55 CANCRI: A COPLANAR PLANETARY SYSTEM THAT IS LIKELY MISALIGNED WITH ITS STAR

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Received 2011 September 23; accepted 2011 October 26; published 2011 November 7

ABSTRACT

Although the 55 Cnc system contains multiple, closely packed planets that are presumably in a coplanar configuration, we use numerical simulations to demonstrate that they are likely to be highly inclined to their parent star’s spin axis. Due to perturbations from its distant binary companion, this planetary system precesses like a rigid body about its parent star. Consequently, the parent star’s spin axis and the planetary orbit normal likely diverged long ago. Because only the projected separation of the binary is known, we study this effect statistically, assuming an isotropic distribution for wide binary orbits. We find that the most likely projected spin–orbit angle is \( \sim 50^\circ \), with a \( \sim 30\% \) chance of a retrograde configuration. Transit observations of the innermost planet—55 Cnc e—may be used to verify these findings via the Rossiter–McLaughlin effect. 55 Cancri may thus represent a new class of planetary systems with well-ordered, coplanar orbits that are inclined with respect to the stellar equator.

Key words: planets and satellites: detection – planets and satellites: dynamical evolution and stability – planets and satellites: formation – planets and satellites: general

1. INTRODUCTION

The 55 Cancri planetary system contains five known planets in low-eccentricity orbits between 0.01 and 5.75 AU (Butler et al. 1997; Marcy et al. 2002; McArthur et al. 2004; Fischer et al. 2008). Recently, the innermost planet in the system—the \( \sim 8 M_{\oplus} \) 55 Cnc e—was found to transit (Winn et al. 2011; Demory et al. 2011). This is particularly intriguing because it may allow observers to measure (among other properties) the spin–orbit angle of the planetary system via the Rossiter–McLaughlin effect (see Gaudi & Winn 2007).

Rossiter–McLaughlin measurements have revealed that the orbits of many hot Jupiters are highly inclined relative to their host star’s spin axis and are even retrograde in some cases (e.g., Anderson et al. 2010; Triaud et al. 2010; Winn et al. 2010). This conflicts with standard models of planet migration (Lin et al. 1996) because protoplanetary disks are generally thought to be aligned with the stellar equator, as has been confirmed by debris disk measurements (Watson et al. 2011). The origin of highly inclined or retrograde planetary orbits may therefore be dynamical. Several recent papers have shown that such orbits may be produced by tidal circularization of highly eccentric/inclined planets after a phase of planet–planet scattering (Nagasawa et al. 2008) and/or Kozai interactions with a binary star or massive planet (Fabrycky & Tremaine 2007; Naoz et al. 2011; Katz et al. 2011; Lithwick & Naoz 2011).

Another noteworthy feature of 55 Cnc is that it also has a 0.27 \( M_{\oplus} \) binary companion at a projected distance of 1065 AU (Mugrauer et al. 2006). While there have been many dynamical studies of this planetary system (e.g., Raymond et al. 2006, 2008; Barnes & Greenberg 2007; Fischer et al. 2008), none have investigated the effects of the binary companion. Presumably, this is because this well-ordered system displays none of the excited orbits expected from severe impulses or Kozai interactions with its binary companion. Here we show that this binary companion does in fact play a major role in the planetary system’s dynamics. Using numerical simulations, we demonstrate that it is very likely this binary has driven the planetary system to a very high (and possibly retrograde) spin–orbit angle with respect to the parent star’s spin axis. Moreover, the Kozai oscillations studied in recent works do not produce this high spin–orbit angle. Rather, it is a mechanism first described in Innanen et al. (1997), where the entire planetary system smoothly precesses as a rigid body.

