The Kepler Pixel Project

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Although *Kepler's* original mission is over, its photometry is so precise that new ways can be developed to harvest the great wealth of quasi-continuous data that has never been accessible from the ground. We have initiated a new program that we dub the Kepler Pixel Project in order to explore new approaches and to discover new pulsating stars and other time-variable objects. In this endeavour we examine individual pixels of the original *Kepler* mission to find interesting objects around the main *Kepler* targets. Specifically, we launched a project to discover background, faint RR Lyrae stars that are missing from the *Kepler* sample. In this contribution the first results of the Kepler Pixel Project are presented. We discuss the project, the search algorithms, and our findings. We also show other results and examples (flares, outbursts, new eclipsing binaries) to demonstrate the potential and future avenues of the project.

1 Introduction

Kepler-quality RR Lyrae light curves enabled the discovery of new phenomena (period doubling, additional modes, resonances) and the study of nonlinear dynamical phenomena in detail, like the complexity of the Blazhko modulation, its temporal behavior, etc. (Szabó et al., 2010; Benkő et al., 2010; Kolláth et al., 2011; Molnár et al., 2012; Guggenberger et al., 2012; Benkő et al., 2014; Moskalik et al., 2015).

In addition, all RR Lyrae light curves are unique and extremely rich in information which motivates the search for more representatives of this class. For example, as canonical RRd stars are quite rare, none has been found in the original *Kepler* field. Fig. 1 shows the ~50 known RR Lyrae stars in the *Kepler* field.

2 There is More in the *Kepler* Data than Meets the Eye

Part of our motivation was that we found a faint, background RR Lyrae stars serendipitously in the original *Kepler* data. Also, a new dwarf nova was discovered in the aperture of another *Kepler* target (Barclay et al., 2012). These findings motivated us to initiate a new program that we dub the Kepler Pixel Project in order to explore new approaches to the *Kepler* data and to discover hitherto unknown pulsating stars and other time-variable objects. In this program, we examine individual pixels of the original *Kepler* mission to find interesting objects around the main *Kepler* targets. Specifically, we launched a project to find background, faint RR Lyrae stars that are missing from the *Kepler* sample. Since the photometric quality is extremely high (Gilliland et al., 2010), there is hope to find variable objects (especially large-amplitude variable stars) in those pixels that used to be considered as 'background' of the main *Kepler* targets.

