Discovering Exoplanets Transiting Bright and Unusual Stars with K2

PhD Thesis Proposal, Department of Astronomy, Harvard University

Andrew Vanderburg

Advised by David Latham

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After four years of surveying one field of view, the Kepler space telescope suffered a mechanical failure which ended its original planet-hunting mission, but has enabled a new mission (called K2) where Kepler surveys different fields across the sky. The K2 mission will survey 15 to 20 times more sky than the original Kepler mission, and in this wider field of view will be able to detect more planets orbiting rare objects. For my research exam, I developed a method to analyze K2 data that removes strong systematics from the light curves and enables planet detection. In my thesis, I propose to do the science enabled by my research exam work. I have already taken the work I completed for my research exam, upgraded and improved the method, and developed an automatic pipeline to search for transiting planets. I have searched K2 light curves for planets, produced a catalog of candidates, identified interesting planet candidates, and organized follow-up observations to confirm the discoveries. I propose to continue improving my software pipeline to detect even more planets, and produce a new catalog, and I propose to measure the mass of at least one of the resulting discoveries with the HARPS-N spectrograph. The resulting catalog will be a resource for astronomers studying these planets, and the investigations on interesting single objects will help us understand topics ranging from planet composition to the evolution of planetary systems.

Introduction: The Kepler space telescope is a 1 meter telescope in an Earth-trailing orbit, designed for high precision photometry of about 100,000 stars across a 10x10 degree field of view. The Kepler mission's goal was the discovery of transiting exoplanets in a deep survey to learn about the population of small planets around other stars. Kepler has discovered thousands of planets, which taught astronomers most of what we know about the inner parts of extra-solar systems, but most of the planets discovered by Kepler orbit faint stars due to its deep and narrow survey design. This made it only feasible to perform the most interesting follow-up observations (like mass measurements of small rocky planets) on the brightest planet host stars in the original Kepler field of view.

When the second of four reaction wheels (small gyroscope-like devices used to point the spacecraft) failed in 2013, Kepler was unable to precisely point itself at its original target field. However, clever engineering made it possible to balance the spacecraft against solar radiation pressure to keep the spacecraft pointed precisely for about 80 days at a time. Kepler is therefore now surveying many new target fields across the ecliptic plane in its new K2 mission.

K2 provides many of the same benefits of Kepler, but extends them to many different fields. K2 will observe 15-20 times the solid angle as in the original Kepler mission, meaning that it will find many bright stars with planets amenable to detailed characterization. K2 will also survey rarer types of stars (for example, bright white dwarfs and stars in well-characterized open clusters) and search for planets around these objects as well.

K2 can help answer questions about the composition of exoplanets. Mass measurements of planets discovered by the Kepler mission have revealed a population of gaseous sub-neptune sized planets larger than 1.6 Earth radii, and a population of dense, rocky planets with compositions similar to planets in the solar system with radii smaller than 1.6 Earth radii. Open questions include: What is/is there a dividing line between rocky planets and planets with a thick gaseous envelope? K2 will discover many new planets orbiting stars bright enough to make follow-up mass measurements feasible.

K2 will also help answer questions about the evolution of planetary systems. K2 will survey many nearby and bright open clusters, which provide a unique opportunity to learn about the age of exoplanets. Do the radii and masses of planets show evidence for age dependence? Is the occurrence rate of planets different in young open clusters than old open clusters? K2 will also survey many white dwarfs. Searching for planets transiting white dwarfs can address the question of how planetary systems age and evolve. Can planets be perturbed into close orbits after the host star evolved off the main sequence?

Previous work:

As of April 2016, I have published four papers as first author relating to this project. The first of these was the basis of my research exam, and I plan to incorporate the other three into my thesis. A fifth paper is being prepared for submission.

1. *A Technique for Extracting Highly Precise Photometry for the Two Wheeled Kepler Mission*. In this paper, I analyzed K2 data taken during a 9 day engineering test, the first such data to be publicly available. I quickly noticed that unlike the pristine photometric data from the original Kepler mission, K2 data were dominated by systematics. These systematics were of high enough amplitude to make it very difficult to detect small transiting exoplanets. In the paper, I showed that the systematics present are caused by the telescopes's reduced pointing precision — in particular, the systematics were strongly dependent on where the telescope was pointing at any given time. I then developed a technique to disentangle light curves from the pointing related systematics, and applied the technique to the whole dataset. Finally, I showed that after removal of the systematics, K2 data were of a quality similar to that of the original Kepler mission for a stars of a wide range of brightnesses, and that it would be possible to detect small planets at high significance. This paper was the basis for my research exam.

2. *Characterizing K2 Planet Discoveries: A Super-Earth Transiting the Bright K-Dwarf HIP 116454:* This paper presented the discovery of the first planet discovered by K2. I found this planet in the 9 days of engineering data described in paper #1. The planet only transited once during the 9 days of data, so we did not know the period. We were able to measure the planet's spectroscopic orbit with HARPS-N. We performed an analysis of the star and planetary system and showed that K2 can find planets, including super-Earths amenable to radial velocity (and atmospheric) follow-up observations.

