Empirically Derived Dynamical Models of Complex Exoplanet Systems

Background and Motivation

Prior to 2009, most extrasolar planets were discovered by measuring the gravitationally induced wobble of their host stars (Figure 1, left). Planets orbiting a star induce stellar motion through conservation of momentum that can be detected by measuring the Doppler shift of spectral lines. Modern instruments (HARPS, Keck HIRES) have achieved high radial velocity (RV) precision (∼1m/s) for over a decade, allowing planet hunters to discover nearly Earth-mass bodies. In the ∼20 years of exoplanet observations, many multiple planet systems have exhibited noticeable gravitational interactions (e.g. resonant interactions), much stronger than the orbital dynamics of the planets in the Solar System. Interpreting such observations accurately requires a self-consistent n-body model and accurate characterization of the parameter uncertainties. Therefore, finding the statistically allowed range of physical parameters can be computationally difficult, especially for a high-dimensional model that is required for a multi-planet system.

Post 2009, the Kepler spacecraft has been dominating planet discoveries via the transit technique (i.e. an exoplanet is aligned such that it periodically passes in front of its host star and casts a shadow on the detector) with its photometric precision, high cadence, and high duty cycle. Not only has Kepler found multi-transiting systems, but also systems with at least 7 planets (KOI-351, Schmitt et al. submitted). In a multi-planet system, the mutual gravitational interactions can cause the times of transit to deviate from the perfectly periodic case, commonly referred to as "transit timing variations" (TTVs). In fact, near-resonant TTVs have been the most productive method both for confirming Kepler planet candidates and for measuring the masses of small planets (e.g. Ford et al. 2012; Wu & Lithwick 2012). However, analyzing TTVs often result in a very rough χ^2 surface that is difficult to navigate, often leading to multi-modal or degenerate solutions. The final chapter of my PhD dissertion will address this challenge.

Previous Research

My research projects up until now can be divided into two categories.

Developing efficient MCMC algorithms: For my master's project, we developed an adaptive Markov chain Monte Carlo (MCMC) algorithm that drastically improves upon the efficiency of parameter space exploration (Ford 2006). Our version implements a "differential evolution" aspect (DEMCMC), which is particularly valuable at sampling high-dimensional spaces where parameter correlations can hinder the model sampling efficiency (ter Braak 2006; Veras & Ford 2009). Using our local computer clusters, the UF High-Performance Computing Center (UF HPC) and the PSU Research Computing and Cyberinfrastructure Group (PSU RCC), our Radial velocity Using N-body Differential Evolution Markov Chain Monte Carlo (`RUN DMC`) algorithm has successfully modeled strongly interacting, multi-planet systems based on RV observations (Johnson et al. 2011, Tan et al. 2013, B. Nelson et al. 2014a, B. Nelson et al. submitted). **It is the first n-body MCMC code applied to exoplanet observations**. In conjunction with members of the UF Computer Science department, we also developed `Swarm-NG`, a library for integrating large ensembles of few-body systems in parallel on graphics processing units (Dindar et al. 2013). In the `Swarm-NG` framework, the runtime for `RUN DMC` is cut by 75-80%.

