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The *K2* RR Lyrae Survey

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Abstract. In the framework of this project, the *K2 RR Lyrae Survey*, we proposed to observe thousands of RR Lyrae stars along the Ecliptic in *Kepler's K2* Mission. The high photometric precision and the 80-to-90-day continuous coverage enabled us to investigate in unprecedented detail the light variations of these variable stars which can trace galactic structure. The survey enabled us to conduct a thorough statistical study of RR Lyrae pulsation dynamics, including both old and more recently discovered dynamical phenomena such as resonances, non-radial modes, period doubling and the Blazhko effect. This talk described the *K2 RR Lyrae Survey*, and discussed the prospects of combining our endeavour with Gaia, LSST and other surveys in the context of studies of Galactic archeology.

Keywords. Stars: oscillations, stars: variables: RR Lyrae, surveys

1. Introduction

K2, the new mission for NASA's *Kepler* space telescope, was conceived and so named (Howell *et al.* 2014) after the failure of the spacecraft's second reaction wheel. During the new mission, the otherwise healthy instrument observes Ecliptic fields for 80–90 days with a precision which is close to that of the original *Kepler* mission. *K2* is a genuine community endeavour; without a central, pre-determined research plan, exoplanets, stellar (asteroseismic and other variable) sources, extragalactic objects, supernovæ, microlensing events, and even Solar System objects have been proposed by community members†. This opened up new possibilities in RR Lyrae research, too; for example, compared to the original *Kepler* field, where roughly 50 RR Lyrae stars were found (Benkő *et al.* 2014, Nemec *et al.* 2011, Moskalik *et al.* 2015), thousands of RR Lyrae stars could be observed with *K2*. Members of the *RR Lyrae and Cepheids Working Group* of the Kepler Asteroseismic Science Consortium initiated a large survey to ensure that as many RR Lyrae stars will be observed with *K2* as possible‡. This report discusses the present status of the undertaking, and its connections to other optical time-domain surveys.

2. The *K2* RR Lyrae Survey

Our group was successful in proposing RR Lyrae targets throughout the entire *K2* Mission. In the *K2 RR Lyrae Survey* RR Lyrae stars are measured in very different environments: the Galactic halo and halo sub-structures (Sagittarius-stream), the Galactic bulge, globular clusters (M 4, M 80), and even in external galaxies (e.g., the Leo IV dwarf spheroidal galaxy; Molnár *et al.* 2014). Fig. 1 gives an overview of the distribution of observed RR Lyrae stars on the sky, while Fig. 2 shows the number of observed or planned RR Lyrae stars during each *K2* campaign. We used all possible variable star

† https://keplerscience.arc.nasa.gov/k2-approved-programs.html
‡ The same strategy applies to Cepheids, both classical and Type II ones

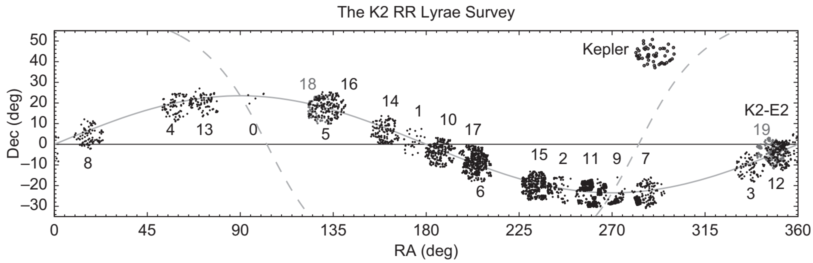

Figure 1. The footprint of the *K2 RR Lyrae Survey* along the Ecliptic. Approved and observed RR Lyrae targets are marked in the *K2* campaign fields. The original *Kepler* field is also plotted for reference.

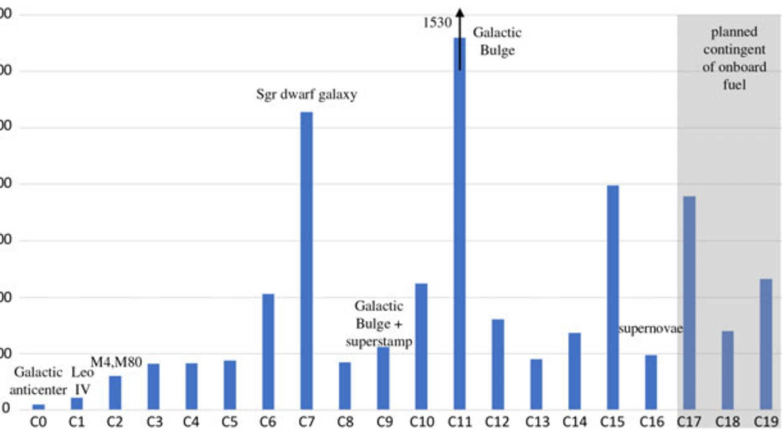

Figure 2. Statistics of the number of observed RR Lyrae targets in the *K2* campaigns. The execution of campaigns C17–C19 depends on the unpredictable amount (pressure) of the remaining onboard fuel. C17 was planned to start on 1 March, 2018.

