Inferring the Rate of Planet Occurrence by Injecting and Detecting Transits in the *Kepler* Light Curves of M Dwarfs

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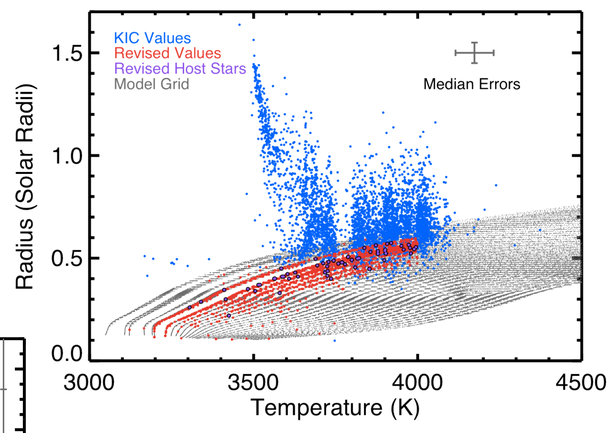
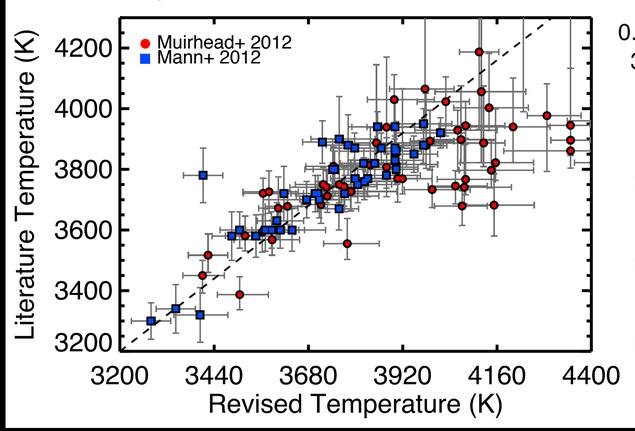
Motivation

Most stars are M dwarfs, so determining the frequency of planets around M dwarfs is crucial for estimating the number of potentially habitable planets in the galaxy. We are conducting an **ongoing project to improve our estimate of the planet occurrence rate** by developing a **customized pipeline to detect transiting planets around *Kepler* M dwarfs**. The *Kepler* M dwarfs are fainter than the majority of *Kepler* targets and frequently demonstrate considerable brightness variations due to spot activity. Our pipeline is designed to **remove stellar variability** while **preserving the signatures of planetary transits**. We are **measuring the detection efficiency** of our pipeline in order to accurately estimate the fraction of stars that host planets. This project builds on our previous work revising the stellar parameters of *Kepler* M dwarfs and estimating the planet occurrence rate around M dwarfs.

Revised Stellar Parameters

Right: Original (blue) and revised (red) **stellar parameters**. The original parameters (Brown+ 2011) were based on ATLAS9 models (Castelli & Kurucz 2004) and were often **nonphysical**. The revised values are based on Dartmouth models (gray) from Dotter+ 2008.



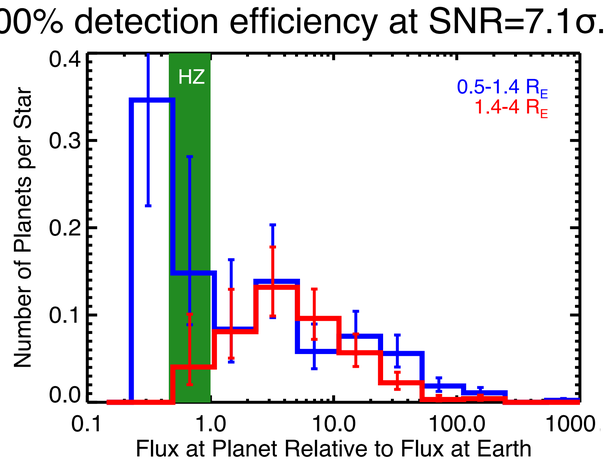


Left: Spectroscopic temperature estimates from Muirhead+ 2012 (red circles) and Mann+ 2012 (blue squares) versus our revised values. The disagreement above 4000K is due to the saturation of the H_2O-K2 index used by Muirhead+ 2012.

Planet Occurrence Rate

In a recent paper, we revised the stellar parameters of the *Kepler* M dwarfs and determined that the occurrence rate of 0.5-4$R_\oplus$ planets with periods <50 days is **0.90 planets per small star.** We found that the mean number of **Earth-size** (0.5-1.4$R_\oplus$) **planets within the habitable zone is 0.15 planets per small star**, implying that the **nearest transiting Earth-size planet is within 21 pc with 95% confidence**. Our previous estimate assumed 100% detection efficiency at SNR=7.1σ.

Right: Planet occurrence rate vs. insolation for 1.4-4$R_\oplus$ (red) and Earth-size (0.5-1.4$R_\oplus$, blue) planets. The green box marks the habitable zone (Kasting+ 1993). Recent work by Kopparapu+ 2013 suggests that the habitable zone may extend to even lower fluxes.



