Outer-planet scattering can gently tilt an inner planetary system

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ABSTRACT
Chaotic dynamics are expected during and after planet formation, and a leading mechanism to explain large eccentricities of gas giant exoplanets is planet-planet gravitational scattering. The same scattering has been invoked to explain misalignments of planetary orbital planes with respect to their host star’s spin. However, an observational puzzle is presented by Kepler-56, which has two inner planets (b and c) that are nearly coplanar with each other, yet are more than 45 degrees inclined to their star’s equator. Thus the spin-orbit misalignment might be primordial. Instead, we further develop the hypothesis in the discovery paper, that planets on wider orbits generated misalignment through scattering, and as a result gently torqued the inner planets away from the equator plane of the star. We integrated the equations of motion for Kepler-56 b and c along with an unstable outer system initialized with either two or three Jupiter-mass planets. We address here whether the violent scattering that generates large mutual inclinations can leave the inner system intact, tilting it gently. In almost all of the cases initially with two outer planets, either the inner planets remain nearly coplanar with each other in the star’s equator plane, or they are scattered violently to high mutual inclination and high spin-orbit misalignment. On the contrary, of the systems with three unstable outer planets, a spin-orbit misalignment large enough to explain the observations is generated 28% of the time for coplanar inner planets, which is consistent with the observed frequency of this phenomenon reported so far. We conclude that multiple-planet scattering in the outer parts of the system may account for this new population of coplanar planets hosted by oblique stars.

Key words: planets and satellites: dynamical evolution and stability – celestial mechanics – stars: individual: Kepler-56

1 INTRODUCTION
As part of the great diversity of known planetary systems, hot Jupiters are frequently observed with spin-orbit misalignment (Hebrard et al. 2008; Fabrycky & Winn 2009; Triaud et al. 2010; Morton & Johnson 2011; Moutou et al. 2011; Albrecht et al. 2012; Hebrard et al. 2013). Planets with even slightly more widely spaced orbits have only rarely allowed spin-orbit measurement, due to observational difficulties.

Kepler-56 belongs to the few discovered systems that contain several, more widely-spaced planets (planets b and c have periods 10.5 days and 21.4 days), and also a spin-orbit measurement. In fact, it was the first such system to show spin-orbit misalignment (Huber et al. 2013). Both inner planets are misaligned with their host star’s spin axis by at least 45°, while being mutually aligned to within about 10°. The geometry of this system, as well as its eventual fate, has been detailed by Li et al. (2014).

In Kepler-56, Huber et al. (2013) also found a radial acceleration consistent with a third giant planet (call it planet d) in a several-AU orbit. That detection inspired them to propose the following scenario to explain the misalignment (following Mardling 2010 and Kaib et al. 2011). Suppose that a fourth planet is initially in the outer parts of the system, and all planets and the stellar spin are coplanar to within a few degrees. The orbits of the two outer planets may go unstable, initiating an epoch of gravitational scattering. Eventually planet d could eject the additional planet, leaving planet d on an eccentric orbit, with an inclination 2i_d. Thus the chaotic dynamics could begin with a relatively flat system of planets and inject inclination into its outer parts. Two-planet scattering simulations leave behind a planet with an inclination at or above 22.5° about 1% of the time (Ford et al. 2001), whereas three-planet simulations do so ~ 30% of the time (Chatterjee et al. 2008). From then on, this inclined outer planet d would slowly cause the inner planets to precess, periodically sampling spin-orbit angles between 0 and 2i_d, assuming planet d’s angular momentum dominates the rest of the system. That tilt would be “gentle” in the sense that the inner planets would maintain coplanarity (Innanen et al. 1999; Kaib et al. 2011; Huber et al. 2013; Boué & Fabrycky 2014). In the spe-
specific case of Kepler-56, the inner planets also have low eccentricities (< 0.1) as determined by the transit timing variation analysis (Huber et al. 2013), further evidence that they did not directly participate in the scattering.

Interestingly, similar dynamics have recently been noted in the Solar System, supposing the solar obliquity is due to a distant perturbing planet (Gomes et al. 2016, Bailey et al. 2016), a revisitation of an old idea (Goldreich & Ward 1972).

Given that spin-orbit misalignment seems to be a generic feature of different kinds of planetary systems, it is of great importance to understand the mechanism(s) that can lead to such an outcome. The weakest part of the scattering scenario seems to be the need for the scattering planets to leave the inner planets undisturbed. This aspect can only be checked via numerical simulations.