catalogues for target selection, and relied heavily on the Catalina Sky Survey results (Drake *et al.* 2014). A more detailed description of the target selection process can be found in Plachy *et al.* (2016). By the end of the *K2* Mission we expect to have light-curves for at least 4300 RR Lyrae stars in the *Kepler* photometric band (Kp). The majority of the targets is being observed with a long cadence (30-min sampling), while a small fraction is being observed with a short cadence (1-min sampling) mode. As spacecraft correction manœuvres are necessary to keep it on-target, light variations of an instrumental source and correlated with the X,Y position of the target on the CCD chips are present in the data; special treatment of the light-curves is therefore needed, in particular for high-amplitude variables. To that end we developed the Extended Aperture Photometry method (Plachy *et al.* 2017) to deliver optimal results for our targets. In that way quasi-continuous light-curves covering 80–90 days are derived with high photometric precision, thus making the *K2 RR Lyrae Survey* unique. The main scientific motivation behind our efforts is a statistical study of the occurrence of dynamical phenomena such as the Blazhko effect (Blazhko 1907), period doubling (Szabó *et al.* 2010), non-radial modes (Szabó *et al.* 2014), etc. in RR Lyrae stars as a function of age, metallicity and Galactic position. Through these investigations we hope to achieve a better understanding of the dynamical phenomena occurring in RR Lyrae stars.

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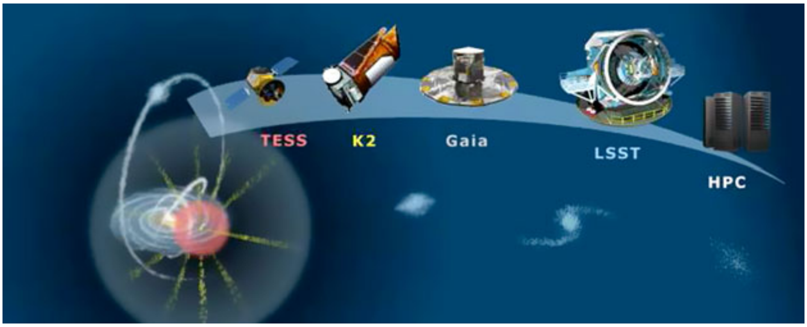

Figure 3. Concept of the *K2 RR Lyrae Survey*, and its synergies with other sky surveys. The schematic figure on the left demonstrates the reach of each survey (TESS, *K2*, Gaia) compared to the visible size of the Milky Way. *K2* Campaigns are denoted by 'pencil beams'; TESS's volume is shown by a small sphere, and Gaia's RR Lyrae horizon by a larger sphere. LSST will observe RR Lyrae stars well beyond the virial radius of the Galaxy. (*Credit: L. Molnár.*)

3. Synergies with Other Surveys

Our project complements other time-domain and synoptic sky surveys. NASA's TESS mission (Ricker *et al.* 2015), which was launched in 2018 April, will provide a (near) full-sky coverage, and will observe thousands of bright RR Lyrae stars. With TESS we will continue to study the RR Lyrae light-curves in detail, including subtle changes and low-amplitude variations due to dynamical effects. Although for some targets only 27 days of TESS observations will be available, it is possible to obtain one year of continuous coverage around the ecliptic pole. While *K2* observes along the ecliptic, the first two years of the nominal TESS mission will avoid ecliptic fields.

Gaia delivers accurate positions, proper motions and distances. TESS and Gaia will be complementary regarding RR Lyrae stars. Gaia parallaxes will be accurate to 10% at 10 kpc distance by the end of the mission, while DR2 will be useful out to 3–5 kpc. An RR Lyrae star at a distance of 10 kpc has an apparent magnitude of 15. For such stars, TESS will deliver photometry that is precise to 1–10% . It follows that all the Galactic RR Lyrae stars with good parallax measurements will be observed by TESS (although the resolution may hinder precise photometry at low Galactic latitudes).

LSST is the US astronomical ground-based flagship project of the next decade (Abell *et al.* 2009). It will provide deep images of the whole sky visible from Chile every three days in *ugrizy* filters. It will be the ultimate time-domain machine, expecting to observe 17 billion stars and 20 billion galaxies. It will provide a more complete and distant RR Lyrae sample. It expects to discover RR Lyrae stars out to 400 kpc in the outer halo, which is equivalent to the virial radius of our Galaxy, and in some cases out to 760 kpc (the distance of M 31). It should expand enormously the volume in which to search for outer-halo structures, and to use RR Lyrae signposts to learn about the history of our Galaxy and beyond (Oluseyi *et al.* 2012), presenting a petascale challenge in data handling.

OGLE is already delivering a very complete census of RR Lyrae stars, especially towards the Galactic Bulge and the Magellanic Clouds (e.g. Soszyński *et al.* 2014). It contains valuable data that complement the *K2 RR Lyrae Survey*, especially on a temporal base and in the number of variable stars observed.

PLATO will be ESA's next exoplanet-hunting photometric space mission, delivering very accurate light-curves that cover at least half the sky (Rauer *et al.* 2014). Fig. 3 shows the synergies and range of some of the future time-domain photometric and astrometric missions in the context of RR Lyrae stars and near-field cosmology.

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4. Summary

The *K2 RR Lyrae Survey* will be a treasure trove for pulsation and dynamical studies for many years to come. It contains representatives of all currently-known sub-types (RRab, RRc, RRd) plus modulated and non-modulated variants as well. Corrected ready-to-use RR Lyrae light-curves from the Survey will be made publicly available (Plachy *et al.* 2017), and from its website at http://www.konkoly.hu/KIK/data_en.html.

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