3. *A Disintegrating Minor Planet Transiting a White Dwarf*: This paper presented the discovery of the first planet-like object transiting a white dwarf. White dwarfs often have heavy elements present in their atmospheres, even though these elements should settle rapidly to the stellar cores because of the star's extreme gravity. These polluted white dwarfs also often come with dusty debris disks. The accepted interpretation of this was that the disks and elements came from the remnants of tidally disrupted planets. When K2 data showed evidence for a white dwarf with a transit signal, we initiated follow-up observations, and eventually saw evidence that the transit was caused by a dust tail coming from a small rocky body. The white dwarf in question (WD 1145+017) has a heavy element polluted atmosphere and a debris disk. This discovery is strong corroborating evidence that the heavy element pollution on white dwarfs comes from disrupted planets.

4. *Planetary Candidates from the First Year of the K2 Mission*: This paper presents a list of planet candidates detected by my pipeline in the first year of data from K2. We searched about 60,000 stars using an automated transit detection pipeline, vetted the results, compiled a list of candidates, estimated stellar parameters, and conducted initial reconnaissance spectroscopy for many of the brighter candidate host stars. We detected 234 planet candidates around stars typically brighter than Kepler host stars, as might be expected for a wide survey like K2.

5. *Five Planets Transiting a Ninth Magnitude Star*: This paper (in prep) presents the discovery of a 5 planet system transiting a particularly bright star. This system is the second brightest multi-transiting planet system known. Follow-up radial velocity observations could measure the masses of two small planets in a new radius/stellar irradiation regime, and a gas-giant outer planet in the system could be well suited for atmospheric characterization and measurement of the planetary oblateness. The outer planet is the best known long-period gas giant planet for transit spectroscopy.

Proposal summary: The future work in my thesis will consist of publishing two "low risk" papers, with the possibility of writing more "high risk" papers should opportunities present themselves. I make this distinction because the K2 data I work with is fully public, and for any given paper, there is a distinct possibility of another group publishing a similar paper first. I define "low risk" papers to be those which either involve a significant amount of proprietary supporting data, or papers will have significant value to the scientific community even if another group is able to publish a similar paper first. The two "low risk" papers I plan to write are an update to my first year planet candidate catalog and a paper using proprietary data collected with HARPS-N to measure the mass of a small exoplanet. I define "high risk" papers to be those concerning investigations of single objects, which other groups are likely to pursue as well. Two examples of these papers among those I have published are the discovery papers for the objects transiting HIP 116454 and WD 1145+017. While I was able to publish first in these two instances, there have been other instances where I was unable to do so, and there is a risk of wasted effort.

Proposed work:

1. An update to the K2 planet candidate catalog I wrote in 2015. There will be two main reasons this paper will be a significant upgrade over the original K2 catalog paper. One obvious reason is that there will be twice as much data, and therefore a significant number of new candidates.

The other main reason is that I will make substantial modifications to my pipeline. To put it simply, I am not satisfied with my pipeline's performance. I wrote the current version of my pipeline in late 2014 and have made some modifications since then, but I have noticed that the current data are pushing the pipeline to the limits of its architecture, and the data quality is beginning to suffer. I am still able to effectively find planets, but I am convinced I am missing many interesting systems.

I plan to explore the following options to improve my pipeline: take into account two-dimensional position information when removing systematics. Model higher-frequency stellar activity when removing the systematics. Implement a common-mode removal system, possibly either principle component analysis (PCA) or SysRem. Implement smart stellar activity removal while searching for transits so that rapidly rotating stars are treated well. Build specialized software to search for planets only transiting twice during the ~80 day dataset. I will also look for inspiration for improvements to my software by identifying planets in the data which were not found by my pipeline. Understanding why these transits were missed will be crucial to improving my pipeline so that other planets in similar situations will be found in the future.

2. A mass measurement of a K2 planet using data from HARPS-N. I am a member of the HARPS-N collaboration, and I provide recommendations to the collaboration for planets discovered by K2 suitable for precise radial velocity observations. Currently, HARPS-N is observing a handful of planet candidates I identified in K2, and several of these are making good progress towards papers.

I will choose a planetary system and send a request the HARPS-N leadership that I lead the paper describing the radial velocity results for that system.

3. “High risk” papers when the opportunity presents itself. I have been successful identifying interesting systems, quickly performing an investigation, and publishing papers describing the system. If I come across a system interesting enough to warrant its own paper, I may devote some time to that object.

Thesis Advisory Committee: If they are willing, I would like to request that my committee include : Dave Latham, Dave Charbonneau, Roseanne DiStefano, John Johnson, and Mercedes Lopez-Morales.

Schedule: It is difficult to predict my future schedule, as it is highly dependent on K2 data releases (which are scheduled every three months, but have often been significantly delayed or early and the times at which any “high-risk” paper opportunities might present themselves. This being said, I have listed a rough schedule below:

April-June 2016: Development of the improved photometric and transit search pipeline. Throughout this time, I will also work on writing a paper somewhat unrelated to this thesis (involving RV data of a transiting brown dwarf in the Kepler field), and help coordinate follow-up of bright K2 candidates with TRES.

June-October 2016: When the data from K2 Campaign 8 is released (the last campaign of the first two years of K2), I will focus my attention on the updated K2 planet candidate catalog. I wrote the first K2 catalog paper on a similar timeframe in 2015. Continue searching for K2 candidates and coordinating follow-up.

October 2016-June 2017: Perform analysis of HARPS-N data and write the paper with a mass measurement of a small exoplanet. Continue searching for K2 candidates and coordinating follow-up.

June 2017-June 2018: Apply for jobs, write thesis, and continue searching for K2 candidates and coordinating follow-up. Sometime around here K2 will run out of fuel and stop observing.

May 2018: Graduate.