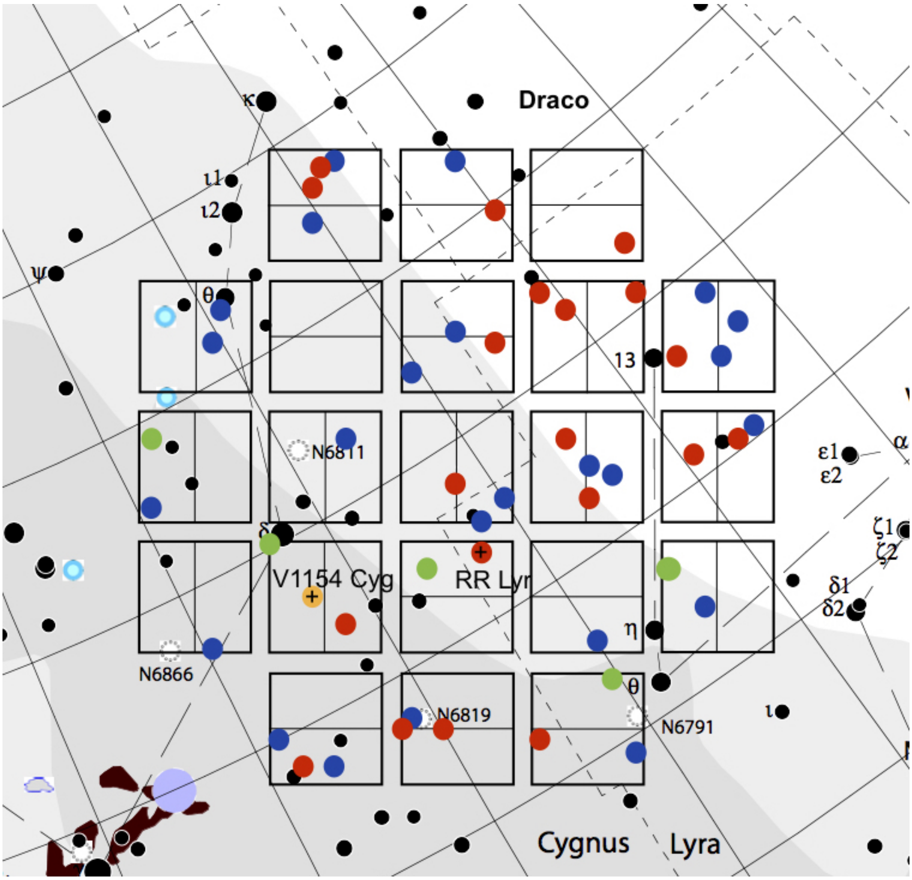

Fig. 1: Known RR Lyrae stars in the original *Kepler* field. Red: Blazhko-modulated RRab stars; blue: non-modulated RRab stars; green: RRc stars; orange: V1154 Cygni, the sole Cepheid in the *Kepler* field.

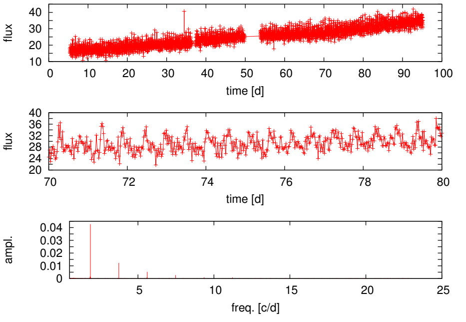

Fig. 2: Output of the searching pipeline. Top: light curve of a single pixel in the entire Q4 quarter. Middle: a small section of the light curve. Bottom: Fourier spectrum of the full Q4 light curve.

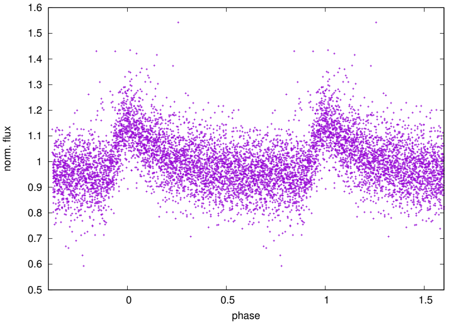

Fig. 3: Phase-folded light curve of the same candidate. This is an RRab candidate with a period of 0.534680 d. No sigma-clipping was performed.

3 Methods

To start with, we selected Q4 quarter, as a particularly quiet one without major technical problems or gaps and free of the initial 'teething problems' seen in earlier quarters. For the time being we do not consider short cadence (1-min) data. After downloading all long-cadence (30-min) target pixel files, we extracted each individual pixel irrespective whether it belongs to a nominal target, or being a background, 'halo' pixel. This procedure resulted in approximately 6 million individual pixel light curves. This is roughly 6% of all the pixels onboard *Kepler*, but as is well-known, only a small fraction of these were downloaded in any given quarter due to bandwidth limitations.

To hunt for RR Lyrae stars the following searching algorithm was employed: we searched for significant periodicity in the $[0.25 - 1.00]$ day period interval. In addition we required the presence of at least two significant harmonics of the main periodicity with monotonically decreasing amplitudes.

This algorithm left us with 12 500 candidate pixel light curves (but much fewer individual objects, since in many cases more than one pixel belonged to the same target). We found that over 90% of these candidates are known or new eclipsing binary stars. It is reassuring that all the known RR Lyrae stars were recovered by our algorithm. The application for further sophisticated selection/classification mechanisms (e.g. machine learning) would be desirable to help in distinguishing between pulsating and eclipsing variables. We plan to apply such a technique in the near future.

