mass for which the observed planet can be explained; the thin parts indicate where these criteria fail.

Figure 2. Distribution of the initial conditions $a_{\text{ZAMS}}$ and $M_{\text{ZAMS}}$, and the resulting core mass $M_{\text{core}}$ (bottom panel) that successfully reproduce the CV HU Aqr. In the top panel, we also present the results of our analysis for the two planets. The circles give the initial semi-major axis of the inner planet. The triangles give the initial semi-major axis for the outer planet. The symbols are coloured (red for the inner planet and blue for the outer) if at least 10 out of 20 calculations for the orbital integration over 1 Myr turn out to be dynamically stable (see Section 4). With these initial conditions both planets migrate to within 1 per cent of their observed orbital period with an eccentricity of $e_s = 0.20 \pm 0.01$ and $e_s = 0.33 \pm 0.03$ with $n_s = 0.15 \pm 0.01 M_\odot$ yr$^{-1}$.

We repeat the calculation presented in Fig. 1 for a range of masses from $M_{\text{ZAMS}} = 1$ to $8 M_\odot$ with steps of 0.02 $M_\odot$; the results are presented as the shaded region in Fig. 2.

### 3 EFFECT OF THE CE PHASE ON THE PLANETARY SYSTEM

The response of the orbit of the planet to the mass loss depends on the total amount of mass lost in the CE and the rate at which it is lost. Numerical CE studies indicate that for an in-spiralling binary $\dot{m} \simeq 2.0 M_\odot$ yr$^{-1}$ (Ricker & Taam 2012). At this rate the entire envelope $M_{\text{RLOF}} - M_{\text{core}} \sim 0.46-5.8 M_\odot$ is expelled well within one orbital period of the inner planet, which leads to an impulsive response and the possible loss (for $M_{\text{RLOF}} - M_{\text{core}} \gtrsim 1.92 M_\odot$) of the planet. The fact that HU Aqr is orbited by a planet indicates that at the distance of the planet $n_s \ll (M_{\text{RLOF}} - M_{\text{core}})/P_{\text{planet}} \sim 1 M_\odot$ yr$^{-1}$. The eccentricity of the inner planet in HU Aqr (see Table 1) can be used to further constrain the rate at which the CE was lost.
from the planetary orbit. The higher eccentricity of the outer planet indicates a more impulsive response, which is a natural consequence of its wider orbits with the same \( \dot{m} \). This regime between adiabatic and impulsive mass loss is hard to study analytically (Li 2008).

### 3.1 The response of the inner planet

We calculate the effect of the mass loss on the orbital parameters by numerically integrating the planet orbit. The calculations are started by selecting initial conditions for the zero-age binary HU Aqr – \( M_{\text{ZAMS}} \), \( \dot{m}_{\text{ZAMS}} \), and consequently \( \dot{m}_{\text{circ}} \) – from the available parameter space (shaded area) in Fig. 2, and integrating the equations of motion of the inner planet with time. Planets were assumed to be born in a circular orbit (\( e_a = 0 \)) in the binary plane with semi-major axis \( a_a \).

The equations of motion are integrated using the high-order symplectic integrator Huayno (Pelupessy, Jänés & Portegies Zwart 2012) via the AMUSE framework. During the integration we adopted a constant mass-loss rate \( \dot{m} \) applied at every 1/100th of an orbit, and we continued the calculation until the entire envelope is lost (see Section 2.2 and Fig. 2), at which time we measure the final semi-major axis and eccentricity of the planetary orbit. During the integration, we allow the energy error to increase up to at most \( \Delta E/E = 10^{-13} \).