2. NUMERICAL METHODS

To model the dynamics of the 55 Cancri system, we use the wide binary algorithm of the MERCURY integration package (Chambers 1999; Chambers et al. 2002). All of our simulations include both the primary and secondary stars of 55 Cnc as well as one or more of the system’s known planets. In each simulation, the primary’s mass (55 Cnc A) is set to 0.905 \( M_{\odot} \) (von Braun et al. 2011), while the secondary’s mass (55 Cnc B) is fixed at 0.27 \( M_{\odot} \) (Mugrauer et al. 2006). In total, we perform 501 simulations. 450 of our runs include 55 Cnc d, the most distant and massive planet in the system, as well as a hypothetical Saturn-mass planet we designate as 55 Cnc g. Our motivation for using such systems is discussed in Section 3. These simulations are integrated for 10.2 Gyr, as this matches the most recent age estimate of the system (von Braun et al. 2011). These runs are divided into nine 50-simulation subsets. In each subset, 55 Cnc B is assigned a different semimajor axis: 750, 1000, 1250, 1500, 2000, 3000, 4000, 5000, or 8000 AU. All of its other orbital elements are drawn randomly from an isotropic distribution.

In our remaining simulations, we repeat some of our two-planet simulations using a different planetary configuration. For 48 of these reruns, we use the four outermost planets (55 Cnc b, c, f, and d) in place of 55 Cnc g and d. These simulations are only run for 1 Gyr because the orbit of 55 Cnc b necessitates a timestep of just 1 day. Finally, we also rerun three of these simulations using all five planets. These five-planet simulations are run for only 50 Myr, as they require a timestep of \( \sim 1 \) hr. The initial orbits and masses assumed for 55 Cnc’s planets are shown in Table 1.

In addition to the planets’ and stars’ mutual gravitational interactions, we also include external perturbations from the
3. RESULTS AND DISCUSSION

In Figure 1, we display the inclination evolution seen in one of our simulations. This simulation is one of our four-planet simulations, and 55 Cnc B is placed on an initial orbit with $a = 1250$ AU, $e = 0.93$, and $i = 115^\circ$. (Based on projected separation, the most probable semimajor axis is $\sim 1340$ AU; Fischer & Marcy 1992.) We see in this figure that the planets of 55 Cnc leave their initial orbital plane very rapidly. In fact, within 30 Myr the planets have reached a retrograde configuration relative to their original orbital plane. If the parent star’s spin is decoupled from but initially aligned with the planets’ orbits, this means that the spin–orbit angle of the system quickly diverges from 0$. For this entire Gyr simulation, the planets continue to precess between prograde and retrograde configurations in a very regular manner. Interestingly, the inset plot of this figure illustrates that all four planets maintain a very tight coplanar configuration throughout this evolution.

The dynamical mechanism that drives this inclination evolution was first documented in Innanen et al. (1997). In a system consisting of just one planet embedded within a binary star system, perturbations from the secondary star will cause the planetary orbit to undergo Kozai-like behavior, where the inclination and eccentricity of the planet oscillate exactly out of phase as the longitude of pericenter ($\omega$) circulates or librates (Kozai 1962). The frequency of this oscillation is a function of the star’s mass, semimajor axis, and eccentricity as well as the planet’s semimajor axis. However, when more planets are added to the system the behavior can change. This is because the evolution of $\omega$ may no longer be dominated by the stellar companion’s perturbations. Instead, the mutual interactions between the planets can drive the evolution of the longitude of pericenter. As long as the precession timescale of $\omega$ is much shorter than the Kozai timescale due to the binary’s perturbations, the evolution of the planetary orbits will not resemble a Kozai resonance. Indeed, integrations of the 55 Cnc planets in isolation indicate that $\omega$ of planet d circulates every 2.5 Myr. In contrast, integrations with only planet d and a binary companion ($a = 1340$ AU, $e = 0.95$) yield a much larger typical circulation period of $10^{7-8}$ Myr. Thus, the Kozai mechanism will not operate, and the planets’ eccentricities and mutual inclinations remain low.

However, in addition to $\omega$, the longitude of ascending node ($\Omega$) also precesses in the reference frame of binary orbital plane (Innanen et al. 1997). Unless the binary star’s orbital plane and the initial planetary orbital plane coincide, the precession of $\Omega$ in the binary’s reference frame will translate to an inclination precession with respect to the initial planetary plane. Although each planet would have a different $\Omega$ precession rate in isolation, the self-gravity of the system causes the planets to precess at a uniform rate (Takeda et al. 2008; Batygin et al. 2011). Consequently, the system maintains a rigid, coplanar shape, even though its orbital plane can become greatly inclined to
the star’s spin axis (assuming this axis is perpendicular to the original planetary orbital plane).

