An Empirically Derived Three-Dimensional Laplace Resonance in the Gliese 876 Planetary System

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ABSTRACT

We report constraints on the three-dimensional orbital architecture for all four planets known to orbit the nearby M dwarf Gliese 876 (=GJ 876) based solely on Doppler measurements and demanding long-term orbital stability. Our dataset incorporates publicly available radial velocities taken with the ELODIE and CORALIE spectrographs, HARPS, and Keck HIRES as well as previously unpublished HIRES RVs. We first quantitatively assess the validity of the planets thought to orbit GJ 876 by computing the Bayes factors for a variety of different coplanar models using an importance sampling algorithm. We confirm that a four-planet model is indeed preferred over a three-planet model. Next, we apply a Newtonian MCMC algorithm (\texttt{RUN DMC}, \textit{Nelson et al.} [2014a]) to perform a Bayesian analysis of the planet masses and orbits using an n-body model that allows each planet to take on its own orbit in three-dimensional space. Based on the radial velocities alone, the mutual inclinations for the outer three resonant planets are constrained to $\Phi_{cb} = 2.8^{\pm 1.7}$ degrees for the $c$ and $b$ pair and $\Phi_{be} = 10.3^{\pm 6.3}$ degrees for the $b$ and $e$ pair. We integrate the equations of motion of a sample of initial conditions drawn from our posterior for 10$^{7}$ years. We identify dynamically unstable models and find that the GJ 876 planets must be roughly coplanar ($\Phi_{cb} = 1.41^{\pm 0.62}$ degrees and $\Phi_{be} = 3.9^{\pm 2.9}$ degrees), indicating the amount of planet-planet scattering in the system has been low. We investigate the distribution of the respective resonant arguments of each planet pair and find that at least one resonant argument for each planet pair and the Laplace argument librate. The libration amplitudes in our three-dimensional orbital model supports the idea of the outer-three planets having undergone significant past disk migration.

1 INTRODUCTION

GJ 876 is a 0.37 $M_\odot$ M4V star\textsuperscript{1} hosting four known planets. This remarkable system represents several milestones: the first detection of a planet around an M-dwarf (GJ 876 b)\textsuperscript{2} \cite{Marcy1998, Delfosse1998}, the first example of multi-planet system orbiting in a mean-motion resonance (MMR)\textsuperscript{3} \cite{Marcy2001}, the first example of an MMR chain amongst three planets (Rivera et al.\textsuperscript{4} 2010), and the closest multi-planet exosystem to date (4.689 pc, van Leeuwen\textsuperscript{5} 2007).

The star has a lengthy Doppler (or radial velocity, RV) history spanning two decades and multiple observing sites. Planet $b$ was detected contemporaneously by \textit{Marcy et al.} [1998] using the Lick Hamilton Spectrograph and Keck HIRES and \textit{Delfosse et al.} [1998] using the ELODIE and CORALIE spectrographs. Both estimated a moderate eccentricity for $b$ ($\sim$0.3) and an orbital period of 61 days for this gas giant from their radial velocity model. With more RV observations, \textit{Marcy et al.} [2001] uncovered a second gas giant, $c$, orbiting near 30 days. This planet’s RV signature previously masqueraded as a larger eccentricity for planet $b$ due to the near 2:1 period commensurability of their orbits \cite{Anglada-Escudé2014, Ford2011}. As the Keck RV dataset grew, \textit{Rivera et al.} [2013] revealed a third planet $d$ orbiting near 1.9 days and was the lowest mass exoplanet around a main-sequence star at the time ($m \sin i=5.89 M_\oplus$). Photometric measure-
ments showed planet \( d \) did not transit \citep{Rivera_2005, Laughlin_2005, Shankland_2006, Kammer_2014, Correia_2010}, published new HARPS RVs which by themselves could constrain the mutual inclination between planets \( c \) and \( b \). Around the same time, \cite{Rivera_2010} published new Keck RVs which showed an additional RV signal around 124 days, dubbed planet \( e \). Numerically integrating their solutions beyond the last observation, the outer three planets \( (c, b, \text{ and } e) \) appear to be in a Laplace resonance, much like the three closest Galilean moons orbiting Jupiter. Other studies have placed limits on the existence of additional planets and massive companions in the system through observations \citep{Leinert_1997, Luhman_2002, Patience_2002} and considerations of long-term dynamical stability \citep{Jones_2000, Ji_2006, Rivera_2007, Gerlach_2012}

For RV systems, we only observe the component of the planetary induced stellar wobble projected onto our line-of-sight. Most of the time, there is a degeneracy between the true mass \((m)\) and on-sky inclination \((i)\), where an edge-on system is \( i_{\text{sys}} = 90^\circ \), so we can only place a lower limit on the orbiting companion’s mass. However, if the self-interactions in a multiple planet system are strong, the RV model becomes sensitive to the true masses of the planets, thereby breaking the \( m \sin i_{\text{sys}} \) degeneracy. There are many RV systems where the true masses can be meaningfully constrained, including HD 209964, 24 Sextantis \citep{Johnson_2011}, HD 82943 \citep{Tan_2013}, and other dynamically active systems \citep{Veras_2010}.

For GJ 876 \( c \) and \( b \), \cite{Laughlin_2001} and \cite{Rivera_2001} performed self-consistent Newtonian fits and constrain the planetary masses and their on-sky coplanar inclination. \cite{Rivera_2005} found an on-sky inclination for the three-planet system \( i_{\text{sys}} = 50^\circ \pm 3^\circ \), assuming coplanarity. \cite{Bean_2009} combined the RVs from \cite{Rivera_2005} and Hubble Space Telescope astrometry from \cite{Benedict_2004} and measured the mutual inclination \( \Phi \) between \( c \) and \( b \), where

\[
\cos \Phi_{cb} = \cos i_c \cos i_b + \sin i_c \sin i_b \cos (\Omega_c - \Omega_b),
\]

\( \Omega \) is the longitude of ascending node, and \( c \) and \( b \) denote the two planets considered. They find \( \Phi_{cb} = 5.0^{+3.9}_{-3.5}^\circ \). Based on the HARPS RVs alone, \cite{Correia_2010} find a lower value \( \Phi_{cb} = 1.00^\circ \). With their four-planet model, \cite{Rivera_2010} finds a best fit value \( \Phi_{cb} = 3.7^\circ \). All of the above values are generally consistent with a nearly coplanar system. When incorporating the effects of correlated noise, \cite{Baluev_2011} finds a larger and wider range of mutual inclination \( \Phi_{cb} = 5 - 15^\circ \).

Arguably the most studied exoplanet system displaying a MMR, the GJ 876 system has been a prime testbed for dynamical and planet formation theory for the past decade. The 2:1 MMR of the \( c \) and \( b \) pair is of particular interest, since the libration amplitude of the resonant arguments are a valuable indicator of the system’s long-term dynamical stability \citep{Kincsita_2001, Ji_2002, Gozdziewski_2002, Beaugé_2003, Haghigipour_2003, Zhou_2003}. The most likely mechanism for the planets’ current orbital periods and eccentricities is through a combination of planet-planet interactions and disk migration, while most studies have focused on migration through a gas disk \citep{Snellgrove_2001, Murray_2002, Lee_2002, Kley_2004, Lee_2003, Lee_2004, Podlewska-Gaca_2012, Batygin_2013, Lega_2013}. (Semi-)analytic models describing the secular evolution of the system have also been developed \citep{Beaugé_2003, Veras_2007}.

Other studies of the GJ 876 system include the search for debris disks, thermal properties of \( d \), and interior structure models of \( d \) \citep{Rivera_2010} and references therein. More recent analyses include how the star’s UV radiation field affects habitability \citep{France_2012, France_2013} and the detectability of additional hypothesized planets in the system \citep{Gerlach_2012}. Although the system’s orbital architecture appears atypical, GJ 876 does fit into a larger portrait of exoplanet systems around M dwarfs, including population statistics of giant planets \citep{Montet_2014} and the coplanarity of multi-planet systems \citep{Ballard_2014}.

