K2 Observations of Galactic RRd Stars

Pawel Moskalik,1 James M. Nemec,2 László Molnár,3,4 Emese Plachy,3,4 Róbert Szabó,3,4 Katrien Kolenberg5,6

1 Nicolaus Copernicus Astronomical Centre, Warsaw, Poland
2 Department of Physics & Astronomy, Camosun College, Victoria, Canada
3 Konkoly Observatory, MTA CSFK, Budapest, Hungary
4 MTA CSFK Lendület Near-Field Cosmology Research Group, Budapest, Hungary
5 Institute of Astronomy, KU Leuven, Heverlee, Belgium
6 Physics Department, University of Antwerp, Antwerp, Belgium

Abstract

We have analysed high-precision photometry of 77 double-mode RR Lyrae (RRd) stars observed by NASA’s Kepler-K2 mission during Campaigns 1-18. Among those stars, we have identified several low-period ratio variables, belonging either to a subclass of ‘anomalous’ RRd stars (Soszyński et al., 2016) or to a separate shorter-period subclass recently identified by Prudil et al. (2017).

A non-radial mode with the period ratio of $P_2/P_0 \sim 0.015$ has been detected in most RRd stars of our sample. In majority of these variables, at least one subharmonic of the non-radial frequency is also present. Our findings indicate that excitation of the non-radial mode is a common property of the RRd stars. The same non-radial pulsation is also commonly detected in the RRc stars. We show that properties of this puzzling mode are essentially the same in both groups of RR Lyrae-type pulsators.

1 Introduction

RRd stars are a subclass of the RR Lyrae variables, in which two radial modes, the fundamental and the first overtone, are simultaneously excited. Such variables are rare and not a single one has been found the original Kepler field (Nemec et al., 2013). Only with the Kepler-K2 mission a high precision space photometry has finally been collected for a large sample of RRd stars. We are now in position to study their pulsation in great detail.

In this report we discuss 77 RRd variables observed during K2 Campaigns 1-18. For most of these objects we have derived accurate photometry either with the EAP pipeline (Plachy et al., 2018) or with the PyKE pipeline (Still & Barclay, 2012). For the remaining ones, we have used the standard Kepler PDCSap photometry provided by the K2 archive. The latter is generally of somewhat lower quality. For all the stars we have performed detailed frequency analysis, using a standard Fourier Transform, followed by a consecutive frequency prewhitening. We note that four stars of our sample have already been studied before by other authors (Molnár et al., 2015; Kurtz et al., 2016; Plachy et al., 2017).

A paper presenting full results of our analysis is being readied for publication (Nemec et al., 2019).

2 RRd variables in K2 fields

In Fig. 1 we present the Petersen diagram (the period ratio vs. period diagram) for the K2 RRd stars (plotted with red asterisks). For comparison, we also display the “classical” RRd stars of the Galactic bulge (Soszyński et al., 2014), the anomalous RRd stars collected from several stellar systems (Smolec et al., 2015; Jurecik et al., 2015; Soszyński et al., 2016; Smolec et al., 2017a) and the so-called “Prudil’s stars” (Prudil et al., 2017).1

Most of the RRd variables of the K2 sample are typical double-mode RR Lyrae pulsators and fall on a tight progression defined by the classical RRd stars. There are several objects, though (marked with large red symbols), which behave differently. Three K2 variables are placed firmly among anomalous RRd pulsators. In two of them pulsation modes are modulated (Smolec et al., 2015; Plachy et al., 2017). This is a very frequent phenomenon in anomalous RRd stars, but is not observed in the classical RRd pulsators. Four other K2 variables with low period ratios and short periods belong to a subclass of the “Prudil’s stars”. In all seven exceptional objects, pulsations are strongly dominated by the radial fundamental mode $A_0/A_1 = 1.4 - 7.6$, which is another difference between them and the classical RRd pulsators.

---

1For full discussion of different subclasses of the RRd pulsators the reader is referred to Smolec et al. (2017b).
3 Secondary modes

For all RRd stars of our sample we have conducted a search for secondary low-amplitude pulsations. After prewhitening the data of the two radial modes, their harmonics and their combination frequencies, we have detected in many K2 RRd variables an additional variability with frequency, \( f_x \). Linear combinations of \( f_x \) with frequencies of the radial modes are also usually present. The period ratio of this secondary mode to the first radial overtone, \( P_x / P_1 \), is always close to 0.615 and its amplitude is always very low and rarely exceeds 10mmag. This is the same period ratio which is commonly observed in the first overtone RR Lyrae (RRc) stars (Moskalik et al., 2015; Netzel et al., 2015b). This period ratio cannot be explained with any two radial modes, implying that frequency \( f_x \) must be associated with a nonradial mode of pulsation. In many RRd stars a significant signal has also been found at \( \sim 0.5 f_x \) or \( \sim 1.5 f_x \), or both. These subharmonics always appear together with the parent mode, \( f_x \), and never alone. The presence of the subharmonic (half-integer) frequencies is another similarity to the RRc variables. Interestingly, the \( f_x \) mode has been detected only in the classical RRd variables. It has not been detected in any of the ‘Prudil’s stars’ or the anomalous RRd stars.