The plan for this paper is as follows. In section 2, we describe the suite of numerical simulations: the method and initial conditions. In section 3, we give a few examples that lead to ejections or collisions of the outer planets, yielding a system with misaligned inner planets. Section 4 will be dedicated to the statistical outcomes, and their interpretation. We will discuss absolute inclinations as well as mutual inclinations. Finally, we conclude the paper with a summary of our results in section 5.

2 SCATTERING SIMULATIONS FOR THE KEPLER-56 SYSTEM

We investigate the scattering hypothesis for the case of four or five initial planets, and see if it can lead to spin-orbit misalignment for a system such as Kepler-56. We simulate the dynamics of the system for three sets of initial parameters, as discussed below. Events such as an ejection or collision of outer planets may leave us with a distant planet to create the observed radial velocity trend (Huber et al. 2013) and subsequently produce spin-orbit misalignment of the inner two planets. However, simulated systems that retain their outer planets on calm orbits will not create any significant misalignment; we do not record them in the plots of section 5.

For our simulations, we use Mercury (Chambers 1999), an N-body simulation code. The Burlisch-Stoer integrator is used with an accuracy parameter of $10^{-12}$. Collisions between planets are assumed to result in a perfect merger. Beyond a critical distance, a planet is considered ejected, and is taken out of the integration. For the two outer-planet runs, 100 AU is used; for the three outer-planet runs, 1000 AU is used. In all integrations, the host star mass $M_{\text{star}} \approx 1.32 M_{\odot}$.

For planetary masses and radii, for models with the inner planets, we took values corresponding to Kepler-56b and Kepler-56c (see Table 1 in Huber et al. 2013). For the outer planets, we took one Jupiter mass and 3 Jupiter radii, representing their radius at an early age (Burrows et al. 2001).

We assume that on scattering timescales, the star’s spin orientation will not change. Even on secular timescales, this assumption seems justified (e.g., Huber et al. 2013, Boué & Fabrycky 2014). In this work, we assume that the stellar spin remains oriented perpendicular to the initial plane of the planets, from which their inclinations are measured. Thus we interpret final inclinations to be equivalent to spin-orbit misalignment angles, and we forgo modelling the stellar spin.

The initial inclinations were chosen to be:

- Zero for the outermost planet;
- A uniform-random number chosen from the interval [0, 5°] for the others.

Thus we choose an almost planar configuration for all planets. The initial angular parameters — argument of periastron $\omega$, nodal angle $\Omega$, and mean anomaly $M$ — were chosen randomly between $[0, 2\pi]$ for the outer planets, but fixed for the inner two. Kepler-56b and c’s initial angular parameters are from table S6 of Huber et al. (2013), which we repeat for convenience – as well as summarizing the other initial conditions – in Table 1 and Table 2.

The mutual inclination $i$, a crucial parameter to test the scattering hypothesis for two misaligned planets, is defined with the orbital node $\Omega$:

$$\cos i = \cos i_b \cos i_c + \sin i_b \sin i_c \cos \Omega. \quad (1)$$

The initial eccentricities were chosen randomly within $[0, 0.01]$ for all planets.

We ran three sets of simulations.

The first set of simulations were 173 runs with two inner planets with Kepler-56 b and c properties, and two outer gas giants, called d and e. Its properties are detailed in Table 1.

We followed Ford et al. (2001) to initialize the outer planets. The initial parameters are:

- $a = a_d/a_e$ in the range $[0.769, 0.781]$, where $a_d = 5 AU$ (≈ Jupiter orbit) and $a_e$ are the semi-major axes of the two outer planets (see section 3 of Ford et al. 2001 for a justification of this range);
- Total integration time: $5.23 \times 10^9$ days $\approx 1.43 \times 10^7$ years $\approx 1.47 \times 10^8$ OUTER1 orbits; Ford et al. (2001) integrate until $1.6 \times 10^6$ Jupiter orbits, and we see from their figure 2 that the branching ratios are in place by $\approx 10^6$ Jupiter orbits, at least for the two-planet case.