By repeating this calculation while varying \( a_a \) and \( \dot{m}_{\text{circ}} \), we iterate (by bisection) until the result is within 1 per cent of the observed \( a_{\text{HU Aqr}}(a) \) and \( e_{\text{HU Aqr}}(a) \) of the inner planet observed in HU Aqr. The converged results of these simulations are presented in Fig. 2 (circles), and these represent the range of consistent values for the inner planet’s orbital separation \( a_a = 183–752 \, \text{R}_\odot \), as a function of \( M_{\text{ZAMS}} = 1–8 \, \text{M}_\odot \) and consistently reproduce the observed inner planet when adopting \( \dot{m}_{\text{circ}} = 0.124–0.267 \, \text{M}_\odot \, \text{yr}^{-1} \). The highest value for \( \dot{m} \) is reached for \( M_{\text{ZAMS}} = 2.85 \, \text{M}_\odot \) at an initial orbital separation of \( a_a = 427 \, \text{R}_\odot \).

The orbital solution for the inner planet is insensitive to the semi-major axis of the zero-age binary \( a_{\text{ZAMS}} \) (for a fixed \( M_{\text{ZAMS}} \)), and each of these solutions was tested for dynamical stability, which turned out to be the case irrespective of the initial binary semi-major axis (as discussed in Section 4).

### 3.2 The response of the outer planet

We now adopt in Section 3.1 the measured value of \( \dot{m} \) to integrate the orbit of the outer planet. The effect of the mass outflow on the planet is proportional to the square of the density in the wind at the location of the planet (Kudritzki et al. 1992). We correct for this effect by reducing the mass-loss rate in the CE that affects the outer planet by a factor \( (a_i/a_o)^{3/2} \).

We use the same integrator and assumptions about the initial orbits as in Section 3.1, but we adopt the value of \( \dot{m} \) from our reconstruction of the inner planet (see Section 3.1). To reconstruct the initial orbital separation of the outer planet \( a_o \), we vary this value (by bisection) until the final semi-major axis is within 1 per cent of the observed orbit (see Table 1). The results are presented in Fig. 2 (triangles). The post-CE eccentricity of the outer planet then turns out to be \( e_o = 0.38 \pm 0.07 \).

### 4 STABILITY OF THE INITIAL SYSTEM

After having reconstructed the initial conditions of the binary system with its two planets, we test its dynamical stability by integrating the entire system numerically for 1 Myr using the Huayno integrator (Pelupessy et al. 2012). To test the stability, we check the semi-major axis and eccentricity of both planets every 100 yr. If any of these parameters changes by a factor of 2 compared to the initial values or if the orbits cross we declare the system unstable; otherwise, they are considered stable. The calculations are repeated with the fourth-order Hermite predictor–corrector integrator ph4 (McMillan et al. 2012) within AMUSE to verify that the results are robust, which turned out to be the case. We then repeated this calculation 10 times with random initial orbital phases and again with a 1 per cent Gaussian variation in the initial planetary semi-major axes. In Fig. 2 we present the resulting stable systems by colouring them red (circled) and blue (triangles); the unstable systems are represented by open symbols.

From the wide range of possible systems that can produce HU Aqr, only a small range around \( M_{\text{ZAMS}} = 1.6 \pm 0.2 \, \text{M}_\odot \) turns out to be dynamically stable. The eccentricity of the outer orbit of the stable systems (which were stable for initial conditions within 1 per cent) \( e_a = 0.32 \pm 0.02 \), which is somewhat smaller than the observed value for HU Aqr (Horner et al. 2012b, \( e = 0.38 \pm 0.16 \)). These values are obtained with \( \dot{m}_a = 0.15 \pm 0.01 \, \text{M}_\odot \, \text{yr}^{-1} \). The small uncertainty in the derived value of \( \dot{m} \) is a direct consequence of its sensitivity to \( e_a \) and the small error on \( M_{\text{ZAMS}} \) from the requirement that the initial system is dynamically stable.