Figure 1 also shows that although our simulated system spends time in retrograde configurations, its inclination never exceeds a certain value, $i_{\text{max}}$ (in this case $i_{\text{max}} \simeq 130^\circ$). The reason for this is that the vertical component of the planetary orbital angular momentum, $L_z$, is always observed to be conserved in the reference frame of the binary orbital plane. Another way of saying this is that as $\Omega$ precesses, the angle between the orbit normal of the planetary system and the orbit normal of the binary is fixed. Thus, the inclination with respect to the original planetary orbital plane reaches a maximum after $\Omega$ has precessed $180^\circ$ in the binary orbital frame. In the reference frame of the original planetary orbital plane

$$\cos i_{\text{max}} = \cos 2i_{\text{bin}},$$

(1)

where $i_{\text{bin}}$ is the inclination of the binary with respect to the planetary orbital plane.

In the above simulation, we do not include the innermost planet of the 55 Cnc system, planet e. Because of its tiny orbital period, the computing costs to follow such an integration for 1 Gyr would be prohibitive. However, this planet is only 0.1 AU from the next nearest planet (b), and it is subject to powerful perturbations from interplanetary gravitational interactions just as all the other planets are. Consequently, it too should conform to the rigid body nature of the evolution displayed in Figure 1.

Fortunately, verifying this does not actually require a 1 Gyr integration. A few of our four-planet simulations have inclination precession rates even faster than the system shown in Figure 1 (due to a lower pericenter and semimajor axis for the binary orbit). These configurations with faster precession rates allow us to use shorter numerical simulations to verify that planet e follows this rigid body precession. In Figure 2, we display one such case. This figure actually displays inclinations from two different simulations: planet e’s inclination in a five-planet simulation and the inclinations of planets b, c, f, and d from a four-planet simulation. The same binary orbit is used in both simulations. We see that the behavior of each system is very similar, with inclinations oscillating between $0^\circ$ and $\sim 95^\circ$. In addition, the period of oscillation is nearly the same, although the five-planet system precesses a little slower (due to the fact that planet e has a smaller “natural” $\Omega$ precession rate and slows the mean rate down slightly). Because planet e is so close to its parent star, we include general relativistic precession as well as a $J_2$ component to the parent star’s potential ($J_2 = 5 \times 10^{-7}$). However, the behavior of planet e does not change noticeably whether we include these effects or not. Thus, we conclude that the inclination behavior seen in our four-planet simulations is an excellent proxy for planet e’s inclination as well.

Although we can use our four-planet simulations to extrapolate the behavior of all five planets in 55 Cnc, this is still not an ideal computing situation. Because of planet b’s short orbital period, even our four-planet simulations use a timestep of $\sim 1$ day, and we would like to integrate our planetary systems for 10 Gyr rather than 1 Gyr. In addition, we would like to evolve many hundreds of systems, each with a different binary star orbit, since only the binary’s projected separation is known.

We now argue that 55 Cnc’s inclination evolution can be modeled accurately using integrations that include just the outermost planet (d) accompanied by a fictitious inner planet (g), rather than the known configuration. The reason for this
is that planet d contains most of the total planetary mass of 55 Cnc. Therefore, planet d dominates the system’s self-gravity that maintains its rigid behavior. The other planets should almost behave as test particles being dragged along with planet d. The only role that the other planets play in this evolution is perturbing planet d’s longitude of pericenter to prevent Kozai oscillations. Consequently, the inclinations of any configuration of inner planets will evolve similarly as long as they are stable and perturb planet d’s $\omega$ sufficiently. Considering this, we choose to replace the inner four planets with a Saturn-mass planet at 3.5 AU (which we call planet g). Such a planet is known to be stable (Raymond et al. 2008), and its large semimajor axis enables us to increase our integration step from 1 day to 125 days.

To demonstrate the accuracy of these new simulations, we compare our 48 four-planet simulations with simulations using planet g in place of b, c, and f. For both our four-planet simulations and our two-planet simulations, we measure the maximum planetary inclination attained during the first Gyr. These are plotted against each other in Figure 3(a). We see that there is a tight 1:1 correlation between the inclinations attained in both simulation sets. Another parameter we can compare between the two-planet and four-planet systems is the precession rates of their planetary inclinations. This is done in Figure 3(b) where we plot the precession periods (obtained from a fast Fourier transform) from both simulation sets. We see that in general the two precession periods are very near each other, although the tighter configuration of the four-planet system does systemically yield a slightly lower precession rate. Given that the inclination behaviors of these two simulation sets are nearly identical, we conclude that our two-planet simulations are a suitable model for the inclination of the real 55 Cnc system.