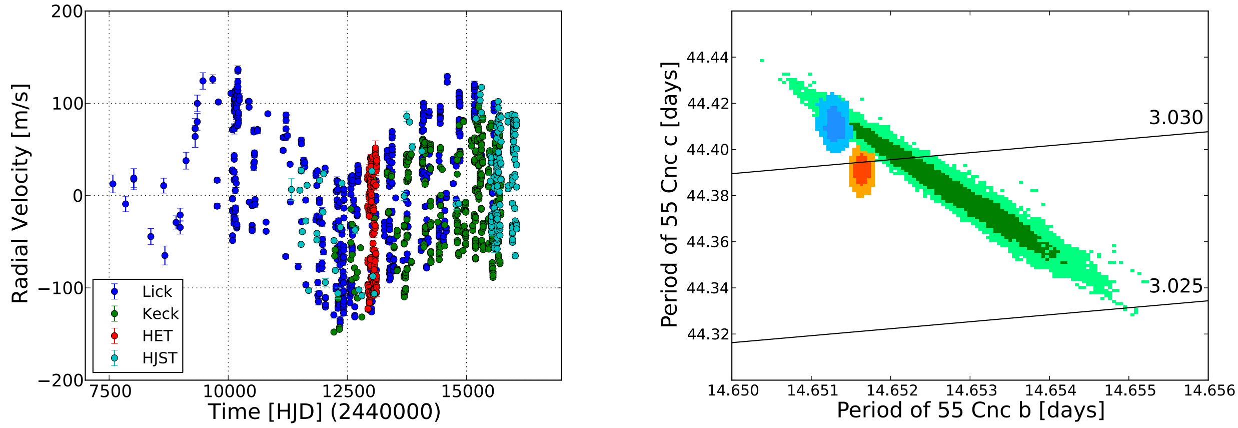

Figure 1: The importance of using an n-body model when analyzing the 55 Cancri RV data. **Left**: 1,418 RV observations of 55 Cancri spanning ∼23 years. **Right**: Constraints on the period ratio of planets "b" and "c". Lines of constant period ratio show how close these planets are to a mean-motion resonance. The contours represent 1-sigma (darker) and 2-sigma (lighter) credible intervals under the following assumptions. The orange and green contours are the result of fitting the RV time series with a Keplerian and n-body model respectively. The semi-major axes of "b" and "c" show significant variability, so we time average the orbital elements to get the blue contour. The difference amongst these distributions demonstrates why an n-body model is necessary to accurately characterize the orbital dynamics of 55 Cancri system.

Applications to Dynamically Complex Exoplanet Systems: After analyzing many 2-3 planet systems with relative ease, we pushed toward 4+ planet systems to test the robustness of `RUN DMC`. The higher dimensionality of these systems requires much more computational power and time, partially motivating the development of `Swarm-NG`. We selected 55 Cancri, an extremely diverse 5-planet system around a Solar-like star, as our test case for its long (∼23 year) observing baseline (Figure 1, left) and the recent detection of a transiting super-Earth size planet (Winn et al. 2011). Nearly every study until this point estimated the orbital parameters based on a Keplerian (i.e. no planet-planet interactions) model due to limitations in computational power. However, despite ∼40 model parameters and over 10^7 model evalulations, `RUN DMC` **found the first fully self-consistent and long-term stable model for the 55 Cancri system**. In particular, two of the planets orbit near a 3:1 mean-motion resonance, creating measurable dynamical effects on the observing timescale (Figure 1, right). An accurate estimation of the model parameters are crucial for studies of internal structure, atmospheric composition (Ehrenreich et al. 2013; Madhusudhan et al. 2012), orbital evolution, and long-term stability (Kaib et al. 2011; B. Nelson et al., submitted). This can also shift around the stable zones where undetected planets could potentially reside and thus motivate future observations.

`RUN DMC` was also able to better infer the properties of planet "e", the only known transiting Super-Earth around a naked-eye star. We found "e" cannot be highly misaligned with the orbital plane of the outer-four planets on a 10^5 year timescale, but there did oddly exist some nearly stable retrograde solutions. These stable solutions for "e" also show very low TTV amplitudes (~2s). Knowing its orbit is regular is important for scheduling future space-based transit observations. Our mass estimate (7.99 ± 0.25) improve upon previous results [8.63 ± 0.35 (Winn et al. 2011), 8.37 ± 0.38 (Endl et al. 2012)]. This result pushes the planet's inferred bulk composition away from magnesium silicates and more toward the silicate carbides and carbon planets (Madhusudhan et al. 2012). This lower mass also makes the existence of a large envelope (>10% by mass) of supercritical water less likely (Madhusudhan, private communication).