The second set of simulations consists of 73 integrations with the same two outer planets as 73 of the first set, but excluding the two inner planets. This is in order to check the rates of different outcomes. The reason for doing this was to (i) compare with the two-planet runs of Ford et al. (2001), and (ii) see if the branching ratios of outer planet ejections, collisions, and stable systems, are different from the four-planet case. In principle, the inner planets could change the outcome probabilities by modifying the scattering (e.g., Mustill et al. 2015).

A third set of simulations has three outer planets, as well as the inner planets representing Kepler-56 b and c. From Chambers et al. (1996), we recognize that three planets can be spaced much wider than two planets and still go unstable. We choose initial semi-major axes: 5.0000 AU, 7.1220 AU, and 10.1446 AU, and the same random selection of other orbital elements as above, which resulted in a wide range of instability timescales. We integrated $10^8$ yr for this set, and continued integrating even after the outer planet system became unstable. See Table 2 for a summary of these initial conditions.
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Table 1. Initial conditions for 4-planet simulations: set 1.

| Planet name | semi-major axis $a$, [AU] | eccentricity $e$ | inclination $i$ [deg] | nodal angle $\Omega$ [deg] | periapse angle $\omega$ [deg] | mean anomaly $M$ [deg] | mass $M_{\text{Jupiter}}$ | radius $R_{\text{Jupiter}}$ |
|-------------|--------------------------|-----------------|-----------------------|--------------------------|--------------------------|----------------------|-------------------------|-------------------------|
| Kepler-56 b | 0.1028                   | [0.0, 0.01]     | 0.5                   | 0.0                      | 0.0                      | 57.0                 | 0.0695                  | 0.581                   |
| Kepler-56 c | 0.1652                   | [0.0, 0.01]     | 0.5                   | 0.0                      | 0.0                      | 182.0                | 0.569                   | 0.875                   |
| OUTER1      | 5.0000                   | [0.0, 0.01]     | [0, 360]              | [0, 360]                 | [0, 360]                 | [0, 360]             | 1.0                     | 3.0                     |
| OUTER2      | [6.4020, 6.5020]         | [0.0, 0.01]     | 0.0                   | [0, 360]                 | [0, 360]                 | [0, 360]             | 1.0                     | 3.0                     |

Table 2. Initial conditions for 5-planet simulations: set 3.

| Planet name | semi-major axis $a$, [AU] | eccentricity $e$ | inclination $i$ [deg] | nodal angle $\Omega$ [deg] | periapse angle $\omega$ [deg] | mean anomaly $M$ [deg] | mass $M_{\text{Jupiter}}$ | radius $R_{\text{Jupiter}}$ |
|-------------|--------------------------|-----------------|-----------------------|--------------------------|--------------------------|----------------------|-------------------------|-------------------------|
| Kepler-56 b | 0.1028                   | [0.0, 0.01]     | 0.5                   | 0.0                      | 0.0                      | 57.0                 | 0.0695                  | 0.581                   |
| Kepler-56 c | 0.1652                   | [0.0, 0.01]     | 0.5                   | 0.0                      | 0.0                      | 182.0                | 0.569                   | 0.875                   |
| OUTER1      | 5.0000                   | [0.0, 0.01]     | [0, 360]              | [0, 360]                 | [0, 360]                 | [0, 360]             | 1.0                     | 3.0                     |
| OUTER2      | 7.1220                   | [0.0, 0.01]     | [0, 360]              | [0, 360]                 | [0, 360]                 | [0, 360]             | 1.0                     | 3.0                     |
| OUTER3      | 10.1446                  | [0.0, 0.01]     | 0.0                   | [0, 360]                 | [0, 360]                 | [0, 360]             | 1.0                     | 3.0                     |

Figure 1. System S1. This plot shows the eccentricities over time of the outer two planets. Here, the ejection took place late in the simulation.

3 EXAMPLES OF THE DYNAMICAL EVOLUTION

The examples that follow are from simulation sets 1 and 3, and they focus on cases where both inner planets have a final inclination larger than 100 with respect to their host star’s spin axis. The final values are given in Table 3 and labelled by S1, S2, etc.

3.1 Examples with three initial outer planets

3.1.1 System S1 - secular excitation during scattering

Here we have a common case where one of the outer two planets has been ejected, and we are left with a three planet system. Figure 1 shows the eccentricities of the outer two planets over time. As we can see, the eccentricity of OUTER2 approaches unity and is ejected toward the end of the integration time.