RV surveys have discovered a couple dozen strongly-interacting multi-planet systems, motivating the need for analysis procedures to incorporate a self-consistent Newtonian model. \cite{Nelson_2014} developed a Newtonian MCMC algorithm which has been successful in analyzing systems that require a large number of model parameters \citep[e.g. 55 Cancri;][]{Nelson_2014}. The GJ 876 observations have a similar observing baseline and require almost as many model parameters, making it compatible with such an algorithm.

In this work, we present a detailed characterization of the orbits and masses of the GJ 876 planets employing a full three-dimensional orbital model used to fit the Doppler observations. In §3 we describe the RV observations made with multiple spectrographs (ELODIE, CORALIE, HARPS, and HIRES), including a new set of HIRES measurements. In §4 we describe our orbital and observational model and investigate the effects of correlated noise in the observations. In §4 we report our results for a coplanar orbital model. Before advancing to a more complex orbital model, we evaluate the evidence for planets \( d \) and \( e \) by computing Bayes factors as described in §4.4. In §5 we report the results of the fitting and n-body simulations for a three-dimensional orbital model. In §6 we investigate the evolution of the resonant angles and statistics regarding their libration amplitude. In Appendix A we test for possible observational biases in these results. We conclude with a discussion of the key results and the applications of our posterior samples in §7.

2 OBSERVATIONS

Our dataset includes publicly-available RVs from four different instruments. We include 46 ELODIE, 40 CORALIE, and 52 HARPS observations \citep{Correia_2010}. The inclusion of these data extends our observing baseline to roughly 580 days before the first Keck HIRES observation. The 162 Keck observations are reduced by the Carnegie Planet Search
Table 1. New Keck HIRES velocities for GJ 876.

| BJD-2450000 [days] | Radial Velocity [m s\(^{-1}\)] | Uncertainty [m s\(^{-1}\)] |
|--------------------|-------------------------------|-----------------------------|
| 3301.808032        | -33.89                        | 2.06                        |
| 3301.816875        | -36.49                        | 2.37                        |
| 3301.822986        | -28.19                        | 2.60                        |
| 3301.871412        | -39.54                        | 1.99                        |
| 3302.72523         | -91.03                        | 1.91                        |
| 3302.728666        | -89.20                        | 2.02                        |
| 3302.735567        | -81.93                        | 1.92                        |

Table 1 is presented in its entirety as Supporting Information with the online version of the article. This stub table is shown for guidance regarding its form and content.

3 METHODS

We characterize the masses and orbits of the GJ 876 planets using the GPU version of the Radial Velocity Using N-body Differential evolution Markov Chain Monte Carlo code, \textsc{RUN DMC} (Nelson et al. 2014a), which incorporates the \textsc{Swarm-NG} framework to integrate planetary systems on graphics cards (Dindar et al. 2014). \textsc{RUN DMC} has analyzed the 55 Cancri planetary system, which required a high-dimensional (\sim 40) model. Compared with 55 Cancri, the problem of GJ 876 seems to be similarly challenging but more computationally tractable due to having fewer observations, a shorter observing baseline, a larger integration timestep, and a lower dimensional model (e.g., one less planet to account for). On the other hand, the presence of extremely strong planet-planet interactions can result in a challenging posterior distribution that could be more difficult to sample from.

3.1 Model Parameters

We characterize the system model with a fixed star mass \((M_\star = 0.37 M_\odot)\) (von Braun et al. 2014), plus each planet’s mass \((m)\), semi-major axis \((a)\), eccentricity \((e)\), inclination \((i)\), argument of periastron \((\omega)\), longitude of ascending node \((\Omega)\), and mean anomaly \((M)\) at our chosen epoch (first ELODIE observation) for each planet, plus the RV zero-
point offsets ($C$) and jitters (i.e. unmodeled instrumental and astrophysical noise, $\sigma_{ui}$) for each observatory. We report the orbital periods ($P$) based on Kepler’s Third Law and each body’s $m$ and $a$ based in a Jacobi coordinate system. Planet masses and semi-major axes can be readily rescaled to account for any updates to the stellar mass.

The GJ 876 planets are well approximated by a coplanar system, i.e. $\Omega = 0$° and $i$ is the same for all planets. Due to the symmetrical nature of a radial velocity system on the sky, a planetary system at $i_{\text{sys}}$ is indistinguishable from one at an inclination of $180° - i_{\text{sys}}$. So in $\S$ we restrict the planets to a coplanar system that can take on any value of $0° < i_{\text{sys}} < 90°$. Similarly, the entire system can be rotated about the line-of-sight. In $\S$ the individual $i$ and $\Omega$ for each planet become free parameters in our model that are fit to the observations. We set $\Omega_q = 0$° to ground our coordinate system.

3.2 Model of Observations

RUN DMC allows for fitting multiple zero-point offsets and magnitudes of jitter (e.g. combined astrophysical and/or instrumental noise). HIRES received a CCD upgrade and new Doppler reduction process in August 2004 (JD 2453241.5). The Carnegie time series was split based on this pre- and post-upgrade era, which was modeled by two zero-point offsets, but the entire dataset is still modeled with one jitter term. The California RVs also have a separate offset and one jitter term. The other instruments (ELODIE, CORALIE, HARPS) were each modeled by one RV zero-point offset and jitter term. In total, we account for six offsets and five jitter parameters.

Our dataset does not include the HST astrometry from Benedict et al. (2002) or any informative priors regarding the inclinations of the GJ 876 planets.

3.3 Magnitude and Timescale for Correlated Noise

Our likelihood function described in Equations 4 and 5 of Nelson et al. (2014a) assumes that the observational errors are uncorrelated, which may not be a sufficient approximation for high precision RV measurements of stars with significant stellar activity. Balucè (2011) showed that correlated (=red) noise in the RV data could lead to bias or misestimated uncertainty in some of the orbital parameters (e.g., $e_d$). Recently, some discoveries of planets orbiting M dwarfs have been shown to be more likely mere artifacts resulting from stellar activity (Robertson et al. 2014, Robertson & Mahadevan 2014). Therefore, we take a closer look at the role of stellar activity in contributing astrophysical noise to RV observations of GJ 876. In $\S$ we perform a complementary analysis by computing Bayes factors for a finite set of models.

High-precision photometry of GJ 876 (Rivera et al. 2003) revealed a rotation period of $97 \pm 1$ days. Examining the variability of the activity-sensitive Hα and Na I D absorption lines in the publicly-available HARPS spectra of the star\footnote{Based on data obtained from the ESO Science Archive Facility under request number 129169} we confirm the rotation period, finding an Hα periodicity of $95\pm1$ days (Figure 1 top panel). The appearance of the rotation period in the photometry suggests the presence of starspots, which can affect the measured RVs (e.g. Boisse et al. 2011, Dumusque et al. 2014). The results from Balucè (2011), Rivera et al. (2003), and our own examination of the spectral activity tracers suggest a complete treatment of activity will yield only marginal improvements in the accuracy of the RV model, and is not necessary to achieve the goals of this study.

Boisse et al. (2011) showed that rotating starspots will induce RV periodicities at the stellar rotation period $P_{\text{rot}}$ and its integer fractions ($P_{\text{rot}}/2$, $P_{\text{rot}}/3$, etc.). Given that none of the planets in the GJ 876 system have periods near the rotation period or its integer fractions, we conclude that rotating starspots have not produced large-amplitude periodic RV signals such as might be misinterpreted as planet candidates. Although the RV amplitude of the outermost planet $e$ (3.5m s$^{-1}$) is closest to the amplitudes expected for activity signals produced by a chromospherically quiet star such as GJ 876, we are unaware of any physical mechanism that would create an RV signal on this timescale.

