The Orbits of Long Period Exoplanets

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Introduction: The field of exoplanetary astronomy has experienced significant growth since the announcement of the first confirmed planet orbiting a star beyond our own in the mid 1990's. To date, there are thousands of confirmed extra-solar planets (Bowler, 2016). The majority of known planets have been detected because of the influence they have on their host star- by inducing wobbles in the star's velocity or by periodically eclipsing the star - rather than by direct observation (e.g., Wright, 2017, Winn & Fabrycky, 2015). Obtaining images of planets is difficult, due to their relative faintness and proximity to the overpowering luminosity of the host star (Kraus, 2016).

However, technological advancements have begun to reveal a small number of planet companions that can be directly imaged (e.g., Chauvin, et. al. 2004). The direct imaging method is most sensitive to very large mass planets far from their host stars. Directly imaged planets can be several tens of Jupiter masses, and can orbit hundreds and even thousands of times further away than Earth is from the Sun (Bowler, 2016). These wide orbit exoplanets challenge proposed formation mechanisms (Bryan et. al 2016). Existing planet formation models are unable to form large planets at 100's of AU, where building up of such large mass required tens of billions of years, much longer than the ages of the host stellar systems. However, they are also unlikely to be the lowest-mass binary star companions, because binary formation occurs so early that the companion would accumulate enough mass to become a star itself. Therefore, comprehensive study of the characteristics of these objects is essential for understanding what they can tell us about planetary system formation (Kraus, 2016).

Dr. Adam Kraus and colleagues at the University of Texas and beyond have collected images of several of these wide exoplanet systems going back as far as a decade. These images were made using adaptive optics (which corrects atmospheric distortion of images) and the NIRC2 infrared camera at Keck Observatory on Mauna Kea in Hawai'i. Since January 2017, my research project has been to very precisely measure the position of both star and planetary companion in each image across years of observations, in order to measure the orbit of the companion. A highly-elongated orbit would indicate the planet may have formed very close in to the star (consistent with planetary system formation models) and was ejected out to wide orbit by another close-in planet. A more circular orbit would favor formation in its current place. Determining what orbits are allowed by observation is essential for testing possible formation mechanisms.

Methodology: The first phase of my project was to measure star and companion locations in each image as precisely as possible – a technique known as astrometry. I am currently studying one wide exoplanet system, GSC 6214-210 (Ireland et. al. 2011). My data consists of multiple infrared images of host star and companion from NIRC2, spanning about ten years of observations. For each image, I measure the relative position of the planet from the star, and so measure how it has moved over the course of the observation time period.

To do this, I built a custom Markov Chain Monte Carlo (MCMC) algorithm, which is a method for statistically fitting models to data. My algorithm works by making a model of the data, and fitting the model to observation as robustly as possible. It begins with an initial guess for the model parameters - positions, brightness, shape, and orientations - computes the goodness of fit, then systematically modifies each parameter (with new values drawn from probability distributions), computes if the new value is a better fit than previous, and decides if it should adopt the new parameter. In this way, it systematically "walks" around the parameter space until the range of statistically allowed parameters has been thoroughly explored. Once the positions in pixel space are determined, the algorithm calculates the companion's relative position, correcting for various systematic distortions. Using the measured position in each image over several observation epochs, I determine the object's motion in the plane of the sky over time. The MCMC method is advantageous over other more common astrometric methods because it delivers a distribution of values for each parameter, allowing a robust method of determining uncertainty in position measurement in each individual image, which gives a more correct determination of uncertainty in the orbital measurements. Combined with the robust systematic corrections, my algorithm achieves a level of precision not commonly found in ground-based astrometry.

Figure 1 shows an infrared image of the star GSC6214-210 and its companion, and the relative direction of motion I have measured for the companion over the course of 9 years of observation. Figure 2 shows a plot of the same companion's position angle (relative to north) and separation (relative to the star) over the observation period.

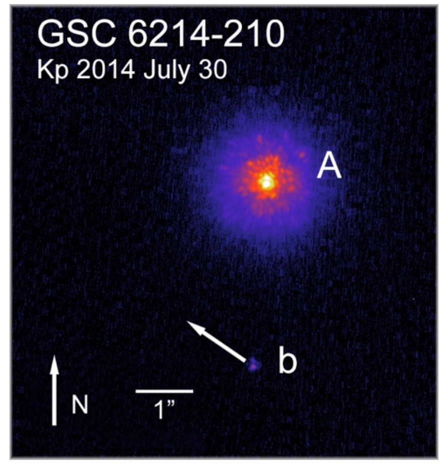

Figure 1: NIRC2 image of GSC6214-210 (“A”) and companion (“b”, seen directly to the south). The arrow indicates the direction of motion in the plane of the sky as measured by my research.

The second phase of my project is to use these precise position measurements to determine what orbital shapes are consistent with the data. Because these objects are very far from their star, they move very slowly, and even a decade worth of images will only have recorded a tiny fraction of their orbit. Therefore, to fit orbits to these observations, I built my own custom implementation of a method recently developed by Blunt et. al. (2017) called Orbits For The Impatient (OFTI). OFTI is specifically designed for objects with only a small fraction of their orbit known. Rather than MCMC, OFTI is a rejection sampling algorithm with several features designed to speed up calculation. While the methodology was recently published, OFTI code is not publically available. Therefore, I built my own implementation which reproduces the OFTI methodology, with further improvements for speed and use of more realistic priors, and is able to reproduce results for the systems she analyzed in her recently published journal article.