3.1.2 System S2 - torquing following scattering

Here we show a system where the ejection happened earlier, with the excitation of the outermost planet’s eccentricity above 1 (fig. 2). After the ejection occurred, the surviving outer planet has an inclination of 90. The inner planets’ inclinations then enter a periodic pattern of inclinations between a few and ~ 200 (fig. 3). Again,
3.1.3 System S3 - Ejection of second-outermost planet

We do not find many systems that ejected the second-outermost planet. Interestingly, it is such a system that produced the largest final inclinations for both inner planets we found in our simulations of two initial outer planets. We attribute this to the complicated scattering history that allowed growth of large mutual inclination. We omit plotting the outer planets’ eccentricities; it looks very similar to Figure 5. Figures 7 and 8 show the inclinations and the orbital distances, respectively, of this system. While the second inner planet’s inclination fluctuates between 30° and 50°, the innermost planet’s inclination achieves a minimum of about 10° and a maximum of over 70°. That greater variation is due to large mutual inclination (see section 4.1), which makes this simulated system a poor match to Kepler-56.

3.2 Examples with three initial outer planets

In the runs that start with three outer planets (simulation set 3, with five planets total), we see various outcomes: collisions between two outer-planets which either eject or retain the third outer-planet, and ejections of two outer-planets. We did not see a merger of all three outer-planets. Thus the outcomes of unstable systems were one or
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Figure 7. System S3. The absolute inclinations of the four planets over time. This is the only system we found that ended up with large inclinations of both inner planets, at 56° and 47°, respectively (note the higher range on the y axis as compared to the previous two examples). However, the mutual inclination of ~ 20° is too large for considering this system a Kepler-56 candidate.

Figure 8. System S3. Development of semi-major, aphelion, and perihelion axes over time for the system that ejected its second-outermost planet.

The different chaotic pathways leave a large variety of outcomes for the inner planets. The inner planets excite to large inclination by various modes. In some cases, during the scattering of the outer planets, the inner planets raise to a certain mutual inclination, and they subsequently do not evolve much in inclination. In other cases, the scattering is fast compared to secular excitation, and it leaves the inclination of the inner two planets oscillating between nearly their original value and a maximum value of tens of degrees.

3.2.1 System S14 - Secular excitation during scattering

An example of secular excitation during scattering of the inner two planets is found in figures 9, 10, and 11. In this run, the scattering of three planets occurs over ~ 1 Myr. For most of the scattering, the outermost planet of the three has been traded into the inner position of the three, whereas the other two planets have crossing, eccentric orbits. The scattering ends when one of those two planets collides with the traded planet. The two resulting planets have separated enough orbits to no longer scatter, but they continue secular cycles of eccentricity. The remnant outer planets have inclinations of ≲ 10°.

During the scattering, the inner two planets (Kepler-56 b and c) never endure any scattering evolution (for instance, their eccentricities remain small; figure 10) but are secularly excited to an inclination of 65° (figure 11). Since the final inclinations of the outer planets are modest, the only indication of the past episode of scattering is the eccentricities of the outer two planets.

The interesting concept here is that different parts of the planetary system react to perturbations differently; the outer planets can change their orbits on orbital timescales due to scattering, whereas the inner planets may only secularly change during this same evolution. As far as we are aware, this is a new mechanism that has not been discussed before in spin-orbit alignment context; it is distinct from the hypothesis of Huber et al. (2013).

3.2.2 System S15 - Impulsive Excitation and Ringing

An example closer to the Huber et al. (2013) hypothesis is shown in figures 12, 13, and 14. A first episode of scattering over 0.7 Myr leads to the ejection of the outermost planet. The other two outer planets are left eccentric and strongly interacting, although not crossing. After 8 Myr of mostly secular interaction, in a second episode of scattering (again over about 0.7 Myr) the outer planet...
increases its semimajor axis and eccentricity, then escapes. The inner planets react to both of those episodes of scattering by quickly changing their modes of inclination variations. They are left ringing between $25^\circ$ and $65^\circ$, due to the inclination of the final remaining outer planet. Only in the upper part of that oscillation are the inner planets sufficiently inclined to explain the spin-orbit data. When the inner planets attain maximum inclination, the now-single outer planet attains its minimum inclination of only $i_d \approx 8^\circ$.