One limitation with the RV method is obtaining the physical masses of planets orbiting a star. An observer on the ground measures the line-of-sight Doppler motion of the star, making it difficult to determine how a planetary system is aligned relative to the plane of the sky. Complimentary observing methods such as astrometry or photometric transit detection can help break this mass-inclination degeneracy. This is also possible for systems with particularly strong planet-planet interactions that need to be described with an n-body model. For these systems, the real masses of the planets and the inclination can be inferred from the RVs alone. This has been done for a couple systems: HD 82943 (Tan et al. 2013) and GJ 876, an M dwarf that harbors a set of planets that orbit near a period ratio chain of 1:2:4 (Rivera et al. 2010). For historical and computational reasons, studies with the RVs (excluding astrometry) usually assumed the planetary orbits to be coplanar (Rivera et al. 2005; Correia et al. 2010). With `RUN DMC`, **we are able to constrain the mutual inclinations of each planet pair and therefore obtain the first empirically derived 3-dimensional dynamical model for GJ 876 planets using only the RV data** (Figure 2). We are currently using a subsample of these models to obtain stability-constrained inclinations using the `Mercury` mixed-variable symplectic integrator (Chambers 1999).

Research Plan

For my dissertation, I want to investigate the orbital architectures of ~~these~~ strongly interacting multi-planet systems and ultimately reveal the statistical properties of this exotic planetary population. This is being carried out in two phases.

Phase 1: I will develop a sister algorithm to `RUN DMC` ("We Use Transit times And Newtonian Gravity" or `WUTANG`) that works with TTVs. Paired with `RUN DMC`, we will provide the most precise, physically realistic estimates of exoplanet orbits and masses. There are studies that utilize DEMCMC to model photometric transits, in particular Eastman et al. 2012 (`EXOFAST`), Carter et al. 2012, and Welsh et al. 2012. However, the prior probability distribution for orbital eccentricity needed to be tuned on a case-by-case basis in order to get a reasonable answer in a timely manner (Carter, private communication). Furthermore, the `EXOFAST` study performed a thorough analysis on the pros and cons of using different eccentricity priors, but the algorithm assumes a Keplerian model. `WUTANG` is built on the DEMCMC template and we will implement more efficient search methods such as parallel tempering and Hamiltonian MCMC. By incorporating the `Swarm-NG` framework, we can obtain accurate results more quickly, allowing us to gain a better intuition for the results and implications.

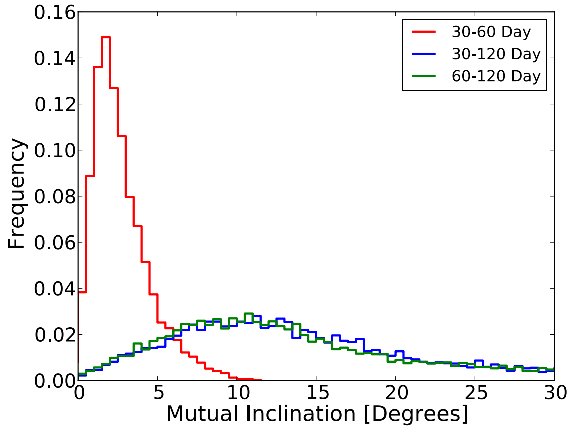

Figure 2: The mutual inclination distributions of planet pairs in the GJ 876 system based only on RV observations. Previous investigations of this system assumed all mutual inclinations were 0 (i.e. a 2-dimensional coplanar case), so our 3-dimensional model adds a new aspect to the formation of this unique system. We are currently performing a long-term (10^8 year) stability analysis on a subset of these models to filter out unstable solutions and better constrain the mutual inclinations.