### 5 DISCUSSION AND CONCLUSIONS

We have adopted the suggestive results from the timing analysis of HU Aqr that the CV is orbited by two planets, to reconstruct the evolution of this complex system. A word of caution is well placed in that these observations are not confirmed, and currently under debate (Tom Marsh, private communication, and comments by the referee). However, the predictive power that such an observation would entail is interesting. The possibility to reconstruct the initial conditions of a CV by measuring the orbital parameters of two circumbinary planets is a general result that can be applied to other binaries. For CVs in particular it enables us to constrain the value of fundamental parameters in the CE evolution. This in itself makes it interesting to perform this theoretical exercise, irrespective of the uncertainty in the observations. On the other hand, the consistency between the observations and the theoretical analysis give some trust to the correctness of these observations.

The presence of one planet in an eccentric orbit around a CV allows us to calculate the rate at which the CE was lost from the inner binary. A single planet provides insufficient information to derive the initial mass of the primary star, but allows us to derive the initial binary separation and planetary orbital separation to within about a factor of 5, and the initial rate of mass loss from the CE to about a factor of 2. A second planet can be used to further constrain these parameters to a few per cent accuracy and allows us to make a precision reconstruction of the evolution of the CV.

We have used the observed two planets in orbit around the CV HU Aqr to reconstruct its evolution, to derive its initial conditions (primary mass, secondary mass, orbital separation and the orbital separations of both planets) and to measure the rate of mass lost in the CE parameter \( \dot{m} \). By comparing the binary parameters at birth with those after the CE phase, we subsequently calculate the two parameters \( a_\lambda \) and \( \gamma \).

The measured rate of mass loss for HU Aqr \( \dot{m}_{\text{circ}} = 0.15 \pm 0.01 \, \text{M}_\odot \, \text{yr}^{-1} \) from the inner planetary orbit, which from the binary system itself would entail a mass-loss rate of \( \dot{m} = 1.9 \pm 0.3 \, \text{M}_\odot \, \text{yr}^{-1} \), when we adopt the initial binary to have a semi-major axis of \( a_{\text{ZAMS}} \simeq 97 \, \text{R}_\odot \), which is bracketed by our derived
range of $a_{\text{ZAMS}} = 25–160 \, R_\odot$. This is consistent with a mass-loss rate of $\dot{m} \approx 2 M_\odot \, \text{yr}^{-1}$ from numerical CE studies (Ricker & Taam 2012).

By adopting that the binary survives its CE at a separation between $\sim 0.87 \, R_\odot$ (at which separation the secondary star will just fill its Roche lobe to the white dwarf) and $\sim 2 \, R_\odot$ (for gravitational wave radiation to drive the binary into RLOF within 10 Gyr), we derive the value of $\alpha \lambda = 0.2–2.0$ (for $a_{\text{ZAMS}} \approx 97 \, R_\odot$ we arrive at $\alpha \lambda \approx 0.45 \pm 0.17$). This value is a bit small compared to numerous earlier studies, which tend to suggest $\alpha \lambda \approx 4.0$. The alternative $\gamma$ formalism for CE ejection (Nelemans et al. 2000) gives a value of $\gamma = 1.63–1.80$ (for $a_{\text{ZAMS}} \approx 97 \, R_\odot$ we arrive at $\gamma \approx 1.77 \pm 0.02$), which is consistent with the determination of $\gamma$ in 30 other CVs (Nelemans & Tout 2005).

The inner planet in HU Aqr formed at $(3.2–20.6) a_{\text{ZAMS}}$, with a best value of $5.3 \pm 0.45 a_{\text{ZAMS}}$, which is consistent with the planets found to orbit other binaries, like Kepler 16 (Doyle et al. 2011) and Kepler 34 and 35 (Welsh et al. 2012), although these systems have lower primary mass and secondary mass stars.

It seems unlikely that more planets were formed inside the orbit of the inner most planet, even though currently there is sufficient parameter space for many more stable planets; in the zero-age binary, there has not been much room for forming additional planets further in. It is, however, possible that additional planets formed farther out and those, we predict, will have even higher eccentricity than those already found.

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