Our computed stellar rotation period of $95 \pm 1$ days beating with one Earth year produces an alias of around 128 days, which is worryingly close to the orbital period of planet $e$ (~124 days). However, subtracting the rotation signal causes the 128-day peak to disappear as well, leading us to suspect that this signal is an alias (Figure 1 bottom panel). If the 124-day signal is an 1-year alias of the rotation period, the variability is likely due to the activity-related noise in the RV data, which could lead to bias or misestimated uncertainty in some of the orbital parameters. Therefore, we take a closer look at the role of stellar activity in contributing astrophysical noise to RV observations of GJ 876.
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3.4 Computing Bayes Factors for Model Selection

When Doppler observations of a system with multiple strongly-interacting planets, the shape of the posterior distribution is often challenging to sample from efficiently. A general Bayesian approach of performing model comparison is to compute the fully marginalized likelihood, sometimes called the evidence, for each model. Formally, the evidence is the probability of generating the observed radial velocity dataset \( \hat{\vec{d}} \) assuming some underlying model \( \mathcal{M} \) that is parameterized by \( \vec{\theta} \),

\[
p(\hat{\vec{d}}|\mathcal{M}) = \int p(\hat{\vec{d}}|\vec{\theta}, \mathcal{M})p(\vec{\theta}|\mathcal{M})d\vec{\theta} \tag{2}
\]

where \( p(\hat{\vec{d}}|\vec{\theta}, \mathcal{M}) \) is the likelihood function and \( p(\vec{\theta}|\mathcal{M}) \) is the prior probability distribution. While the value of \( p(\hat{\vec{d}}|\mathcal{M}) \) is not useful by itself, the ratio of two evidences for two competing models \( \mathcal{M}_1 \) and \( \mathcal{M}_2 \), yields the Bayes factor

\[
\text{BF} = \frac{p(\hat{\vec{d}}|\mathcal{M}_2)}{p(\hat{\vec{d}}|\mathcal{M}_1)} \tag{3}
\]

that provides a quantitative measure of which model is preferred and to what degree.

Marginal likelihoods are notoriously difficult to compute. Integrating Equation (2) analytically may be possible for some idealized problems with one to a few dimensions, but the model required to describe a 3+ planet system needs roughly 20 or more parameters. Numerical integration techniques such as Monte Carlo integration become vastly inefficient with increasing dimensionality.

Therefore, we use importance sampling, a more general form of Monte Carlo integration, to calculate the integral in Equation (2) and make this problem computationally tractable. Following Ford & Gregory (2007), we sample from a distribution \( g(\vec{\theta}) \) with a known normalization. We multiply the numerator and denominator of the integrand in Equation (1) by \( g(\vec{\theta}) \),

\[
p(\hat{\vec{d}}|\mathcal{M}) = \int \frac{p(\hat{\vec{d}}|\vec{\theta}, \mathcal{M})p(\vec{\theta}|\mathcal{M})}{g(\vec{\theta})} g(\vec{\theta})d\vec{\theta}. \tag{4}
\]

While the value of \( p(\hat{\vec{d}}|\mathcal{M}) \) has not changed, Equation (4) can be estimated by drawing \( N \) samples from \( g(\vec{\theta}) \),

\[
\hat{p}(\hat{\vec{d}}|\mathcal{M}) = \frac{1}{N} \sum_{\vec{\theta} \sim g(\vec{\theta})} \frac{p(\hat{\vec{d}}|\vec{\theta}, \mathcal{M})p(\vec{\theta}|\mathcal{M})}{g(\vec{\theta})}. \tag{5}
\]

The key aspect of having importance sampling work efficiently is to pick an appropriate \( g(\vec{\theta}) \). Assuming our parameter space contains one dominant posterior mode, we choose a multivariate normal with mean vector \( \vec{\mu} \) and covariance matrix \( \Sigma \) for \( g(\vec{\theta}) \). For each model considered, we will estimate \( \vec{\mu} \) and \( \Sigma \) from the coplanar MCMC runs described in (4). Our parameterization for \( g(\vec{\theta}) \) is \( P, K, e, \cos \omega, \sin \omega, e \cos \omega, e \sin \omega, M \) for each planet, the system’s orbital inclination \( i \), and one \( \sigma_{ij,t} \) for each observatory. Since we are only interested in computing ratios of \( p(\hat{\vec{d}}|\mathcal{M}) \), the priors in zero-point offsets in the calculation will cancel out.

One good strategy with importance sampling is to pick a \( g(\vec{\theta}) \) that is heavier in the tails than \( p(\hat{\vec{d}}|\vec{\theta}, \mathcal{M})p(\vec{\theta}|\mathcal{M}) \). This makes it easier to sample from low probability parts of the posterior distribution and prevents any samples from resulting in extremely large weights. However, the chance of sampling from the posterior mode will decrease with increasing dimensionality, which could ultimately lead to an estimate of \( p(\hat{\vec{d}}|\mathcal{M}) \) that is not efficient.

One way around this is to sample from \( g(\vec{\theta}) \) within some truncated subspace, \( T \). This new distribution \( g_T(\vec{\theta}) \) is proportional to \( g(\vec{\theta}) \) inside \( T \) and renormalized to be a proper probability density. Equation (5) can be rewritten as

\[
f \times p(\hat{\vec{d}}|\mathcal{M}) \approx \frac{1}{N} \sum_{\vec{\theta} \sim g_T(\vec{\theta})} \frac{p(\hat{\vec{d}}|\vec{\theta}, \mathcal{M})p(\vec{\theta}|\mathcal{M})}{g_T(\vec{\theta})}. \tag{6}
\]

where \( f \) is a factor that specifies what fraction of \( p(\hat{\vec{d}}|\vec{\theta}, \mathcal{M})p(\vec{\theta}|\mathcal{M}) \) lies within \( T \). We can estimate \( f \) with an MCMC sample. By counting what fraction of our posterior samples fell within \( T \), \( f_{\text{MCMC}} \), we can rearrange Equation (6) to give us \( p(\hat{\vec{d}}|\mathcal{M}) \).

\[
p(\hat{\vec{d}}|\mathcal{M}) \approx \frac{1}{N \times f_{\text{MCMC}}} \sum_{\vec{\theta} \sim g_T(\vec{\theta})} \frac{p(\hat{\vec{d}}|\vec{\theta}, \mathcal{M})p(\vec{\theta}|\mathcal{M})}{g_T(\vec{\theta})}. \tag{7}
\]

Guo (2012) and Weingberg et al. (2013) provide more detailed prescriptions and investigations of this method.

There are two competing effects when choosing the size of our subspace \( T \). If \( T \) is large (i.e. occupies nearly all of the posterior distribution), then \( f_{\text{MCMC}} \) approaches 1 and we return to our basic importance sampling algorithm. If \( T \) occupies a much smaller region, then we are more likely to sample from near the posterior mode, but \( f_{\text{MCMC}} \) approaches 0, making it difficult to accurately estimate \( p(\hat{\vec{d}}|\mathcal{M}) \). We must carefully choose \( T \) that will provide a robust estimate of \( p(\hat{\vec{d}}|\mathcal{M}) \). Guo (2012) found that for a three- and four-planet system, truncating the posterior distribution from \(-2\sigma \) to \(+2\sigma \) was roughly optimal, where \( \sigma \) is the standard deviation of each respective model parameter. We tested several subspace sizes and found \( \pm 1.5\sigma \) worked well for our problem.

To draw from this distribution, we create a vector \( \vec{z} \) whose components are independent draws from a standard normal \( N(0, 1) \) truncated at \(-1.5\sigma \) and \(+1.5\sigma \) for each of our vector components. Each \( \vec{\theta} \) is generated as \( \hat{\vec{\mu}} \pm \vec{A}\vec{z} \), where \( \vec{A} \) is the Cholesky decomposition of \( \Sigma \). We generate \( 10^7 \) samples from \( g(\vec{\theta}) \), which provided a robust estimate of \( p(\hat{\vec{d}}|\mathcal{M}) \) for each of our five competing models described in (4).

4 COPLANAR MODELS

Before attempting to relax the coplanarity constraint, we wish to assess the evidence for all the GJ 876 planets, \( e \) in particular.

We apply Run DMC to our cumulative set of 367 RV observations using a coplanar model but allowing for a systematic orbital inclination. In particular, we consider five different...
models: one with just the outer-most three planets (\(M_{\text{3out}}\)), one with just the inner-most three planets (\(M_{\text{3in}}\)), one with the inner-most three planets plus a ~124-day sinusoid to mimic either a fourth planet on a circular orbit or a stellar activity signal (\(M_{\text{3in}+}\)), one with all four planets (\(M_4\)), and one with a putative fifth planet (\(M_5\)).

We calculate five fully marginalized likelihoods (four Bayes factors) and summarize the results in Table 2. Our methodology for computing these probabilities are described in §5.3.