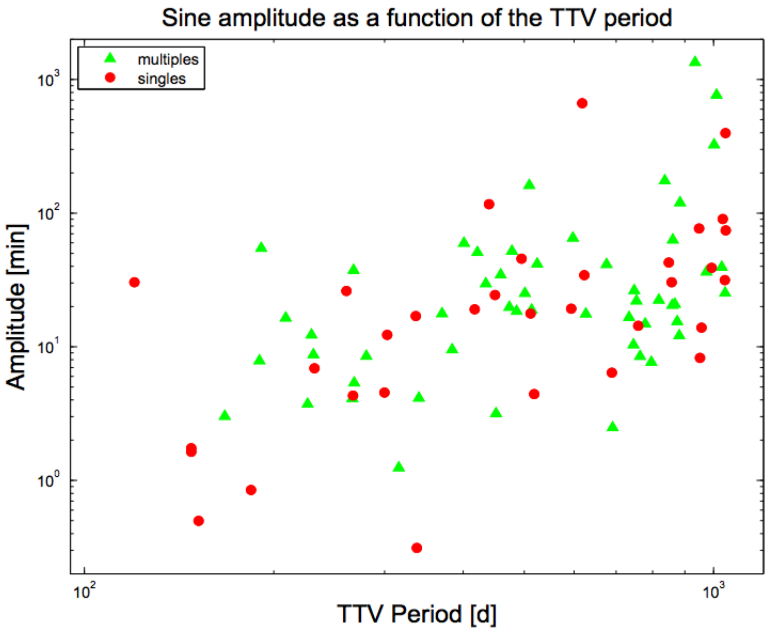

Figure 3: Properties of the known Kepler candidates with detectable TTVs (Mazeh et al. 2013). The horizontal and vertical axes show the period and amplitude of the TTV modulation respectively. Red points represent systems with one known transiting planet, and the green triangles are systems with multiple transiting planets. Applying `WUTANG` and subsequent dynamical simulations to this sample, we plan to better resolve the planet masses and orbital architectures of these systems.

Phase 2: I will apply `WUTANG` to the population of exoplanet systems with the strongest dynamical interactions. Kepler results (Fabrycky et al. 2012) show planet pairs tend to favor nearly resonant orbital periods but very few are technically found in a resonance, and we have 143 known systems with significant TTVs (Mazeh et al. 2013). As a graduate student working with a member of the Kepler Science Team/TTV Working Group, we have the experience and expertise necessary to work with these data. For multitransiting systems with TTVs, the easiest parameters to estimate are the planet-planet mass ratio, the planet-star mass ratio, and orbital period ratios (**reference**). For **XX** bright stars whose masses can be spectroscopically constrained, we can infer physical planetary masses. In the case of single transiting planets with TTVs, the period of the TTV tells us about the proximity to a mean-motion resonance with an unseen companion, though the integer ratio is unknown. However in aggregate, we are still able to investigate the fundamental correlations amongst these variables and infer properties of this exoplanet population in a hierarchical model.

I plan develop a hierarchical Bayesian model to uncover the physical properties of this resonant planet population. Lately, a significant effort has been going into developing such models to infer aspects of the exoplanet population (e.g. composition, Wolfgang & Lopez, in prep.; mass vs. density relation, Rogers et al., in prep.; host star properties vs. system dynamical complexity, Shabram et al. in prep.). Typical methods assume some parametric form (e.g. Gaussian) for the 1-sigma uncertainties of model parameters. With `WUTANG` generating posterior samples for a particular system, we will understand the underlying covariance structure amongst model parameters as well as the real functional form of the distribution. We can further constrain the orbital architecture through the assumption of long-term orbital stability and performing n-body simulations using `Mercury`. By compiling these posterior samples for many systems, we can accurately assess the intrinsic distribution of resonant systems in a hierarchical model, addressing larger questions of planet formation. For example, we would be able to answer if the distance from exact resonance varies as a function of the planet masses, eccentricities, etc. and if nature prefers a particular formation scenario (e.g. gentle planet-disk migration vs. violent planet-planet scattering).