We note that very spin-orbit misaligned inner planets are not necessarily accompanied by a very spin-orbit misaligned companion planet. In both examples S14 and S15, when the inner planets have inclinations above $45^\circ$, the outer planet in the few-AU region has an inclination $\lesssim 15^\circ$. This property contrasts to the naïve prediction of the Huber et al. (2013) hypothesis as discussed in the introduction.

that the outer giant would have an inclination $i_d > 22.5^\circ$. There are two effects contributing: (1) a secular resonance effect, in which the forcing frequency of the torque matches the natural precession frequency of the inner planets, amplifying the response (prominently seen in S14, the left panel of figure 11), and (2) the anti-phased oscillations due to precession in the final system (prominently seen in S15, the late-time behavior of figure 14).
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4 STATISTICAL RESULTS

4.1 Two Initial Outer-Planets

In set 1, we ran a total of 173 four-planet simulations. The first major event recorded by Mercury were as follows: Outer Collisions – 19, Outer Ejections – 67, Stable systems – 67, Inner collisions with star or planet – 20.

We analyze the systems that ended up with three planets, after a collision or an ejection occurred. We do not include stable systems, or systems with destroyed inner planets, as they are not acceptable models for the Kepler-56 system.

Our results indicate that a large-angle (at or above 45°) spin-orbit misalignment between inner two planets and their host star is highly improbable. We find a total of fourteen systems (out of 173) for which both inner planets have inclinations between 10° and 20°; the details of these systems are collected in Table 3. We find an additional seven systems where only one of the two has a larger than 10° inclination. Only one system (System S3 in Table 3) detailed in Section 3.1 is found to have both inner planets’ inclinations around 45° that could model Kepler-56, but here the mutual inclination turns out to be large, about 20°. However, high mutual inclinations are rare: a total of nine systems — including S3 — are found where the mutual inclination exceeds 10°. The system with the highest inclinations had its planet initially at 5 AU – OUTER2 – ejected. Generally however, we find that ejections of the outermost planet (OUTER2) are much more common than ejections of the second-outermost planet.

We see in figure 15 that most systems retain a low mutual inclination - a good sign for reproducing the orbital data of Kepler-56. However, what the histogram does not tell us are the absolute inclinations – this is illustrated in Figure 16 where we show the true mutual inclination I with respect to the absolute inclination of either inner planet. In fact, the preference for low absolute inclinations of the inner two planets forces us to conclude that four-planet initial conditions does not favor the formation of Kepler-56-type systems. For systems with large mutual inclination, we integrated 2 Myr forward in time, and show those systems as a cloud of 100 smaller dots sampling this interval in Figure 16. System S3, despite its usual large mutual inclination, occasionally samples low mutual inclination as well, so it could be an acceptable model for Kepler-56 if observed at a lucky time when it is relatively flat.

We thus conclude that systems in an initial configuration such as we have chosen, while being able to generate some amount of inclination.
Ejection of either outer planet (all outermost, except S3), C and mutual inclination less than 5° systems – 21 systems – 22 systems with the following outcomes:

We exclude the systems in which the 4-planet version that had one eccentric, outer planet remained: in two cases, two outer planets merged and then ejected the other planet. So in 15 cases, two outer planets remained. In the other 45 cases, one eccentric, outer planet remained: in two cases, two outer planets merged and then ejected the other planet.

We looked more closely at the final system architecture of the 19 cases that could explain the Kepler-56 system at some point in their secular evolution, so these points serve as a sample of the hypothesis. In 28% of the samples, the planets' individual inclinations are above 45°. Of the 45 cases, 19 had inclinations that were above 45° or quasi-periodically visited that region. We are presumably seeing the Kepler-56 system at a random phase of its secular evolution, so these points serve as a sample of the hypothesis. In 28% of the samples, the planets' individual inclinations are above 45°.

From these runs, we conclude that the presence of the inner two planets does not statistically affect the outcomes of scattering.

### 4.2 Three Initial Outer-Planets

In set 3 of integrations, we found that three outer-planet scattering much more often produces large spin-orbit misalignments. Of the 100 systems integrated, 28 remained stable 106 years, 27 destroyed one or both inner planets when they went unstable, and 45 went unstable leaving the inner planets intact. In all these 45 cases, the mutual inclination between the inner two remained low, in contrast to many systems in the two-outer-planet scattering simulations. For each of these 45 systems, we selected 100 random times after the instability, sampling one or many secular cycles; the values of inclination and mutual inclination are plotted in figure 17, which is the just the three-outer-planet version of figure 16. Of the 45 cases, 19 had inclinations that were above 45° or quasi-periodically visited that region. We are presumably seeing the Kepler-56 system at a random phase of its secular evolution, so these points serve as a sample of the hypothesis. In 28% of the samples, the planets’ individual inclinations are above 45°.