The Bayes factor for \(M_{\text{3in}}/M_{\text{3out}}\) is \(\sim 10^{31}\), decisively favoring \(M_{\text{3in}}\). This was expected since \(M_{\text{3in}}\) accounts for the three most significant RV signals in GJ 876. The Bayes factor for \(M_{\text{3in}+}/M_{\text{3in}}\) is \(\sim 10^{10}\). Despite the increased parameterization of \(M_{\text{3in}+}\), this model with four signals is decisively favored over \(M_{\text{3in}}\). The Bayes factor for \(M_4/M_{\text{3in}+}\) is \(\sim 9.7\). The ratio of the evidence for a fully interacting four planet model \(M_4\) relative to an interacting three planet model with a decoupled ~124-day signal \(M_{\text{3in}+}\) is modest. Regardless, a model with four signals is overwhelmingly preferred over a model with three signals.

Strictly considering the results above, we would not be able to select \(M_4\) over \(M_{\text{3in}+}\). Nevertheless, we do not expect this ~124 to be due to (an alias of) stellar magnetic activity, Rivera et al. (2010) found that after fitting for the inner-three planets to the Carnegie RVs alone, the residual periodogram strongly peaked at the planet c’s period. The periodogram did not contain a strong signal near the stellar rotation period (see §8.3), so we do not suspect the 124-day signal is an alias.

For \(M_5\), we initialized RUN DMC simulations with a hypothetical planet \(f\) with the following properties: \(P_f = 15.04\) d, \(K_f = 3\) m s\(^{-1}\), \(e_f = 0.007\), \(\omega_f = 78.3^\circ\), and \(M_f = 159.8^\circ\). This set of initial conditions was inspired by an additional candidate signal uncovered by Jenkins et al. (2014) using a global periodogram method and RVs extracted from HARPS spectra using the HARPS-TERRA pipeline (Anglada-Escudé & Butler 2012). One significant difference is that we use an RV signal much closer to the difference is that we use an RV signal much closer to the
A subsample of 1,000 models is integrated for 10^6 years. If at any point a planet collides with another body or the semi-major axis of any planet changes by more than 50% of its original value (i.e., |Δa/a| > 0.5), then the simulation stops and is tagged as being unstable. This is the default setup for our dynamical integrations unless stated otherwise.

For M₃₀₀ₙ, we find 93% of the posterior samples are stable for the duration of the integration. The mode of instability for the remaining 7% was |Δa/a| of planet e exceeding 0.5. This typically happened when e_e > 0.14. For both M₅₀₀ₙ and M₃₀₅ₙ, all of the posterior samples are stable for the same integration timespan. For M₄ₙ, 99% of the posterior samples are stable. For M₅ₙ, only 18% of the posterior samples were stable. 77% of models had |Δa/a| of e exceeding 0.5, and at least 5% of models involve a planetary collision. Some simulations had both instabilities occur.

Based on these previous works and the results of [14, 15], we conclude that M₄ₙ is the best model to generate these observations to date. With a four-planet model decisively chosen, we report estimates of orbital parameters and instrumental properties based on a coplanar model in Tables 3 and 4 respectively.

Before moving onto our three-dimensional model, we consider the significance of the relativistic precession rate ω_rel for planet d, since it is estimated to have a moderate eccentricity (e_d ~ 0.1) and is close to its host star. While the rapid resonant interactions amongst the outer three planets dominate their orbital evolution, the inner-most planet is mostly dynamically decoupled and undergoes secular perturbations. A value of ω_rel comparable to the secular precession rate ω secular tends to aggravate an instability (Ford et al. 2001), while an ω_rel that is much more rapid than ω secular could quench secular effects (Adams & Laughlin 2006b).

We approximate the precession rate

\[ \dot{\omega}_{\text{rel}} \approx \frac{7.78}{1 - e_d^2} \left( \frac{M_*}{M_\odot} \right) \left( \frac{a_d}{0.05 \text{ AU}} \right)^{-1} \left( \frac{P_d}{1 \text{ day}} \right)^{-1} \text{ degrees century}^{-1} \]

where the subscript d refers to planet d and each parameter is measured in the units of their respective normalization (Jordán & Bakos 2008). We evaluate Equation 8 for 1,000 four-planet models described and find \( \dot{\omega}_{\text{rel}} = 3.45 \pm 0.03 \) degrees per century. Baluev (2011) found that the effects of correlated noise results in a smaller estimate of \( \dot{\omega}_{\text{rel}} \), though this does not change \( \dot{\omega}_{\text{rel}} \) significantly. The typical \( \dot{\omega}_{\text{sec}} \) for the same models was 88 ± 2 degrees per century.

Ultimately, we wish to obtain a large sample of stable models but being careful not to neglect any mechanisms that could potentially stabilize a significant fraction of our models. Therefore, relativistic precession will not be included in our final long-term integrations.

### 5 RESULTS FOR 3D MODEL + LONG-TERM ORBITAL STABILITY

The planet-planet interactions in GJ 876 are so strong that the physical planet masses must be used in the modeling process. Next, we allow RUN DMC to consider the full range of parameters associated with a three-dimensional (3-d) orbit for a four-planet model. To provide a frame of reference, we set \( \Omega_0 = 0^\circ \). For our set of initial conditions for RUN DMC, we start with our posterior samples from M₄ₙ and perturb each inclination and ascending node value (excluding \( \Omega_0 \)) by adding a number drawn randomly and uniformly between -1° and +1°. RUN DMC burned-in for about 20,000 generations until a long-term steady state was reached. By modeling these extra variables, our parameter space grows from 32 dimensions (4 planets × 5 orbital elements \{P, K, e, \omega, M\} + \( i_{\text{sys}} + 6 \) offsets + 5 jitters) to 38.

Additionally, we can obtain even more precise estimates by constraining the 3-d orbits of the planets from a direct analysis of the RV data and by demanding orbital stability. In the end, we report 1,000 solutions where the planetary system is dynamically stable for at least 10^7 years. Our full procedure is described below and condensed into Table 5.

We start by randomly drawing 10,000 posterior samples from our initial 3-D MCMC run (Set 1) for our first set of stability tests. Figure 2 shows the joint parameter distribution for \( \Phi_d \) and \( \Phi_{\text{sys}} \) based on Set 1 (contours). The model parameter estimates for these samples are shown in Tables 6 and 7. These systems are integrated for 10^5 years and our conditions for stability are identical to those mentioned in [13]. Only about 11% of our initial conditions passed our stability criterion; 48% of our sample show planet d falling into the central star, and 41% of our sample show planet c’s semi-major axis suddenly changing by |Δa/a| > 0.5. We visually inspected the results and determined which model parameters were most important for distinguishing between “stable” and “unstable” regimes of parameter space. We find that the mutual inclination between planet pairs is the most sensitive parameter in regards to the system’s orbital stability. Henceforth, mutual inclinations between adjacent pairs.

### Table 4. Systematic offset and jitter estimates based on a coplanar orbital model.

| Dataset                     | Offset [m s⁻¹] | Jitter [m s⁻¹] |
|-----------------------------|---------------|---------------|
| HIRES Carnegie (pre-upgrade) | 50.48 ± 0.23  | 2.38 ± 0.25   |
| HIRES Carnegie (post-upgrade)| 52.20 ± 0.56  | 2.95 ± 0.23   |
| HIRES California (post-upgrade) | 8.18 ± 0.94  | 6.82 ± 0.74   |
| ELODIE                        | -1903.81 ± 4.48 | 18.56 ± 1.94   |
| CORALIE                       | -1864.40 ± 3.76 | 20.36 ± 1.30   |
| HARPS                         | -1337.64 ± 0.44 | 1.63 ± 0.24    |

See Section 4 for details.
Table 5. The different orbital parameter constraints applied to \textsc{run dmc}.

| Sample set | Constraints during \textsc{run dmc} | Then Integrate For... |
|------------|-------------------------------------|-----------------------|
| Set 1      | $0^\circ < \Phi_{dc} < 180^\circ$  | $0^\circ < \Phi_{cb} < 180^\circ$ | $0^\circ < \Phi_{be} < 180^\circ$ | $10^7$yr |
| Set 2      | $0^\circ < \Phi_{dc} < 60^\circ$  | $120^\circ < \Phi_{dc} < 180^\circ$ | $0^\circ < \Phi_{cb} < 180^\circ$ | $0^\circ < \Phi_{be} < 13^\circ$ | $10^6$yr |
| Set 3      | $0^\circ < \Phi_{dc} < 60^\circ$  | $120^\circ < \Phi_{dc} < 180^\circ$ | $0^\circ < \Phi_{cb} < 4^\circ$ | $0^\circ < \Phi_{be} < 3 \sqrt{16 - \Phi_{cb}^2}$ | $10^7$yr |

Here we show what range of parameter space \textsc{run dmc} is allowed to explore for each Set of simulations. The initial ensemble for a particular Set is generated based on stable regime found from the previous Set.