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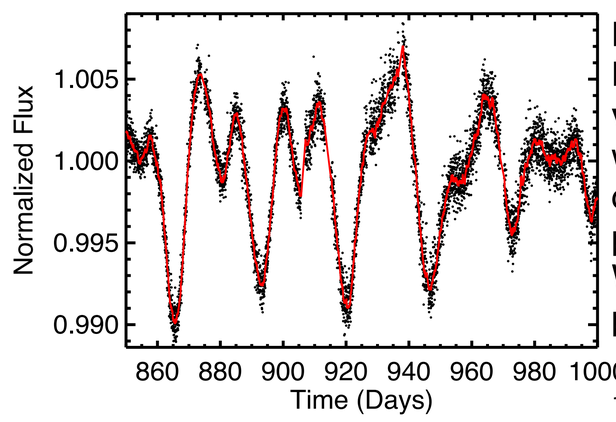
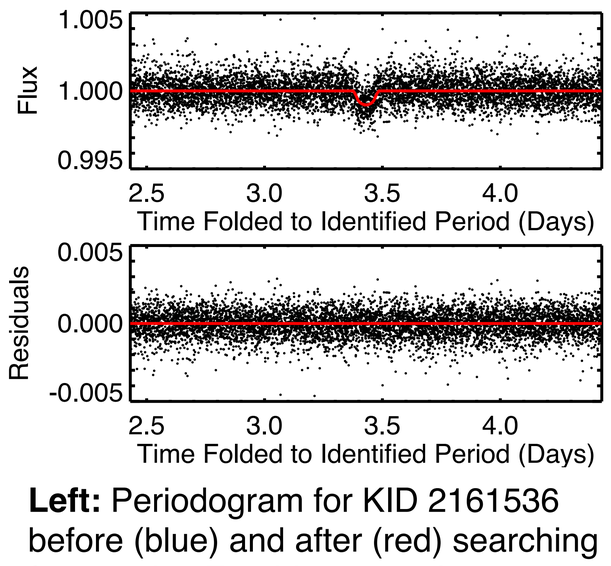
Transit Detection Pipeline

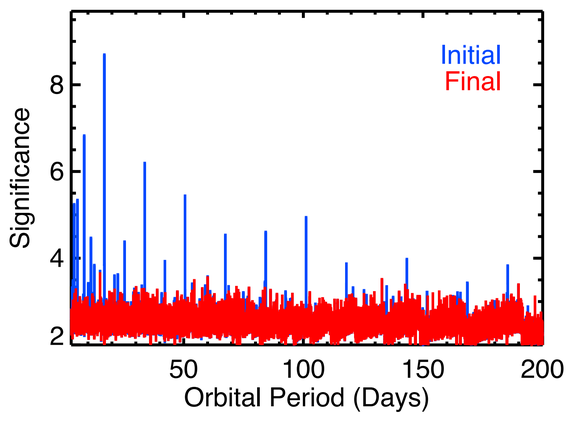
For each *Kepler* M dwarf, we combine data from multiple quarters and **search for box-shaped transits** over a grid of periods, durations, and epochs. If a signal is identified, we use the IDL AMOEBA minimization routine based on Press+ 2002 to fit a Mandel + Agol 2002 transit model.



Left: A section of photometry for star KID 2161536. We **remove stellar variability** by smoothing the data with a 500 minute median filter and dividing the normalized data (black points) by the median fit (red line). We **correct for flares** by discarding points over 6σ above the median.

Right: Best-fit model (top) and residuals (bottom) for a 16.8 day signal identified for KID 2161536. The derived transit parameters **agree well with the published values** for planet candidate KOI 2130.01 (Batalha+ 2013).



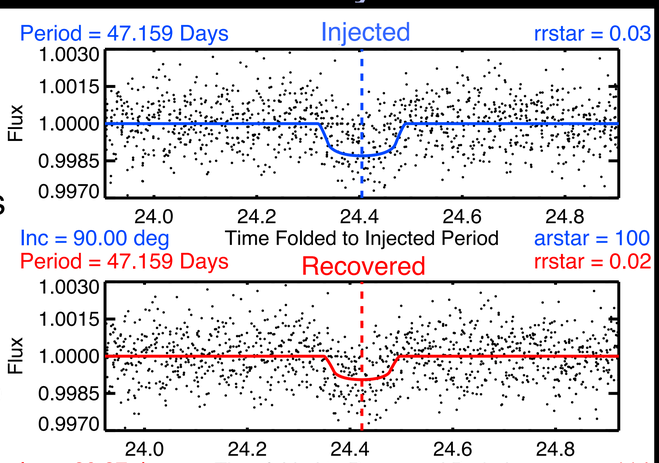


Left: Periodogram for KID 2161536 before (blue) and after (red) searching for transits. For this star, only one planet candidate was detected, but our code is able to detect multiple planets. The code divides out the fitted transit models and continues searching until no significant signals remain.

Transit Injection & Recovery

We are **directly measuring the efficiency of our planet detection pipeline** by injecting transits into light curves and attempting to recover the signals using our detection pipeline.

Right: Injected (blue) and recovered (red) transit signals for the test case of KIC 2557350. The **recovered period is within 40 seconds** of the injected period.



Future Work

We will compare our list of candidate planets to the lists provided by the *Kepler* team and discuss any new candidates. We will combine our completeness calculations, planet candidate list, and revised stellar properties to estimate the frequency of planets around M dwarfs. Our results will complement work by Petigura+ 2013 to develop a customized planet detection pipeline for quiet, Sun-like stars and by Christiansen+ 2013 to investigate transit signal recovery in the *Kepler* pipeline.

Acknowledgments

CD is supported by a Graduate Research Fellowship from the National Science Foundation. We acknowledge support by the NASA Kepler Participating Scientist Program through grant NNX12AC77G. Funding for *Kepler* is provided by the NASA Science Mission Directorate.