We looked more closely at the final system architecture of the 19 cases that could explain the Kepler-56 system at some point in their secular cycle. The most common outcome (13 cases) was ejection of one outer planet, leaving the other two outer planets stable with respect to each other. In two other cases, two outer planets merged and the merger product was stable with respect to the third outer planet. So in 15 cases, two outer planets remained. In the other four systems, one eccentric, outer planet remained: in two cases, two outer planets were ejected; in the other two cases, two of the planets merged and then ejected the other planet.

### Table 3. Properties of our three examples (S1 to S3) with two-outer planets, plus all systems from simulation set 1 with individual inclinations larger than 10°

| System | History | inclination | inclination | Mutual inclination | semi-major axis | semi-major axis | eccentricity | eccentricity |
|--------|---------|-------------|-------------|--------------------|----------------|----------------|--------------|--------------|
| Kepler-56 | E or C | > 45 | > 45 | ≃ 5 | 0.10 | 0.17 | < 0.1 | < 0.1 |
| S1 | E | 17.4 | 15.0 | 3.4 | 0.11 | 0.17 | 0.02 | 0.01 |
| S2 | E | 14.7 | 13.7 | 3.4 | 0.10 | 0.17 | 0.02 | 0.02 |
| S3 | E | 55.8 | 46.8 | 20.5 | 0.10 | 0.16 | 0.38 | 0.03 |
| S4 | E | 12.1 | 10.1 | 2.9 | 0.11 | 0.16 | 0.24 | 0.10 |
| S5 | E | 11.5 | 10.3 | 1.5 | 0.11 | 0.16 | 0.04 | 0.07 |
| S6 | E | 11.4 | 11.6 | 3.5 | 0.10 | 0.16 | 0.03 | 0.01 |
| S7 | E | 17.9 | 19.4 | 1.5 | 0.11 | 0.17 | 0.01 | 0.02 |
| S8 | E | 10.8 | 12.4 | 2.2 | 0.10 | 0.16 | 0.04 | 0.02 |
| S9 | E | 10.7 | 12.4 | 2.2 | 0.11 | 0.17 | 0.06 | 0.02 |
| S10 | E | 10.9 | 10.7 | 0.4 | 0.11 | 0.16 | 0.04 | 0.03 |
| S11 | E | 11.4 | 10.6 | 2.1 | 0.10 | 0.16 | 0.03 | 0.02 |
| S12 | E | 10.4 | 11.3 | 3.4 | 0.10 | 0.17 | 0.02 | 0.01 |
| S13 | E | 10.5 | 10.2 | 3.9 | 0.11 | 0.16 | 0.05 | 0.01 |
| S14 | C | 50-65 | 50-65 | 2.4 | 0.10 | 0.17 | 0.02 | 0.01 |
| S15 | E,E | 25-65 | 25-65 | 1.8 | 0.10 | 0.17 | 0.02 | 0.01 |
In all of these successful cases, a planet of mass 1 or 2 $M_{\text{Jup}}$ was left with a semi-major axis between 2.1 and 4.6 AU, and an eccentric orbit.

In the 15 cases where the inner planets are inclined and a second outer planet remains bound to the system, it does so in a long-period orbit whose signal is inaccessible to Doppler observations. Quantitatively, in only one of those runs does this extra planet produce an acceleration greater than 3.2 m/s/yr (see this value’s relevance in the conclusions), and it does so only about a quarter of the time (near periastron of an eccentric, 10 AU orbit). So even though our results suggest planet-planet scattering with at least three initial outer planets is responsible for the misalignment, we only predict an acceleration greater than 1 m/s/yr less than 10% of the time – usually in our runs, such an acceleration is even smaller in amplitude, or non-existent.

5 CONCLUSION

We have run simulations attempting to implement the idea of Huber et al. (2013) for tilting the inner planets via scattering of outer planets, and found it to be unlikely in the case of two-planet scattering but plausible in the case of three-planet scattering.