Figure 2. The joint mutual inclination distribution for planets $c$ and $b$ (vertical axis) and $b$ and $e$ (horizontal axis). Contours map the approximate 1-$\sigma$ (68%) and 2-$\sigma$ (95%) credible regions for the initial 10,000 posterior samples from Set 1 before any stability tests are performed. The dashed vertical line at $\Phi_{be} = 13^\circ$ indicates the cutoff for obtaining Set 2 and the dash-dotted line indicates the cutoff for obtaining Set 3, both described in §5 and Table 5. Green dots show a sample of 1,000 systems from Set 3 that were stable for at least $10^7$ years.

of planets will be labeled as such: e.g. $\Phi_{dc}$ for the mutual inclination between planets $d$ and $c$ (see Equation [1]). For planet $d$, $60^\circ < \Phi_{dc} < 120^\circ$ causes $d$ to undergo Kozai-like perturbations, pumping its eccentricity enough so that its periastron crosses the stellar surface (Figure [3]). For planet $e$, all initial conditions with $\Phi_{be} > 13^\circ$ led to a sudden and large change in planet $e$’s semi-major axis. Therefore, we perform a new set of \textsc{run dmc} simulations in which we restrict the parameter space to exclude the unstable mutual inclinations found above, i.e. $60^\circ < \Phi_{dc} < 120^\circ$, $\Phi_{be} > 13^\circ$. © 0000 RAS, MNRAS 000, 000–000
Although we see some large values of $\Phi_{cb}$ correspond to an instability, we do not restrict the range of $\Phi_{cb}$ for analysis in Set 2. **RUN DMC** is applied again on the same RV dataset, but now the resulting posterior sample (Set 2) is not as heavily diluted by wildly unstable models.

We repeat the above procedure one more time, integrating the Set 2 for $10^7$ years. We find the initial conditions are unstable, unless $0^\circ < \Phi_{cb} < 4^\circ$ and $0^\circ < \Phi_{bc} < 3 \sqrt{16 - \Phi_{bc}^2}$. We run **RUN DMC** once more while implementing these tighter constraints to obtain a new set of posterior samples for Set 3, which are subsequently integrated for $10^7$ years. Parameter estimates of 1,000 stable solutions from Set 3 are shown as the bottom value of each cell in Table 6 as the solid green histogram in Figure 4 and as green dots in Figure 2.

Performing everything described above, we find the radial velocities alone estimate $\Phi_{cb} = 2.8 \pm 1.3$ degrees and $\Phi_{bc} = 10.3 \pm 5.3$ degrees. However if we expect the system to remain stable over the course of $10^7$ years, the system must be roughly coplanar: $\Phi_{cb} = 1.41 \pm 0.62$ degrees and $\Phi_{bc} = 3.9 \pm 2.0$ degrees.

### Table 8. Libration Amplitudes of Resonant Angles.

| Angle | Amplitude, coplanar [$^\circ$] | Amplitude, 3D [$^\circ$] |
|-------|-------------------------------|--------------------------|
| $\phi_{cb}^b$ | $4.0 \pm 1.0$ | $7.0 \pm 1.0$ |
| $\phi_{cb}^e$ | $13.4 \pm 1.0$ | $18.69 \pm 1.0$ |
| $\omega_c - \omega_b$ | $14.7 \pm 1.0$ | $20.6 \pm 1.0$ |
| $\phi_{cc}^b$ | $31.3 \pm 1.9$ | $47.9 \pm 2.4$ |
| $\phi_{cc}^e$ | circulating | circulating |
| $\omega_b - \omega_c$ | circulating | circulating |
| $\phi_{cc}^b$ | $67.5 \pm 2.4$ | $103.2 \pm 2.3$ |
| $\phi_{cc}^e$ | circulating | circulating |
| $\omega_b - \omega_c$ | circulating | circulating |
| $\phi_{Laplace}^b$ | $33.0 \pm 1.2$ | $50.5 \pm 1.0$ |

See Section 6 for details.

6 **BEHAVIOR OF RESONANT ANGLES**

With the final 3-d orbital solutions from Set 3 of 4 we investigate the behavior of the critical angles associated with the mean-motion resonances relevant for this system. For both our stable coplanar and 3-d orbital models, we compute the root-mean-square of the variability in each angle $\times \sqrt{2}$. For a system undergoing small amplitude sinusoidal libration, this is an excellent approximation for the libration amplitude.

For the $c$ and $b$ pair, the angles associated with the 2:1 MMR are the resonant angles, $\phi_{cb}^b = \lambda - 2\lambda_b + \pi_c$ and $\phi_{cb}^e = \lambda - 2\lambda_e + \pi_c$, and the secular angle $\pi_c - \pi_b$, where $\lambda$ and $\pi$ are the mean longitude and longitude of pericenter respectively. We find each of these angles is librating with low amplitude about $0^\circ$. Figure 1 shows the distribution of the libration amplitude for angles associated with the $c$ and $b$ pair. Similarly for the $b$ and $e$ pair, the angles associated with the 2:1 MMR are the resonant angles, $\phi_{bc}^e = \lambda_e - 2\lambda_e + \pi_b$ and $\phi_{bc}^c = \lambda - 2\lambda_e + \pi_e$, and the secular angle $\pi_e - \pi_c$. We find $\phi_{bc}^e$ librates about $0^\circ$ and the other two angles are circulating. Figure 5 shows the distribution of the libration amplitude for angles associated with the $b$ and $e$ pair. For the $c$ and $e$ pair, the angles associated with the 4:3 MMR are the resonant angles, $\phi_{bc}^c = \lambda_c - 4\lambda_c + 3\pi_c$, $\phi_{be}^b = \lambda_b - 4\lambda_b + 3\pi_e$, $\phi_{be}^e = \lambda_e - 4\lambda_e + 3\pi_e$, and $\phi_{ce}^c = \lambda_c - 4\lambda_c + 3\pi_c$, and the secular angle $\pi_c - \pi_e$. To distinguish these angles, the subscript refers to the multiplier in front of $\pi_e$. We find that four of the five angles are circulating. $\phi_{bc}^c$ librates about $0^\circ$ with low to medium amplitude. Figure 5 shows the distribution of the libration amplitude for $\phi_{bc}^c$.

We report all of our libration amplitudes for coplanar and dynamically stable 3-d orbital models in Table 8.

We find the secular angle $\omega_c - \omega_b$ is circulating, in contrast to previous studies that reported libration about $180^\circ$. This underscores the importance of performing self-consistent dynamical and statistical analyses when characterizing the evolution of interacting planetary systems.

The measured amplitude is interesting as it is neither so small as to imply strong dissipation nor so large as to suggest the absence of damping. Given the importance of this result, we performed additional tests to verify that our algorithm accurately characterizes the libration amplitude of the Laplace angle for both regular and chaotic systems. The methods and more detailed results of these test are presented in Appendix A.

