K2 Observations of Double-Mode RR Lyrae Stars

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We present preliminary analysis of double-mode RR Lyrae variables observed by NASA's *Kepler–K2* mission.

1 Introduction

Double-mode RR Lyrae stars, or RRd stars, are pulsating variables in which two radial modes (fundamental and first overtone) are simultaneously excited. They are relatively rare objects. None were identified among more than 50 RR Lyrae stars in the original *Kepler* field (Nemec et al., 2013). Only during the *Kepler–K2* mission has a substantial number of RRd stars been observed. With the benefit of very high-precision space photometry, we can now study their pulsations in great detail.

In this preliminary report we discuss RRd variables observed during Campaigns 0-13 of the *K2* mission. The current sample consists of 39 RRd stars, four of which have already been studied (Molnár et al., 2015; Kurtz et al., 2016; Plachy et al., 2017). For all the stars, we have performed Fourier analysis using long-cadence photometry. For about half of the objects, we have derived accurate photometry with the Extended Aperture Photometry (EAP) pipeline (Plachy et al., 2018). For the remaining ones we have used data provided by the *K2* archive, obtained with the standard *Kepler* Pre-searched Data Conditioning Simple Aperture Photometry (PDCSAP) pipeline (Smith et al., 2012). The EAP photometry is generally of higher quality in terms of the noise level in the Fourier transform, which is crucial for detecting low amplitude secondary modes. In the final analysis, we intend to use EAP photometry for all stars.

2 Petersen Diagram

In Fig.1 we present the Petersen diagram (the period ratio vs. period diagram), in which the *K2* RRd stars are plotted with red asterisks. For comparison, we also display with black dots the "classical" RRd stars of the Galactic bulge (Soszyński et al., 2014), as well as double mode variables belonging to two newly identified subgroups: anomalous RRd stars (Soszyński et al., 2016, plotted with open blue circles) and "Prudil's stars" (Prudil et al., 2017, plotted with filled blue triangles).

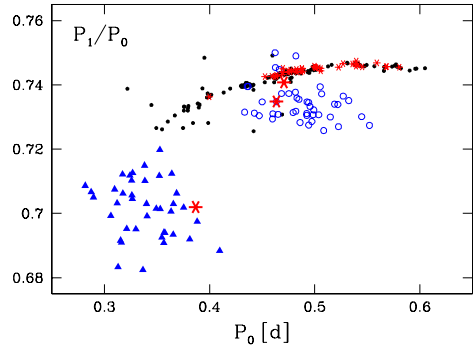

Fig. 1: Petersen diagram for the dominant modes of RRd stars. The *K2* RRd stars are plotted with red asterisks. With black dots and with filled blue triangles we display, respectively, "classical" RRd stars and "Prudil's stars" of the Galactic bulge. Open blue circles represent anomalous RRd stars collected from several stellar systems: the Galactic bulge (Smolec et al., 2015), the Magellanic Clouds (Soszyński et al., 2016), as well as the globular clusters M3 (Jurcsik et al., 2015) and NGC6362 (Smolec et al., 2017b).

For the discussion of different subtypes of double-mode RR Lyrae pulsators one is referred to Smolec et al. (2017a).

The majority of the RRd stars observed by the *K2* mission fall on a tight progression defined by the classical RRd variables. In other words, these stars are typical double-mode RR Lyrae pulsators. There are three noticeable exceptions which have been marked in the plot with asterisks of a larger size. Two objects with anomalously low period ratios, EPIC 205209951 and EPIC 225045562, are placed firmly among anomalous RRd stars. They share other properties of this group as well. In both variables, pulsation modes are modulated. In the case of EPIC 205209951, the modulation was discovered by Plachy et al. (2017). The modulation timescale could not be determined but seems to be only slightly longer than the length of the observing run (78 days). In the case of EPIC 225045562 $\equiv$ OGLE-BLG-RRLYR-02530, slow periodic modulation with $P_{\rm mod} = 469$ d has been discovered with ground-based OGLE data (Smolec et al., 2015). In both stars, the fundamental mode has significantly higher amplitude than the first overtone. Amplitude modulation and strong dominance of the fundamental mode are very common in the anomalous RRd stars (Soszyński et al., 2016), but are not observed in the classical RRd stars.