4 Preliminary Results

In Fig. 2 a typical output from our RR Lyrae searching pipeline is shown. The upper panel displays the entire Q4 long-cadence light curve of the individual pixel. It is very common that long-term trends are present in these light curves, most of which disappear when multiple pixels belonging to the same target are co-added. The middle panel shows a 10-day section of the light curve, which is better situated

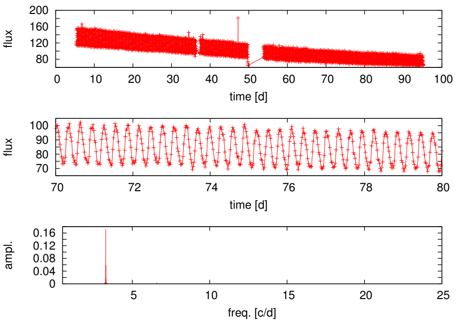

Fig. 4: The same as Fig. 2 for another individual pixel.

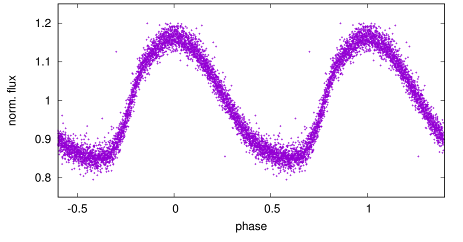

Fig. 5: Phase-folded light curve of the same candidate. This is an RRc candidate with a period of 0.304110 d.

to reveal any large-amplitude variations. The ultimate check is the Fourier spectrum shown in the bottom panel, which easily reveals any periodicities in the data that would remain hidden during a visual inspection. Fig. 3 shows the same data, but this time, detrended and phase-folded with the found periodicity. The result is a typical RRab light curve with a rather high scatter. This is a previously unknown faint background RR Lyrae. Figs 4 and 5 show the results from another individual pixel, this time revealing a new RRc variable.

The project is ongoing, therefore the presented results are preliminary. After visually inspecting one third of our candidate light curves, the search revealed 13 new RR Lyrae stars. Out of these two are Blazhko-modulated RRab stars, 9 are RRab stars, where no modulation is evident at the first glance. The lower-than-expected modulation rate can be easily explained by the faintness of our objects, and hence the elevated noise in the light curves. In addition, one RRc (Figs 4 and 5) and one canonical RRd star is found. The latter is a first-overtone dominated RRd with a period ratio of $P_1/P_0 = 0.7433$ and featuring a P_x additional mode with a period ratio of $P_\mathrm{x}/P_1 = 0.616$.

Besides finding RR Lyrae and other pulsating variable stars, we initiated several sub-projects to discover eclipsing binary stars, flare events, cataclysmic variables, etc. These are typically student projects and are well-suited to teach data reduction and analysis, time-frequency analysis, and basic astronomical concepts to BSc and MSc students. In the framework of these studies, we discovered several new flare events and eclipsing binary systems related to/being background objects. We note that our flare searching algorithm was also sensitive to RRab light curves that show steep ascending branch variations, and several objects were found in common with our described RR Lyrae search algorithm. These results will be published elsewhere.

5 Summary

We demonstrated that investigating individual (even ‘background’) pixels is an efficient way to find RR Lyrae stars, other pulsating, eclipsing binaries, or stars showing flares. Our methods will be helpful to fully explore space data of other ongoing and future space photometric missions, like *K2* (Howell et al., 2014), *TESS* (Ricker et al., 2015), and *PLATO* (Rauer et al., 2014). A more elaborated version of this work and the Kepler Pixel Project itself will be published in a separate paper.

Acknowledgements. Project no. 115709 has been implemented with the support provided from the National Research, Development and Innovation Fund of Hungary (NKFIH), financed under the K_16 funding scheme. The author wishes to thank the entire *Kepler* Team for their excellent job that allowed the acquisition of such a fantastic dataset. Funding for the *Kepler* mission was provided by the NASA Science Mission directorate. I thank my students, Bálint Seli, Dóra Pintér, Ottó Hanyecz, and Levente Benkóczy for their contribution and valuable discussions. I also thank the RRL2017 conference organizers for a very pleasant and fruitful meeting.

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