Upon the discovery of the outer-most planet, **Rivera et al. (2010)** found that their best fit systems exhibit a 4:2:1 Laplace resonance. The associated angle, $\phi_{Laplace} = \lambda_c - 3\lambda_c + 2\lambda_e$, evolves chaotically. Based on the Carnegie RVs alone, they found that $\phi_{Laplace}$ librates about $0^\circ$ with an amplitude of $40 \pm 13^\circ$ for a coplanar four-planet model. Figure 7 shows our results for the posterior distribution for the libration amplitude for the Laplace argument for both the coplanar ($33 \pm 12^\circ$) and 3-d ($50.7 \pm 7.9^\circ$) cases. The measured amplitude is interesting as it is neither so small as to
Table 6. Estimates of the osculating orbital elements for all the known GJ 876 planets from self-consistent, 3-d dynamical fits. The top value in each cell are estimated directly from the radial velocities, and the bottom value imposes dynamical stability for $10^7$ years.

| Parameter | Planet d | Planet c | Planet b | Planet e |
|-----------|----------|----------|----------|----------|
| $P$ [d]   | 1.937891±0.000017 | 30.0758±0.0084 | 61.094±0.013 | 123.50±0.63 |
|           | 1.937870±0.000025 | 30.0706±0.0065 | 61.087±0.012 | 124.72±1.18 |
| $K$ [m s$^{-1}$] | 6.13±0.39 | 88.74±0.56 | 213.63±0.90 | 3.18±0.51 |
|           | 6.11±0.35 | 88.33±0.47 | 213.71±0.43 | 3.44±0.41 |
| $m_0$ $M_\star$ [M$_\odot$] | 7.03±0.55 | 274.2±10.1 | 850.5±16.6 | 15.45±2.32 |
|           | 6.90±0.40 | 267.9±5.9  | 848.5±17.1 | 17.16±1.96 |
| $a$ [AU]  | 0.02183945±0.00000004 | 0.135984±0.000026 | 0.218609±0.000034 | 0.3495±0.0031 |
|           | 0.02183930±0.00000022 | 0.135985±0.000019 | 0.218589±0.000026 | 0.3518±0.0024 |
| $e$       | 0.113±0.053 | 0.2532±0.0012 | 0.0371±0.0019 | 0.046±0.041 |
|           | 0.108±0.050 | 0.2530±0.0013 | 0.0365±0.0030 | 0.031±0.027 |
| $e \sin \omega$ | −0.038±0.049 | 0.2208±0.0087 | 0.0345±0.0021 | 0.019±0.027 |
|           | −0.034±0.049 | 0.2259±0.0052 | 0.0340±0.0022 | 0.004±0.014 |
| $e \cos \omega$ | −0.096±0.049 | −0.1236±0.0135 | −0.0137±0.0024 | −0.020±0.033 |
|           | −0.089±0.049 | −0.1160±0.0073 | −0.0137±0.0022 | −0.006±0.020 |
| $i$ [degrees] | 87.44±1.97  | 51.63±2.64  | 52.61±1.44  | 55.51±1.34 |
|           | 88.26±3.80  | 53.06±1.77  | 52.82±1.54  | 54.29±1.36 |
| $\omega$ [degrees] | −139.25±288.00 | 119.26±2.73 | 111.81±4.57 | 122.34±4.00 |
|           | 162.52±6.57 | 117.12±1.70 | 112.27±4.13 | −54.2±2.46 |
| $M$ [degrees] | 301.24±27.44 | −223.46±1.17 | −286.01±4.30 | −184.28±231.29 |
|           | 300.58±25.88 | −221.76±1.72 | −286.82±4.24 | −92.97±119.00 |
| $\omega + M$ [degrees] | 162.52±6.57 | −104.33±0.73 | −174.26±0.57 | −54.24±23.68 |
|           | 162.26±7.28 | −104.60±0.57 | −174.64±0.45 | −42.46±8.91 |
| $\Delta \Omega$ [degrees] | $\Delta \Omega_{cb} = -2.72_{-1.29}^{+2.02}$ | $-1.29_{-0.89}^{+0.90}$ | $\Delta \Omega_{bc} = -5.01_{-2.89}^{+1.17}$ | $1.29_{-0.99}^{+0.89}$ |

See Section 5 for details.

Table 7. Systematic offset and jitter estimates based on a 3-d orbital model.

| Dataset                  | Offset [m s$^{-1}$] | Jitter [m s$^{-1}$] |
|--------------------------|---------------------|---------------------|
| HIRES Carnegie (pre-upgrade) | 50.44±0.34 | 2.40±0.23 |
|                          | 50.49±0.31 | 2.36±0.24 |
| HIRES Carnegie (post-upgrade) | 52.04±0.55 | 2.36±0.23 |
|                          | 52.12±0.65 | 2.36±0.23 |
| HIRES California (post-upgrade) | 8.02±0.90 | 6.76±0.75 |
|                          | 8.05±0.95 | 6.93±0.74 |
| ELODIE                   | −1904.25±4.58 | 18.97±5.70 |
|                          | −1903.83±4.58 | 18.95±5.70 |
| CORALIE                  | −1864.32±3.53 | 19.96±4.03 |
|                          | −1864.48±3.53 | 19.94±4.03 |
| HARPS                    | −1337.68±0.47 | 1.52±0.27 |
|                          | −1337.58±0.44 | 1.57±0.27 |

See Section 5 for details.
imply strong dissipation nor so large as to suggest the absence of damping. Given the importance of this result, we performed additional tests to verify that our algorithm accurately characterizes the libration amplitude of the Laplace angle for both regular and chaotic systems. The methods and more detailed results of these test are presented in Appendix A.

7 SUMMARY AND DISCUSSION

We have meaningfully constrained the three-dimensional orbital architecture of the GJ 876 planetary system, based on 367 Doppler observations from several observing sites.

To verify the nature of the \( \sim124 \)-day signal, we performed Bayesian model comparison of five different physical models, spanning three to five planets. Since each evaluation of the likelihood requires an n-body integration for a strongly interacting planetary system like GJ 876, Bayesian model comparison becomes computationally costly. Therefore, it was particularly important that we apply efficient and parallelizable algorithm. We refined and applied a modified importance sampling algorithm to compute the fully marginalized likelihood, or Bayesian evidence, starting from a posterior sample computed via MCMC methods (Ford & Gregory 2007; Guo 2012; Weinberg et al. 2013). The algorithm parallelizes readily and was implemented on GPUs using the Swarm-NG framework (Dindar et al. 2013). While previous studies have computed Bayes factors using other algorithms (e.g. nested sampling (Feroz et al. 2009; Kipping 2013; Placek et al. 2014), geometric-path Monte Carlo (Hou et al. 2014)), these studies have assumed that the motion can be described as the linear superposition of Keplerian orbits, which is unsuitable for strongly interacting planetary systems such as GJ 876. We believe this study to be the first example of rigorous Bayesian model comparison applied to strongly interacting planetary systems. This algorithm is relatively easy to implement and worked well even for our high-dimensional (\( \sim30-40 \) parameter) models.

We determined that a four-planet model is most appropriate for the present data, based on a self-consistent Bayesian and n-body analysis (§3.3 and 5.4). When com-
and 3-d (solid orange) orbital model. For the vast majority of our sets of initial conditions, the other resonant argument and the secular angle are circulating.

Through numerical integrations of systems where planet \( e \) was treated as a test particle, [Rivera et al. (2010)] explored the parameter space near the best-fit GJ 876 solution to the Carnegie RVs. These tests suggested that the true system might be chaotic and was likely surrounded by regions of phase space with short-lived (unstable) orbits. [Martí et al. (2013)] studied the two reported 4-planet solutions to the radial velocity data using the MEGNO method (e.g. Cincotta & Simó (2000)) and found that these trajectories were both chaotic and in the Laplace resonance. We show that the most probable Lyapunov time to be \( \sim 10 \) years for both our coplanar and dynamically stable 3-d models (Appendix A3). This timescale is consistent with the results of Batygin et al. (2015) which were based on combining a simplified dynamical model and a point estimate for orbital parameters.

Strongly interacting planetary systems like GJ 876 could have unusually large transit timing variation amplitudes, enabling detailed characterization via the transit timing technique. Upcoming missions such as TESS and PLATO would easily detect and confirm a similar system to the one we measure a stellar rotation period of 95 ± 1 days. This does not directly correspond with any of the planets’ orbital periods. As expected, the stellar rotation period and annual observing cycle lead to an alias with a frequency of \( \sim 128 \) days. In our coplanar model, the orbital period of \( e \) is 124.5 ± 1.3, differing from the 128-day alias at slightly more than 2-\( \sigma \) level. If the signal were due solely to aliasing of the annual observing cycle with the stellar rotation period, then there should be an even stronger signal corresponding to the stellar rotation in the periodogram of the RV residuals (after subtracting the RV signal due to the inner-three planets).