The third exceptional star, EPIC 216764000 ($P_0 = 0.39$ d; $P_1/P_0 = 0.70$), belongs to the group of variables recently identified by Prudil et al. (2017). In these double-mode pulsators the period ratios are also anomalously low and the mode of the longer period always strongly dominates. Both properties hold for EPIC 216764000. Unlike in classical or anomalous RRd stars, in "Prudil's stars" the mode of shorter period cannot correspond to the radial first overtone. Its identity remains unknown.

3 Secondary Modes

In addition to the two main pulsation frequencies f_0 and f_1 and their harmonics, in the double-mode variables we also see numerous combination frequencies of the form $mf_0 + nf_1$. After subtracting all these components from the time series data

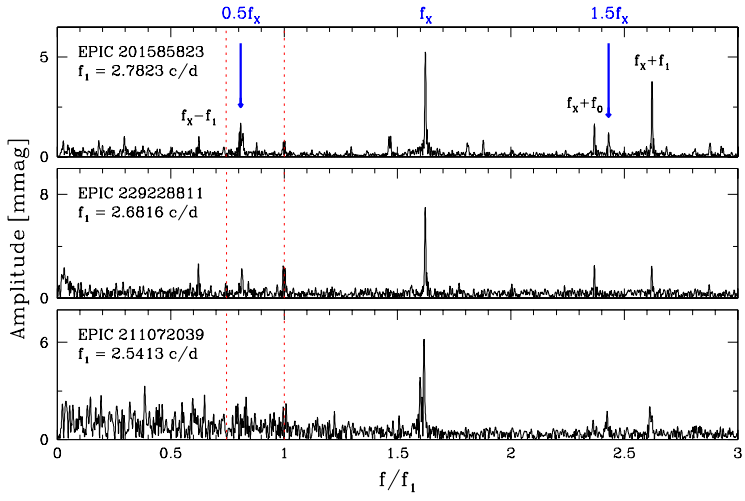

Fig. 2: Fourier frequency spectra of non-modulated RRd stars, after prewhitening the data of all signal related to radial modes. Vertical dashed lines mark frequencies of the (removed) radial modes. The broadened peak at $f/f_1 = 1.47$ in EPIC 201585823 is an artefact corresponding to the *Kepler* thruster firing frequency of $\sim$4.08 c/d.

(prewhitening), we detect in many *K2* RRd stars an additional frequency, $f_{\rm x}$. Its amplitude is extremely low and rarely exceeds 10 mmag. The period ratio of this secondary mode to the first radial overtone, $P_{\rm x}/P_1$, is in a narrow range around 0.615. This is the same period ratio that is so frequently observed in the first overtone RR Lyrae (RRc) stars (Moskalik et al., 2015; Netzel et al., 2015b). Linear combinations of $f_{\rm x}$ with frequencies of both radial modes are detected as well. In a number of stars, significant signal is also seen at $\sim 0.5 f_{\rm x}$, $\sim 1.5 f_{\rm x}$, or both. The presence of these subharmonic frequencies is another similarity to the RRc variables. Their amplitudes are even lower than for the $f_{\rm x}$ mode and are always below 3 mmag.

In Fig. 2 we display Fourier frequency spectra for 3 non-modulated RRd stars of different periods. They are computed after prewhitening the data, which has removed the two radial modes, their harmonics, and their linear frequency combinations. The horizontal axis is normalized by the frequency of the first radial overtone, f_1. Such normalization is chosen in order to show how similar the frequency patterns are in the RRd stars. Subharmonics are visible in all 3 variables (although in EPIC 229228811 only one of them is present). We note that the peak at the frequency $f_{\rm x}$ is sometimes broadened or even split, indicating that the signal is not coherent. A time dependent analysis reveals that both the amplitude and the phase of $f_{\rm x}$ are highly variable. This is in sharp contrast to the behavior of the two radial modes, which are almost perfectly stable.