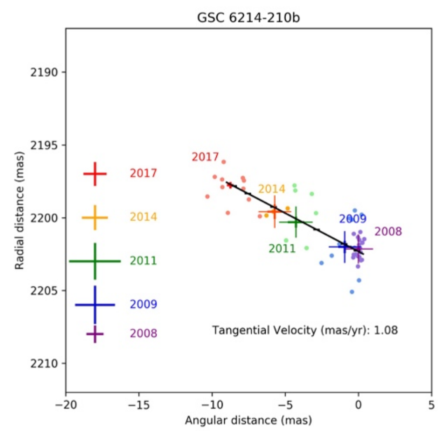

Figure 2: Relative position angle and separation for GSC6214-210b over time. The circles represent individual image measurements, and the error bars indicate the average position for each observation epoch. The error bars to the left indicate the median error on the individual image measurements.

Results and future work: As of this writing, both the position measurement and orbit fitting algorithms are complete and are being applied to the systems named above. I am working on analyzing and further improving the astrometric measurements by accounting for atmospheric refraction and other systematic errors. When that is complete for all systems, I will run OFTI to sample the allowed orbital parameters for all relevant systems.

Figure 3 shows a preliminary OFTI result for GSC6214-210b. This plot shows 100 accepted orbits for the companion around the host star. I will generate a similar plot, as well as a statistically robust presentation of accepted orbital parameters, for each system under study, which will be written up in an article and submitted for publication in 2018.

These preliminary results suggest interesting conclusions. The accepted orbits are not elongated enough for the planet to have formed close in to the star and flung out to its present location by interactions with another planet. In fact, orbits of eccentricity required for dynamical scattering are strictly not allowed by my analysis. The planet therefore more likely formed in situ at a wide orbit, where traditional models of planet formation say there is not enough mass or time to form such large objects.

Additionally, combining my results with light curves from the host star allows an analysis of the spin of the star to the allowed orbit of the companion. Misalignment of spin and companion orbit implies formation through turbulent fragmentation, while formation in situ would exhibit spin-orbit alignment. My orbit analysis could allow for a statement about the spin-orbit alignment of the system. These results represent only one wide exoplanet system. A robust study of a wide selection of these systems is essential for understanding how this class of objects fits the planet formation picture. I have similar data for several more systems, for which this process can be repeated. Further funding of this project will provide the exoplanet community with more evidence for discussion on this important question.

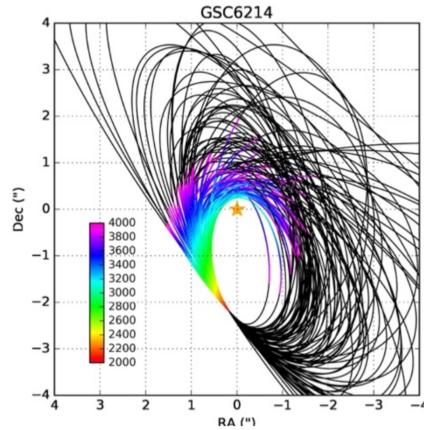

Figure 3: 100 accepted orbits for GSC6214. Colors represent time since the year 2000, and give an indication of the speed of the object.

My contribution and what I learned: My project was completed entirely by me under the guidance of Dr. Adam Kraus. I developed all the tools myself using very little pre-made code. I learned fundamental theories underlying MCMC and rejection sampling, and how to code them into a functional and statistically robust tool. Dr. Kraus pushed me to develop these tools myself, rather than use publically available ones, so that I could gain the "under-the-hood" knowledge of how MCMC and rejection sampling work and develop my programing skills. In addition to coding, I undertook a significant amount of time to learn the mechanics of Keplerian orbits; processing, manipulating, and measuring telescope images; the many influences on astrometric measurements and how to correct for them; and more. I traveled to Keck Observatory with Dr. Kraus this summer to collect observations of my systems for the 2017 epoch.

I am coming to the field of astronomy later in life. After obtaining a degree in chemistry from Purdue University in 2003, I enjoyed a successful career as an officer in the US Navy, followed by 6 years as a middle school science teacher. With this experience behind me, I have a better understanding of who I am and what I want from my second-time undergraduate experience, and from my future career. I chose to return to school for astronomy because it has been my hobby my entire life. Introducing young students to science and space reignited my interest and showed me that doing science was where I really needed to be. Conducting research at the University of Texas, along with classes, confirmed that this is the only career I wish to pursue. I feel I am doing what I was made to do. It has been very challenging, but because of this project's experience, I know that exoplanet research is the right field for me, and the only thing I want to be doing from here on out. Being an older student does come with some challenges, many of them financial. The support of a Goldwater award will enable me to continue to excel in my studies and research at UT, and to pursue competitive opportunities in graduate school and beyond.

References:

Blunt, S., et.al. 2017, AJ, 153, 229; Bowler, B. 2016, PASP, 128, 102001; Bryan, M., et. al. 2016, ApJ, 827, 100; Chauvin, G. et. al. 2004, A&A, 425, L29; Kraus, A. 2016, The Star Formation Newsletter, 280; Ireland et.al. 2011, ApJ, 726, 113; Winn & Fabrycky, 2015, ARA&A, 53, 409; Wright, J. 2017, arXiv, 1707.07983