Studying Planetary System Architecture using Radial Velocity Methods

I propose to study planetary system structures around low-mass stars by conducting radial velocity (RV) observations of known single-planet transiting systems observed by *Kepler/K2* and the Transiting Exoplanet Survey Satellite (TESS). RVs and spectroscopy will be completed with MAROON-X[1], an instrument with which I will have **guaranteed clear-sky observing time** as a student at the University of Chicago. I will address if there is a separate population of single planet low-mass stellar systems or if they have an inclined inner-most planet. **This study will result in the publication of compelling individual systems as they are identified and a full statistical analysis once the full sample has been obtained.**

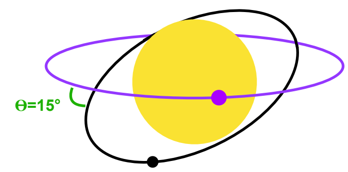

Figure 1: The inner-most planet (black) lies 15° off the plane of the system and does not transit, while an outer planet (purple) does.

<u>Background & Research Proposal</u>: Planet formation models predict planetary systems form in the same orbital plane. However, there are several systems[2] that suggest the inner-most planet may be inclined by a significant degree. Heavily inclined planets would go undetected during exoplanet transit surveys (observing stellar flux over time), Figure 1. The analysis of *Kepler/K2* transiting exoplanet system yield an overabundance of single transiting planets, Figure 2.[3] It is possible the single transits detected are the inner-most inclined planet and the remaining planets have a different orientation.

The overabundance of single transiting planets is most notable around low-mass M-dwarf stars (70% of the Milky Way population). M-dwarfs are smaller and cooler than the Sun (< 0.7 M_{Sun}, T_{eff}< 4000K). With nearly 300 current planet detections from NASA's *Kepler/K2* missions, it is estimated each M-dwarf hosts at least 2 small planets (< 4 R_{Earth}); TESS is predicted to find 500 additional planets orbiting M-dwarfs.[4] **By studying planets around M dwarfs, I will be studying the dominant environment of planet formation in our galaxy.**

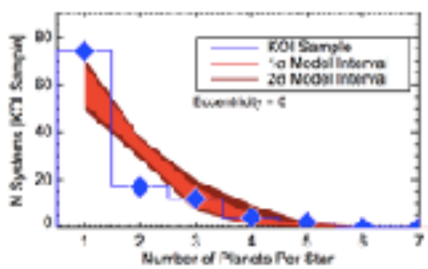

Figure 2: Comparison of the Kepler multi-planet yield (blue) to the best-fit models (red). Models under-predict the number of singly transiting systems and over-predict the number of multiple transiting systems.

Follow-up RV measurements of planetary systems will allow us to identify planets that do not transit. I will be searching for non-transiting companions to known transiting planets to understand the population of planetary systems with mutual inclinations. By conducting a large RV survey of transiting planets with the MAROON-X spectrograph, under construction at the University of Chicago and to be commissioned on the Gemini North observatory in early 2019, I will answer the following questions: **Do low-mass stars have**

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[1] Seifahrt, A., Bean, J. L., Stürmer, J., et al. 2016 "Development and construction of MAROON-X," in [Ground-based and Airborne Instrumentation for Astronomy VI], Proc. SPIE 9908, 990845
[2] Montet, B. T., Morton, T. D., Foreman-Mackey, D., et al. 2015, ApJ, 809, 25; Rodriguez, J. E., Becker, J. C., Eastman, J. D., et al. 2018, ArXiv e-prints, arXiv:1806.08368
[3] Ballard S. and Johnson J. A. 2016 ApJ 816 66
[4] Barclay, T., Pepper, J., & Quintana, E. V. 2018, ArXiv e-prints,arXiv:1804.05050

significantly inclined inner-most planets? If so, what physical mechanisms are responsible for causing the inclination shift? If not, why do these systems only host one planet?

I will compile an initial catalog of M-dwarf systems from the Exoplanet Archive and the TESS Input Catalog prior to data release. Once data are available, I will run the TESS data through my developed software, ELLIE, to search for planet candidates. I will vet candidates, prioritizing stars in my catalog, and determine RV follow-up feasibility based on predicted planet radius and levels of stellar activity identified in the light curve. This process will be repeated until July, 2020, when the entire sky observable by MAROON-X has been observed by TESS.

I am choosing MAROON-X to conduct this study because it is optimized for the red optical (peak emission of low-mass stars) and obtains spectra of the stars. By obtaining spectra of stars, I will be able to calculate accurate stellar parameters, following methods developed during my internship at NASA Goddard Space Flight Center. Additionally, MAROON-X has a predicted precision of <1 m/s, allowing for potential detections down to 1 M_{Earth}. By pursuing my PhD at the University of Chicago with the MAROON-X instrument science team, I am guaranteed to obtain data, regardless of bad scheduled nights. **I propose to conduct 5 full nights of observing per semester for 3 years, for a total of 240 observing hours.**

I will obtain mass and density measurements of transit detected planets in addition to identifying new planets. Measuring both parameters will prove essential when choosing planets for atmospheric characterization with the James Webb Space Telescope, currently set to launch in 2021. Obtaining both a radius (via the transit) and mass (via RV) measurements will help us better understand the compositions of relatively nearby planets, improving our understanding of planet formation around the most common stars in the Milky Way.

Intellectual Merit & Broader Impacts: My years of previous research experience, including publishing papers and giving talks, have prepared me well for the challenges which lie ahead. **I have the necessary knowledge of Python and other tools necessary to complete the project proposed here.** I have experience efficiently and accurately analyzing large data sets[5] and observations[6], and vetting planet candidates.[7] I am ready to undertake the project presented here.

My current outreach experiences have prepared me for future plans to speak about my research at local K-12 schools. I plan on working with local teachers to **improve STEM education and educator development at the elementary/middle school level** by creating educational in-class astronomy activities as well as create a website that follows my work that teachers will be able to use in the classroom. Interactive tools will include how to create light curves and how the presence of different objects will change a light curve. I will attend the National Science Teachers Association national conference to give a demonstration on how to use my website. I also plan on taking advantage of events hosted in Chicago. Such events include Astronomy on Tap: Chicago, which brings the universe into a local Chicago pub, and Soapbox Science, which promotes women in STEM by placing them on a box in highly populated areas in downtown Chicago to talk about their work.

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[5] Feinstein, A. D., Montet, B. T., et al (in prep)
[6] Feinstein, A. D., Schlieder, J. E., Livingston, J. H., et al, 2018, AJ (submitted)
[7] Liang, Y., Crossfield, I. J. M., Schlieder, J. E., et al, 2018, ApJ 156 22; Crossfield, I. J. M., Guerrero, N., David, T., et al, 2018, ArXiv e-prints, arXiv:1806.03127