It is important to establish how often the $f_{\rm x}$ mode is excited in the RRd stars. Because this mode is always of very low amplitude, we should use only the highest quality data to address this question. Therefore, we have limited our sample to only those RRd variables for which EAP photometry is available. At the moment of writing this report, this subsample consists of 19 objects. The modulated variable EPIC 205209951 is the only object of this sample in which the $f_{\rm x}$ mode is not

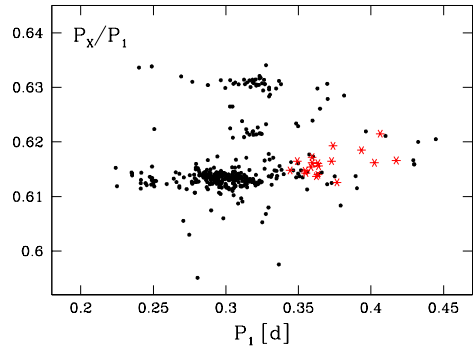

Fig. 3: Petersen diagram for secondary modes of RRd and RRc stars. Period ratios are plotted vs. first overtone period, P_1. The RRd variables of *K2* sample are displayed with red asterisks. The RRc stars of the Galactic Bulge (Netzel et al., 2015a,b) are displayed with black dots.

detected. In the other 18 non-modulated RRd variables, the f_x mode is detected in *every star*. Subharmonic frequencies are more difficult to detect, but still, at least one subharmonic is found in 15 non-modulated RRd stars.

In the case of EPIC 220254937 a comment is required. A secondary signal yielding the expected period ratio of ~ 0.61 is present in this star. However, its frequency of 4.08 c/d is identical to the known artefact corresponding to the *Kepler* thruster firing frequency. There is no way to tell if the detected signal is intrinsic to the star or not. Thus, for the purpose of making statistics, the star should be excluded from the sample. This does not change the final conclusion: the f_x mode is present in all, and its subharmonics in almost all, non-modulated RRd stars.

4 RRd Stars vs. RRc Stars

Secondary modes with period ratio $P_x/P_1 \sim 0.61$ have been detected in nearly 300 RRc variables (see Smolec et al., 2017a). When plotted on the Petersen diagram (Fig. 3), these stars form 3 separate sequences, centered at $P_x/P_1 = 0.613$, 0.623 and 0.631. The RRd stars of the *K2* sample fit very nicely to the pattern established by the RRc stars. They all fall on the lowest sequence on the Petersen diagram, which is perhaps not surprising, considering that this sequence is by far the most populated. The RRd stars occupy the long period end of the sequence, but otherwise RRd and RRc variables are very similar.

The similarity of the f_x modes in RRd and in RRc stars does not end there:

- in both groups of stars the amplitudes of the f_x mode are in the mmag range;
- in both groups of stars the f_x modes are non-stationary, while the dominant radial mode(s) are almost perfectly stable;
- the f_x mode is detected in every non-modulated RRc and RRd star for which high precision space photometry is available (see Sec. 7.1 of Moskalik et al., 2015, for a discussion of the incidence rate in RRc stars). Apparently, excitation of this mode is very common and most likely happens in all or almost all RRc and RRd variables;

- in both RRc and RRd stars the $f_{\rm x}$ mode is very often accompanied by subharmonic (half-integer) frequencies at $\sim 0.5 f_{\rm x}$ and/or $\sim 1.5 f_{\rm x}$.

The similarity of the $f_{\rm x}$ modes in both subgroups of RR Lyrae variables is striking. We conclude that the same phenomenon is being observed in RRc and RRd stars, and that for both groups of pulsators a common explanation should be sought for $f_{\rm x}$. The measured period ratios $P_{\rm x}/P_1$ immediately exclude identification of this frequency with any radial mode of pulsation. Thus, $f_{\rm x}$ corresponds either to a nonradial mode or, as recently proposed by Dziembowski (2016), to the first harmonic of a nonradial mode. If the latter interpretation is correct, then the excited nonradial mode of $\ell = 8$ or $\ell = 9$ would be located at a subharmonic frequency $0.5 f_{\rm x}$.

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