Draft version January 15, 2019
Typeset using LaTeX default style in AASTeX62

A Search for Transits Across Pulsating Stars

Benjamin J. S. Pope,[1,2] Simon J. Murphy,[3,4] David W. Hogg,[1,5,6,7] and friends

[1]Center for Cosmology and Particle Physics, Department of Physics, New York University, 726 Broadway, New York, NY 10003, USA
[2]NASA Sagan Fellow
[3]Sydney Institute for Astronomy, School of Physics, University of Sydney, Sydney, NSW 2006, Australia
[4]Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark
[5]Center for Data Science, New York University, 60 Fifth Ave, New York, NY 10011, USA
[6]Max-Planck-Institut fur Astronomie, Konigstuhl 17, D-69117 Heidelberg
[7]Flatiron Institute, 162 Fifth Ave, New York, NY 10010, USA

(Received January 1, 2018; Revised January 7, 2018; Accepted January 15, 2019)

Submitted to ApJ

ABSTRACT

Planets around hot stars have until recently been hard to detect, because many hot stars vary with coherent pulsations that can hide the small planetary signals both in RV and in photometric transit.

By modelling out these coherent oscillations and correcting for residual systematics, we conduct a deep search of all hot pulsating stars in *Kepler* to find eclipsing binaries and planetary transits.

The methods applied here generalize naturally to the much larger samples of classical pulsators in *K2* and TESS.

1. INTRODUCTION

Only three planets have been confirmed to transit stars hotter than 8000 K: KELT-9, KELT-20, and *Kepler*-1115. There are few planets known to transit upper main sequence stars (spectral types OBA) because of the stars' intrinsic rarity, and because many such stars are intrinsically highly variable both in photometry and radial velocity.

Sowicka et al. (2017) conducted a search for transits around pulsating stars in *Kepler* by first modelling the stellar pulsations and then subtracting these. This search was limited to stars with short-cadence observations for stars with temperatures 6000K $< T <$ 8500 K, and found only two candidates: KIC 5613330 and KIC 8197761, the latter of which was confirmed by RV to be an eclipsing binary. This neglected both the high-temperature end of the stellar population and the many stars for which short-cadence observations were not obtained.

We adapt the methods of Sowicka et al. (2017) to the entire *Kepler* sample of hot stars (temperature range TBD), including long-cadence only targets. We especially focus on looking for eclipses of those pulsating stars identified by Murphy et al. (2018) as binaries from the phase-modulation of their pulsations due to the Rømer delay or light travel time effect (LTTE), finding several of these to be 'heartbeat stars.'

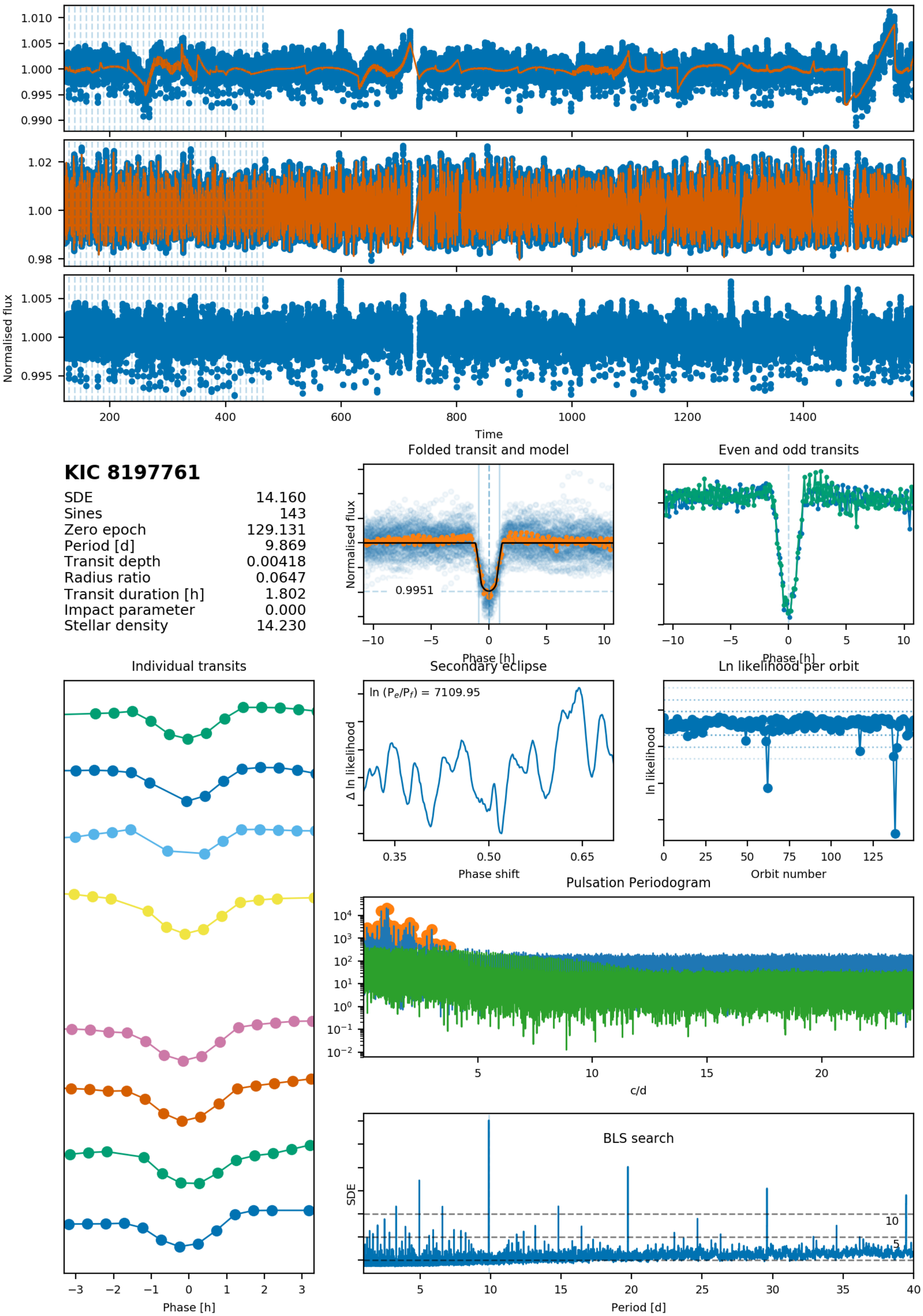
We believe our results here are a useful pathfinder for deploying similar methods at-scale to data from *Kepler*-2 (K2) and especially the Transiting Exoplanet Survey Satellite (TESS), in which many thousands more hot stars than in *Kepler* either have been or will be observed.