Rivera et al. (2010) and Baluev (2011) looked for but did not find this effect, concluding that the signal is best explained by planet \( e \).

On one hand, a Bayes factor of \( \sim 10 \) is not large enough by itself to definitively choose the four planet model. On the other hand, we find no reason to suspect that stellar activity is masquerading as a planetary signal. Looking at activity-sensitive indicators in publicly available HARPS spectra, we can decisively choose a model with four signals with Bayes factors exceeding \( 10^3 \). We find a Bayes factor of \( \sim 10 \) when comparing a four planet model (\( \mathcal{M}_4 \)) to a model with three planets plus a decoupled sinusoid, which could result from either a fourth planet in a circular orbit or a stellar activity signal (\( \mathcal{M}_{3\text{nu},+~} \)).
particular, the perturbations from GJ 876 e become evident only on multi-year timescales (Libert & Renner 2013).

While previous studies have assumed that the planets in GJ 876 follow coplanar orbits, we relax the assumption of coplanarity and allow for non-coplanar orbital configurations. We analyze the Doppler observations of GJ 876 and find that the three planets participating in the Laplace resonance must be nearly coplanar. The absolute range of the mutual inclination constrained by just the RVs is impressive for both planet pairs: $\Phi_{cb} = 2.8 \pm 1.3^\circ$ degrees for the $c$ and $b$ pair and $\Phi_{be} = 10.3 \pm 4.7^\circ$ degrees for the $b$ and $e$ pair. Demanding orbital stability further restricts this range providing precise constraints on the mutual inclinations: $\Phi_{cb} = 1.41 \pm 0.97^\circ$ degrees and $\Phi_{be} = 3.9 \pm 2.9^\circ$ degrees. Despite its rather unique orbital architecture, it seems that GJ 876 fits in with a population of M dwarf systems with several, coplanar planets (Ballard & Johnson 2014).

By performing the first self-consistent, Bayesian analysis of the four planets in GJ 876, we are able to accurately characterize the current dynamical state of all four planets and particularly the evolution of the resonant angle associated with the Laplace resonance. We measure the amplitude of variations to be $33 \pm 2.3^\circ$ degrees for coplanar models or $50.5 \pm 7.9^\circ$ degrees for fully three-dimensional models.

When measuring a positive definite quantity, observational uncertainties can bias measurements, particularly when using point estimates. For example, the best-fit models of Doppler observations of a population of planets with nearly circular orbits will typically overestimate the planets’ orbital eccentricities (Zakamska et al. 2011), particularly when the Doppler amplitude is only a factor of a few greater than the measurement precision. This motivated our Bayesian approach to characterizing the amplitude of variations of the Laplace angle. Additionally, we performed tests of our algorithms using simulated planetary systems that confirm our algorithm accurately characterizes the behavior of the Laplace angle (Appendix A1). We conclude that formation theories for the GJ 876 system need to explain not only the resonant structure, but also the chaotic evolution of the Laplace angle and its sizable amplitude.

The near integer ratio in the planets’ orbital periods are not likely a result of happenstance. The probability of in situ formation yielding such a system is further reduced by the need to become trapped in a chaotic, but long-lived, multi-body resonance. Within the context of current planet formation models, the system most likely reached its current resonant configuration as the result of disk migration. Migration through a smooth gas disk would be expected to result in strong damping of eccentricities, driving the system to a state where the resonant angle librates regularly with small amplitude. Many of our simulations of a smooth migration with eccentricity damping lead to an amplitude of $\sim 1^\circ$, much smaller than we measure for the current system configuration.

While the observed large libration amplitude and chaotic evolution of resonant angles is contrary to the predictions of the simplest migration models (Batygin et al. 2013) recently proposed that that the observed libration of the resonant angles can be explained purely by a turbulent migration. We propose an alternative formation mechanism based on a phase of smooth disk migration which terminates abruptly (Appendix A). In our simplistic migration models, turning off the eccentricity damping impulsively caused the libration amplitude for the Laplace angle to rise from $\sim 1^\circ$ to $\sim$-tens of degrees. Such a scenario could arise naturally as a result of rapid dispersal of inner disk via photoevaporation.

Another potential possible formation scenario involves migration through a gas disk trapping the planets in resonance, followed by a phase of planet or planetesimal scattering. (Chatterjee & Ford 2014) showed that planetesimal scattering will naturally drive a planetary system initially in a 2:1 mean motion resonance farther apart, exciting eccentricities and perhaps even breaking the resonance. We encourage future studies to explore the predictions of three formation models for comparison to the GJ 876 system.

ACKNOWLEDGEMENTS

We thank Geoff Marcy and the entire of the California Planet Survey team for their long-term commitment to high-precision RVs for the GJ 876 system. P.R., acknowledges support from NSF grant AST-1126413 and the Center for Exoplanets and Habitable Worlds. M.J.P. gratefully acknowledges the NASA Origins of Solar Systems Program grant NNX13A124G. E.B.F. and J.T.W. acknowledge NASA Keck PI Data Awards, administered by the NASA Exoplanet Science Institute, including awards 2007B N095Nr, 2010A N147Hr, 2011A&b N141Hr, & 2012A N129Hr. This research was supported by NASA Origins of Solar Systems grant NNX09AB35G. The authors acknowledge the University of Florida High Performance Computing Center and the Pennsylvania State Research Computing and Advanced Cyberinfrastructure Group for providing computational resources and support that have contributed to the results reported within this paper. The Center for Exoplanets and Habitable Worlds is supported by the Pennsylvania State University, the Eberly College of Science, and the Pennsylvania Space Grant Consortium. We extend special thanks to those of Hawaiian ancestry on whose sacred mountain of Mauna Kea we are privileged to be guests. Without their generous hospitality, the Keck observations presented herein would not have been possible.

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APPENDIX A: FITTING SYNTHETIC SYSTEMS WITH KNOWN PROPERTIES

Batygin et al. (2015) provide an elegant explanation of how such a chaotically evolving Laplace angle could have formed, and show that it can provide limits on the system’s early formation: smooth migration can only form systems with relatively small libration amplitude, and regular non-chaotic evolution; stochastic migration is required to form chaotically evolving systems with large libration amplitudes.

At face value, our results (6) provide evidence for chaotic evolution of the Laplace argument in the GJ 876 system. Given the importance of this result, we performed additional tests to determine whether low-libration amplitude is likely to be erroneously classified chaotic orbital evolution. We simulated RV observations of a variety of non-chaotic coplanar systems and then applied our RUN DMC algorithm to verify that the recovered parameter estimates (in particular the libration amplitude of the Laplace angle) are consistent with their input values.

A1 Methodology: Creating Synthetic Planetary Systems and Datasets

Batygin (private communication) provided orbital elements for the results of one of their stochastic migration simulations. We integrated this system forward, confirming that the evolution of the Laplace resonance angle, $\phi_{\text{Laplace}}$, is indeed chaotic, and has a libration amplitude $\sim 80^\circ$. This synthetic system will be referred to as $S_{\text{Chaos,80}}$ henceforth (Figure A1 left).

To complement this, we then performed a number of smooth migration simulations in which the resultant simulations are regular and have low libration amplitudes. These migration simulations used the damped $a$ and $e$ method described in Lee & Peale (2002), which was implemented in MERCURY (Chambers 1999). We set up 3-planet systems so that each initial planetary period ratio was a little larger than 2:1 with their inner neighbor. Then, we applied the damped-migration model to the outer planet until it caught into a 2:1 resonance with the middle planet. We continued the forced, damped migration until this outer resonant pair caught into a 4:2:1 resonance with the innermost planet. Finally, we removed all forms of damping from the system and let them evolve for $\sim 10^5$ years, ensuring that they were in an undamped equilibrium state.

We performed a number of these simulations and selected a system from these with final (i.e. after turning off orbital damping) libration amplitude of $\sim 20^\circ$. Most simulations resulted in a Laplace argument with very small libration amplitude ($\sim 1^\circ$) during the damping phase and rose to several tens of degrees after the damping was removed. This particular system had a libration amplitude significantly smaller than the best-fit from 6, allowing us to test whether our fitting procedure artificially increases the libration amplitude. This synthetic system will be referred to as $S_{\text{Reg,20}}$ henceforth (Figure A2 left).