Figure 3. (a) Maximum planetary inclination measured in four-planet simulations vs. the maximum planetary inclination measured in two-planet simulations. Inclinations are measured relative to the initial planetary orbital plane. (b) The inclination precession period measured in two-planet simulations vs. the precession period measured in four-planet simulations. Data for both plots come only from the first Gyr of each simulation.
In total we perform 450 two-planet simulations that are integrated for 10.2 Gyr. Each simulation includes a binary companion set on a different randomly generated orbit. In a small fraction of our simulations (16%), binary perturbations destabilize the planets, ejecting one or both. Because this has not occurred in the real 55 Cnc system, we ignore these runs. Using only the stable runs, we sample the inclination of planet d relative to its initial plane every Myr between 7 and 10.2 Gyr. The median values of those inclination samplings are plotted as a function of binary semimajor axis in the upper panel of Figure 4. In addition, we use error bars to mark the boundaries of the upper 10% and bottom 10% of inclination measurements in each semimajor axis bin.

If we assume that the parent star’s spin was decoupled from but originally aligned with the planetary orbits, this plot shows the current spin–orbit angle of 55 Cnc. We see that for binary semimajor axes below 4000 AU the most likely spin–orbit angle should be \( \sim 65^\circ \). Beyond semimajor axes of \( \sim 5000 \text{ AU} \), the precession timescale becomes much larger than the system’s age, and the influence of the binary star wanes. Hence, for the very largest binary separations, the planetary system is likely to be found only at low inclinations. Lastly, we note
that although our median inclination is always prograde, 29% of the inclinations recorded in our simulations are retrograde for binaries with $a < 5000$ AU.

In the bottom panel of Figure 4, we show the cumulative probability distribution for the possible semimajor axis of 55 Cnc B. To calculate this distribution, we assumed that the distribution of wide binary semimajor axes is uniform in log space (Poveda et al. 2007). Furthermore, we assumed that for a given semimajor axis, the distribution of all other orbital elements for wide binaries is isotropic. Based on this orbital distribution, we measured the relative fraction of time that projected separations of 1065 AU occur. We have seen in the upper panel that the binary companion has its strongest effects on the spin–orbit angle for $a < 5000$ AU. Our probability distribution in the bottom panel indicates that there is a ~95% probability that the semimajor axis of 55 Cnc B is within this range. Thus, it is very likely that 55 Cnc B has significantly altered the spin–orbit angle of this system.

These simulations indicate that the current spin–orbit angle of 55 Cnc should be quite high and perhaps even retrograde. This result is particularly exciting because 55 Cnc e was just discovered of 55 Cnc should be quite high and perhaps even retrograde. It has been suggested that the spin–orbit angle of this system of 55 Cnc A, even though the planetary system’s self-gravity has preserved the planets’ initial coplanarity. Hence, even very distant binary companions such as 55 Cnc B can substantially alter planetary architectures. Assuming wide binary orbits reflect an isotropic distribution, we demonstrate in Figure 4 that the most likely value of 55 Cnc’s projected spin–orbit angle is $\sim 45^\circ$–$55^\circ$. Furthermore, there is a significant (29%) chance of a retrograde configuration for 55 Cnc. Because 55 Cnc is a closely packed, coplanar system, it would be unique among known highly inclined planetary systems. This feature could distinguish retrograde planets produced from rigid body precession versus those generated from Kozai interactions and/or scattering events. Since planet e of this system transits its parent star, it may be possible to soon verify our findings using the Rossiter–McLaughlin effect.

We thank John Chambers for valuable discussions concerning the MERCURY package. This work was funded by a CITa National Fellowship and Canada’s NSERC. S.N.R. thanks the CNRS’s PNP program and the NASA Astrobiology Institute’s Virtual Planetary Laboratory team. The bulk of our computing was performed on SciNet’s General Purpose Cluster provided at the University of Toronto.

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