We ran 173 simulations of two outer-planets, of which only one produced high enough spin-orbit misalignment of the inner two planets to match the observations. However, for this outcome, the planet’s mutual inclination is about 20° for most of its evolution, too high for a reasonable match with Kepler-56 b and c’s mutual inclination (Huber et al. 2013). We did not find another system with similarly high inclinations, even though we did find a few systems where one of the inner planets ended up with a high inclination. We speculate that the system S3 has its second-outermost planet ejected and the highest inner-planet inclinations came from the same source – an epoch of prolonged scattering which allowed access to these dynamically rarer outcomes.

However, considering our simulations, our hypothesis of the outer planet(s) generating a high spin-orbit misalignment requires particularly violent scattering. This is apparently possible through 3 equal-mass outer planets, but not with 2. In runs with three planets in the exterior parts, scattering can tilt the inner system dramatically. For inner systems that are not disrupted, 28% showed misalignment from the original plane of the outermost planet by more than 45° at a randomly selected time in the future secular evolution of the system.

Our runs showed that usually two outer planets remain after the scattering, whereas in Kepler-56, only one has been found. New data and analysis appears to confirm the existence of a third planet in the Kepler-56 system (Otor, Montet et al., in prep.). It does not exclude the existence of a fourth planet in a large orbit, which could still be hiding. Observationally, a fourth planet has currently an 95% upper limit on a long term radial velocity acceleration of 3.2 m/s/yr (Otor, Montet et al., in prep), which is why we quoted results with respect to this benchmark above. The second outer planet in our simulations almost always had a much smaller effect – it could easily evade that limit.

A useful avenue for future work would be quantifying whether 3 unequal-mass planets can achieve large enough misalignments. Also, our focus was on one particular system (Kepler-56), but one would rather model a population of systems, whose initial distribution is plausible from planet formation theories, to see what distribution of spin-orbit and mutual inclination outcomes are expected for the inner planets.

Misalignment of inner planets is likely not rare. Kepler-56 was the 6th system of multiple transiting planets whose stellar obliquity was measured (Albrecht et al. 2013) – the search turned up an oblique star unexpectedly quickly. Indeed, another system, KOI-89, has recently been found to feature large angle spin-orbit misalignment of its two inner, coplanar planets (Ahlers et al. 2015). In contrast to Kepler-56, there is no known additional object orbiting further out. Nevertheless, it is common enough that if scattering indeed explains this population, then we would suggest multi-planet scattering is more common than two-planet scattering.

There are observational clues that scattering is probably not the sole mechanism generating misalignments. Mazeh et al. (2015) have found stellar misalignment to be a strong function of stellar temperature, but not of planetary multiplicity or coplanar architecture. A third planet does not appear to be needed to produce systems with similar characteristics as Kepler-56, thus weakening scattering as a major mechanism for spin-orbit misalignments of two or more coplanar planets. A host of other mechanisms may also be in play. The protoplanetary disk may have been tilted from its inception (Fremat et al. 2010) or due to magnetic torques in its early stages (Lai et al. 2011). It could have endured a torque from a previously-bound stellar companion (Batygin 2012) or from a flying-by star (Xiang-Gruess 2016). Even more exotic, the internal convection might have even tilted the stellar surface (Rogers et al. 2013) relative to the planetary plane. Most of these mechanisms would likely leave the non-transiting planet in roughly the same plane as the transiting planets. Such a configuration will eventually be testable, as orbital precession of the inner planets due to the outer one will become observable in transit data.
due to the slow but steady duration drifts, the manifestation of planetary precession (Miralda-Escudé 2002).

Our main conclusion is that three outer-planets are necessary for scattering to cause the amount of misalignment inferred for Kepler-56’s planets b and c. Two-planet scattering does not seem sufficient, because the excitation is rarely dramatic enough. Apparently in these cases, scattering in part of the planetary system propagates chaos to all other parts as well. This conclusion is probably much more general than our attempts to model the Kepler-56 system. In particular, it has been the upshot of attempts to model the early days of the Solar System (Brasser et al. 2009, Agnor & Lin 2012, Kaib & Chambers 2016). This conclusion may more broadly apply to exoplanets as well. For instance, since many or most planetary systems of small planets exhibit dynamically packed and rather calm orbits (Fabrycky et al. 2014), and most systems of giant planets have large eccentricity (Cumming 2010), it may suggest that these two types of systems are truly separate, expressing two distinct outcomes of the planet formation process.

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