In Fig. 2 we display Fourier frequency spectra for 3 classical RRd stars. The spectra are computed after prewhitening the data of all the signal related to the radial modes. The frequency axis is normalized by the frequency of the first radial overtone, \( f_1 \). Such a normalization is adopted to better show how similar the frequency patterns in different RRd stars are. In all 3 variables of Fig. 2 the \( f_x \) mode is unambiguously detected. Its subharmonics are also clearly seen, although only in two variables both subharmonics are present. The Fourier peak at \( f_x \) is sometimes visibly broadened or split, indicating that the mode is not stationary. A detailed time-dependent analysis reveals that both the amplitude and the phase of \( f_x \) mode are strongly variable. This is in contrast to the properties of the radial modes, which are usually almost perfectly stable.

It is interesting to establish how often the \( f_x \) mode is excited in the RRd stars. Because this mode is always very weak, we have to use the best data available to get this estimate. Therefore, we limit our sample to only those stars for which EAP or PyKE photometry is available. Furthermore, we limit the sample to the classical RRd stars, the only subclass in which \( f_x \) mode is detected. Such restricted subsample consists of 57 variables. Among those objects, the \( f_x \) mode is clearly detected in 43 RRd variables, which is 75% of the sample. Subharmonics of \( f_x \) have lower amplitude and are even more difficult to detect. Yet, they are found in 34 RRd variables. This constitutes 60% of the RRd sample and 79% of the stars in which \( f_x \) is present.

We can restrict the sample even further by accepting only stars with EAP photometry. The EAP data are somewhat better than PyKE data, especially when the field is crowded. The new subsample is limited to only 40 RRd stars, but this is the highest quality subsample we can select. The incidence rate of detecting the \( f_x \) frequency increases now to 85% (34 stars) and of detecting its subharmonic to 68% (27 stars). Clearly, the better the data the higher the probability of finding the \( f_x \) mode. This indicates that we have probably not yet reached the true incidence rates and the numbers given above should be treated only as lower limits. We conclude that excitation of the \( f_x \) mode and its subharmonics is very common in the RRd stars. The mode appears in the majority and possibly in all of the classical RRd stars. In most cases, the mode is accompanied by at least one subharmonic.
4 Similarity of RRc and RRd stars

Secondary modes with period ratio of $P_x/P_1 = 0.60 - 0.64$ have been detected in nearly 300 RRc variables (Smolec et al., 2017b). On the Petersen diagram the RRc stars form three well-separated horizontal sequences, which are centered on $P_x/P_1 = 0.613, 0.632$ and 0.631 (Fig. 3). The RRd stars of our sample fit into this pattern very nicely. Vast majority of them are placed on the lowest of the three sequences. This is to be expected, because the lowest sequence is the most populated among the three. The properties of the $f_x$ modes are also the same in both groups of variables. In both RRc and RRd stars, the $f_x$ modes:

- have similar period ratio with the first radial overtone;
- are usually accompanied by subharmonics (half-integer frequencies) at $\sim 0.5 f_x$ and/or at $\sim 1.5 f_x$;
- are detected in almost every star for which high precision space photometry is available (see Moskalik et al. (2015) for discussion of the incidence rate in RRc stars);
- have amplitudes in the same range;
- are nonstationary, while dominant radial modes are usually almost perfectly stable;

The similarity of the $f_x$ mode in the RRd and the RRc variables is really striking. Clearly, in both subgroups of RR Lyrae pulsators we observe the same phenomenon. Consequently, for both RRd and RRc stars a common explanation has to be found for $f_x$. Because of the observed period ratio, this signal cannot be identified with any radial mode. Thus, the $f_x$ frequency must be associated with a nonradial mode of pulsation. A promising interpretation has recently been put forward by Dziembowski (2016). In the proposed scenario, the $f_x$ frequency corresponds to the first harmonic of the excited mode of $\ell = 8$ or $\ell = 9$.