Aside from my proposed projects, **our estimates of these planets' physical and orbital properties inferred with `RUN DMC` and `WUTANG` will benefit the science goals of the exoplanet community as a whole**. By analyzing RV and transit/Kepler data in a self-consistent n-body model, we can now accurately estimate key physical quantities that are fundamental in answering interesting science questions. The planetary mass and radius are necessary for refining the planet mass-radius relationship of small planets (Weiss et al. 2013) and differentiating between bulk composition models, e.g. water-world vs. Earth-like (Winn et al. 2011, Madhusudhan et al. 2012). Orbital period and eccentricity are important parameters for modeling star-planet interactions, e.g. tides/tidal evolution (Jackson et al. 2009; Heller et al. 2011); atmospheric dynamics, e.g. heat redistribution from the day-to-night side (Cowan & Agol 2011); and long-term orbital stability. The "typical" planetary system out there looks very different than our own (Swift et al. 2013; Chiang & Laughlin, 2013), so understanding the variety of planetary systems in the Galactic neighborhood allows us to figure out how the Solar System fits in a cosmic context.

We are publicly releasing all of our empirically derived models for community use and are encouraging other research groups to do the same. Our generalized MCMC algorithms will continue to exploit all available data in a self-consistent dynamical model (e.g. Johnson et al. 2011, Tan et al. 2013).

Relevance to NASA's Science Mission Directorate

The outlined research above directly addresses one of the broad scientific questions in the 2010 Science Plan of NASA's SMD for Astrophysics: "What are the characteristics of planetary systems orbiting other stars and do they harbor life?"

needs work

Not only will we provide detailed models of individual systems but accumulate a statistical sample that will aid in answering these big questions. The NASA Earth and Space Science Fellowship would be very valuable for the last year of my graduate studies. It would allow me to pursue my outline research goals, and with the UF HPC and PSU RCC, we have the necessary resources to carry out the required calculations.

References

Carter, J. A. et al. 2012. Science, 337, 556
Chambers, J. E. 1999. MNRAS, 304, 793
Chiang, E. & Laughlin, G. 2013. MNRAS, 431, 3444
Correia, A. C. M. et al. 2010. A&A, 511, A21
Cowan, N. B. & Agol, E. 2011. ApJ, 729, 54
Dindar, S. et al. 2013. New Astronomy, 23, 6
Eastman, J. et al. 2012. PASP, 125, 83
Ehrenreich, D. et al. 2012. A&A, 547, A18
Endl, M. et al. 2012. ApJ, 759, 19
Fabrycky, D. C. et al. 2012. arXiv:1202.6328
Ford, E. B. 2006. ApJ, 642, 505
Ford, E. B. et al. 2012. ApJ, 750, 113
Heller, R. et al. 2011. A&A, 528, 27
Jackson, B. et al. 2008. ApJ, 678, 1396
Johnson, J. A. et al. 2011. ApJ, 141, L16
Kaib, N. A. et al. 2011. ApJL, 742, L24
Madhusudhan, N. et al. 2012. ApJL, 759, L40
Mazeh, T. et al. 2013. ApJS, 208, 16
Nelson et al. 2014a. ApJS, 210, 11
Nelson et al. 2014b, submitted
Rivera, E. J. et al. 2005. ApJ, 634, 625
Rivera, E. J. et al. 2010. ApJ, 719, 890
Schmitt, J. R. et al. 2013. arXiv:1310.5912
Swift, J. J. et al. 2013. ApJ, 764, 105
Tan, X. et al. 2013. ApJ, 777, 101
ter Braak, C. 2006. Stat. Comput., 16, 239
Veras, D. & Ford, E. B. 2009. ApJL, 690, L1
Weiss, L. M. et al. 2013. ApJ, 768, 14
Welsh, W. F. et al. 2012. Nature, 481, 475
Winn, J. N. et al. 2011. ApJ, 737, L18
Wu, Y. & Lithwick, Y. 2012. ApJ, 772, 74