In Section 2 we outline the flow of the methods used here.

Corresponding author: Benjamin J. S. Pope @fringetracker
benjamin.pope@nyu

2. THE ALGORITHM

- **Read in data**
  - Read in all quarters (storing quarter label).
  - Normalize and stitch.
- **CLEAN Algorithm** (iterative sine fitting)
  - Use Astropy (Astropy Collaboration et al. 2013) Lomb-Scargle (Lomb 1976; Scargle 1982; VanderPlas 2018) coarsely to find best frequency in range from $\sim 1c/d$ to Nyquist.
  - If a significant peak is found ($\log FAP < -12$), use L-S on a fine grid in its vicinity to nail the frequency.
  - Then fit a sinusoid at that frequency and subtract.
  - Repeat until no more significant peaks are found or 60 sinusoids are subtracted.
- **Pre-Search Conditioning**
  - Subtract sum-of-sinusoids model from data.
  - Run OxKeplerSC (Aigrain et al. 2017) on each quarter to fit co-trending basis vectors (CBVs), and re-stitch.
  - Re-fit sine model with CLEAN to data with new systematics correction.
- **Transit Search**
  - Run modified version of the Oxford planet search code k2ps (Pope et al. 2016; Parviainen et al. 2016) to do a box-least-squares (BLS) search.
  - Produce vetting diagrams, including:
    * Raw light curve with CBVs/sinusoids/both subtracted.
    * Periodogram of full PDC light curve, with subtracted frequencies highlighted.
    * Periodogram of residuals.
    * Folded PDC light curve on main period.
    * Folded residual light curve on BLS best period.
    * BLS plot.
    * Odd and even transit light curves.
    * Likelihood per transit.
    * Transit parameters.



SDE	14.160
Sines	143
Zero epoch	129.131
Period [d]	9.869
Transit depth	0.00418
Radius ratio	0.0647
Transit duration [h]	1.802
Impact parameter	0.000
Stellar density	14.230

REFERENCES

Aigrain, S., Parviainen, H., Roberts, S., Reece, S., & Evans, T. 2017, MNRAS, 471, 759, doi: 10.1093/mnras/stx1422

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33, doi: 10.1051/0004-6361/201322068

Lomb, N. R. 1976, Ap&SS, 39, 447, doi: 10.1007/BF00648343

Murphy, S. J., Moe, M., Kurtz, D. W., et al. 2018, MNRAS, 474, 4322, doi: 10.1093/mnras/stx3049

Parviainen, H., Pope, B., & Aigrain, S. 2016, K2PS: K2 Planet search, Astrophysics Source Code Library. http://ascl.net/1607.010

Pope, B. J. S., Parviainen, H., & Aigrain, S. 2016, MNRAS, 461, 3399, doi: 10.1093/mnras/stw1373

Scargle, J. D. 1982, ApJ, 263, 835, doi: 10.1086/160554

Sowicka, P., Handler, G., Dębski, B., et al. 2017, MNRAS, 467, 4663, doi: 10.1093/mnras/stx413

VanderPlas, J. T. 2018, The Astrophysical Journal Supplement Series, 236, 16, doi: 10.3847/1538-4365/aab766