Acknowledgments

This research was supported in part by the National Science Center, Poland, through grant No DEC-2015/17/B/ST9/03421 (PM). It was also supported by the NKFH grants K-115709, PD-121203 and PD-116175 (LM, EP, RSz), the János Bolyai Research Scholarship, the LP2014-17 (LM, EP) and LP2018-7 (LM, EP, RSz) Lendület Programs of the HAS and by the FWO-PAS Poland-Belgium scientific cooperation grant VS.091.16N (PM, KK).

References

Dziembowski, W. A. 2016, In High-Precision Studies of RR Lyrae Stars, Communications from the Konkoly Observatory, vol. 105, p. 23.
Jurcsik, J., Smitola, P., Hajdu, G., Sődor, Á., Nuspl, J., Kolenberg, K., Fürész, G., Móór, A., Kun, E., Pál, Á., Bakos, J., Kelemen, J., Kovács, T., Kriskovics, L., Sárncezky, K., Szalai, T., Szing, A., & Vida, K. 2015, ApJS, 219, 25.
Kurtz, D. W., Bowman, D. M., Ebo, S. J., Moskalik, P., Handberg, R., & Lund, M. N. 2016, MNRAS, 455, 1237.
Molnár, L., Szabó, R., Moskalik, P. A., Nemec, J. M., Guggenberger, E., Smolec, R., Poleski, R., Plachy, E., Kolenberg, K., & Kolláth, Z. 2015, MNRAS, 452, 4283.
Moskalik, P., Smolec, R., Kolenberg, K., Molnár, L., Kurtz, D. W., Szabó, R., Benkó, J. M., Nemec, J. M., Chudid, M., Guggenberger, E., Ngeow, C.-C., Jeon, Y.-B., Kopacki, G., & Kanbur, S. M. 2015, MNRAS, 447, 2348.
Nemec, J. M., Cohen, J. G., Ripepi, V., Dzerekas, A., Moskalik, P., Sesar, B., Chudid, M., & Bruntt, H. 2013, ApJ, 773, 181.
Nemec, J. M., Moskalik, P., Molnár, L., Plachy, E., Szabó, R., & Kolenberg, K. 2019, in preparation.
Netzel, H., Smolec, R., & Moskalik, P. 2015a, MNRAS, 447, 1173.
Netzel, H., Smolec, R., & Moskalik, P. 2015b, MNRAS, 453, 2022.
Plachy, E., Klagyivik, P., Molnár, L., & Szabó, R. 2017, In European Physical Journal Web of Conferences, vol. 160, p. 04010.
Plachy, E., Molnár, L., Bódí, A., Skarka, M., Juhász, Á. L., Sődor, Á., Klagyivik, P., & Szabó, R. 2018, In Revival of the Classical Pulsators: from Galactic Structure to Stellar Interior Diagnostics, Proceedings of the Polish Astronomical Society, vol. 6, p. 114.
Prudil, Z., Smolec, R., Skarka, M., & Netzel, H. 2017, MNRAS, 465, 4074.
Smolec, R., Soszyński, I., Udalski, A., Szymański, M. K., Pietrukowicz, P., Skowron, J., Koźłowski, S., Poleski, R., Skowron, D., Pietrzyński, G., Wyrzykowski, L., Ulaczyk, K., & Mróz, P. 2015, MNRAS, 447, 3756.
Smolec, R., Moskalik, P., Kaużyn, J., Pych, W., Różycka, M., & Thompson, I. B. 2017a, MNRAS, 467, 2349.
Smolec, R., Dziembowski, W. A., Moskalik, P., Netzel, H., Prudil, Z., Skarka, M., & Soszyński, I. 2017b, In European Physical Journal Web of Conferences, vol. 152, p. 06003.
Soszyński, I., Udalski, A., Szymański, M. K., Pietrukowicz, P., Mróz, P., Skowron, J., Koźłowski, S., Poleski, R., Skowron, D., Pietrzyński, G., Wyrzykowski, L., Ulaczyk, K., & Kubiać, M. 2014, Acta Astron., 64, 177.
Soszyński, I., Smolec, R., Dziembowski, W. A., Udalski, A., Szymański, M. K., Wyrzykowski, L., Ulaczyk, K., Poleski, R., Pietrukowicz, P., Koźłowski, S., Skowron, D., Skowron, J., Mróz, P., & Pawlak, M. 2016, MNRAS, 463, 1332.
Still, M., & Barclay, T. 2012, In PHOST “Physics of Oscillating Stars” conference