We generate an RV dataset for both $S_{\text{Chaos,80}}$ and $S_{\text{Reg,20}}$ using the same RV time series with their associated offsets and jitters described in 8.2 We include the innermost, non-resonant planet with the following orbital properties and coplanar with the migrated planets: $P_d = 1.937821$ days, $m_d = 2.21 \times 10^{-3} M_J$, $e_d = 0.072$, $\omega_d = -137.09^\circ$, and $M_d = 289.23^\circ$. For each synthetic measurement ($v_{\text{obs}}$), we compute the RV value at that time ($v_{\text{mod}}$), then add two noise terms: one drawn from a standard normal scaled by the measurement uncertainty $\sigma_{\text{obs}}$ and a similar term but scaled by the jitter value corresponding of that observation, i.e. $v_{\text{obs}} = v_{\text{mod}} + N(0,1) \times \sigma_{\text{obs}} + N(0,1) \times \sigma_{\text{jit}}$.

These datasets were then used as simulated input observations for RUN DMC, and a full differential evolution MCMC was performed on each synthetic data set (in the same manner as was performed on the real data, and described in 3.1 and 4). We performed three realizations of the RV time series for both $S_{\text{Chaos,80}}$ and $S_{\text{Reg,20}}$.

A2 Results for Synthetic Planetary Systems

In right panel of Figure A1 we show the $\phi_{\text{Laplace}}$ libration amplitude distribution for the three realizations of the RV time series based on $S_{\text{Chaos,80}}$. The chaotic nature of $S_{\text{Chaos,80}}$ is shown in Figure A1 left where the periodicity and peak-to-peak variation are not constant in time. There is a rough variation of $\sim 160^\circ$ corresponding to an amplitude of $\sim 80^\circ$. For each realization, we find libration amplitudes of $97 \pm 14^\circ$ (blue dash-dotted), $96 \pm 16^\circ$ (red dashed), and $91 \pm 17^\circ$ (green solid) degrees based on 1,000 solutions each. Only a few solutions from each of these realizations were unstable over the short integration baseline (1 kyr). These estimates are qualitatively consistent with the input amplitude.

In right panel of Figure A2 we show the $\phi_{\text{Laplace}}$ libration amplitude distribution for the three realizations of the RV time series based on $S_{\text{Chaos,80}}$. A significant fraction of our posterior sample for each realization was not dynamically stable. Specifically, only 548, 496, and 673 systems remained after the 1 kyr integration. We find that the RV analysis of the synthetic data overestimated the outer-most planet’s mass by $\sim 20\%$, which could be reason for such a large fraction of unstable systems. We find libration amplitudes of $25.6 \pm 4.7^\circ$ (blue dash-dotted), $22.9 \pm 5.8^\circ$ (red dashed), and $19.5 \pm 3.7^\circ$ (green solid) degrees based on the remaining short-term stable systems. Again, these values are qualitatively consistent with the input amplitude of $\sim 20^\circ$.

It is clear from these results that our RUN DMC algorithm does not significantly bias the recovered libration amplitudes for the 4:2:1 resonance of the outer three planets in the GJ 876 system. Thus, we believe that our best-fit libration amplitude for the real data (6) is accurate and the GJ 876 system is in a chaotically librating state, with a high-amplitude libration.

A3 Estimation of Lyapunov times for GJ 876 Orbital Solutions

Batygin et al. (2017) suggests that the GJ 876 system is chaotic, with a characteristic timescale (or Lyapunov time, defined below) for the chaos of roughly 14 years. This theoretical study ignored the innermost planet and treated the system as coplanar. An estimate of the Lyapunov time for the 4-planet, coplanar radial velocity orbital solution of
Here we study the nature of three sets of solutions: first, the 1,000 long-term stable, 3-d orbital models described in §5; 1,000 coplanar models described in §4; and 1,000 coplanar models based on the S\text{Reg}:20. We determine whether or not the orbits are chaotic by evolving simultaneously the standard gravitational equations of motion and the variational equations of motion, which yields an estimate of the Lyapunov time of a trajectory (e.g. Lichtenberg & Lieberman (1992)). The variational equations govern the behavior of small perturbations to an orbit and therefore can be used to study how perturbations evolve in time. For chaotic orbits, small perturbations of length $D$ grow exponentially as $D \sim e^{t/\tau}$ with a characteristic time $\tau$, which in the limit as $t \to \infty$ is defined as the (minimum) Lyapunov time. Our finite time integrations are used to estimate this Lyapunov time as $t_{\text{final}}/\log ([D(t_{\text{final}})])$, where $t_{\text{final}}$ is the total integration time, $D(t = 0) = 1$, and $D(t_{\text{final}})$ is the total length of the “perturbation” at the end of the integration. Note that $D$ in principle can become very large, but since the variational equations are linear in the components of $D$, the absolute length of $D$ need not be small for the variational equations to apply. If an orbit is regular, the reported Lyapunov time will be comparable to the integration time, though integrations cannot prove an orbit is regular. These integrations must therefore be carried out for long enough such that the chaotic and regular orbits have markedly different reported Lyapunov times.

We employed a Wisdom-Holman mapping in canonical...
astrocentric coordinates to integrate both the equations of motion and the variational equations (Wisdom & Holman 1991). A third-order symplectic corrector was implemented to improve the accuracy of these integrations (Wisdom et al. 1996; Chambers 1999; Wisdom 2006). We used a simple prescription for the effects of general relativity which leads to precession of the orbits with the correct timescale (Milani & Nobili 1983). As we will show, the Lyapunov times of the orbits were significantly shorter than the timescale of precession due to general relativity, and so this approximate version of general relativity is sufficient for a good estimate of the Lyapunov times for the orbits studied.

The Wisdom-Holman integrator can be used with a time step as small as a tenth or twentieth of the shortest orbital timescale in the system (Wisdom & Holman 1992; Rauch & Holman 1999). For GJ 876, this corresponds to the time needed to resolve the pericenter passage of the innermost planet. We estimate this using the orbital period of the innermost planet as if its semimajor axis was equal to the pericenter distance, $P_{\text{eff}} \approx P_{\text{orb}}(1 - e)^{3/2} = 1.6$ days, where $e \approx 0.1$ and $P_{\text{orb}} \approx 2$ days. We used a time step of either 0.14 or 0.014 days when integrating the set of 3-d solutions, and, as discussed below, these yield similar estimates of the Lyapunov times. For both coplanar set of solutions, we used a time step of 0.14 days. The maximum fractional energy error $\Delta E/E$ was $\sim 10^{-5}$ for the 3-d set of orbits with a time step of 0.14 days, $\sim 10^{-10}$ for the same set with a time step of 0.014 days, and $\sim 10^{-7}$ for the coplanar set of orbits. These integrations lasted $10^4$ years.

In Figure A3, we show the distribution of Lyapunov times for the 3-d set of solutions resulting from the integrations employing both timesteps, and the distribution of Lyapunov times for the coplanar set of solutions. These integrations all agree that the motion of these orbits is chaotic with a Lyapunov time of roughly 10 years, consistent with the analytic estimate of Batygin et al. (2015). The small peak at $10^3$ years in the distribution of Lyapunov times for the coplanar orbital solutions to the data corresponds to orbits which might be regular. However, the vast majority of coplanar orbits studied were chaotic. The close agreement between Lyapunov times estimated for the 3-d and coplanar sets is also consistent with the analysis of Batygin et al. (2015) and Martí et al. (2013) in that the chaotic motion is captured by a coplanar approximation of the true system.

During the integrations with a time step of 0.14 days, $\sim 10$ orbits in each set (3-d vs. coplanar) were flagged as unstable. With the smaller time step of 0.014 days, no orbit in the set of 3-d orbits was flagged as unstable. This suggests that the smaller time step might be necessary for studying the long-term stability of these orbits using a Wisdom-Holman integrator. However, since the two time steps agree on the distribution of Lyapunov times, we believe these results are robust. Lastly, we do not show the results of the coplanar set of solutions fit to synthetic data, since our integrations suggested that nearly all of these orbits where not only chaotic but also showed instability on short ($10^4$ year) timescales. We defer any further analysis of the stability of these synthetic solutions to future work.