RR Lyraes and Cepheids: the Photometric Revolution from Space

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Continuous, high-precision photometry from space revolutionized many fields of stellar astrophysics, and that extends to the well-studied families of RR Lyrae and Cepheid variable stars as well. After the pioneering work of *MOST*, the *CoRoT* and *Kepler* missions released an avalanche of discoveries. We found signals that needed exquisite precision, such as an abundance of additional modes and granulation. Other discoveries, like period doubling, simply needed us to break away from the day-night cycle of the Earth. And the future holds more possibilities, with the *BRITE*, *K2*, and *Gaia* missions at full swing; *TESS*, taking physical shape; and *PLATO* securing mission adoption. Here I summarize some of these discoveries and the expectations from future missions.

1 From the Beginnings to the *Kepler* Era

Space-based photometry, in general, includes the majority of observations made by space telescopes, for a wide variety of reasons. One broad application focuses on the temporal variation of the measured fluxes, via time series photometry. The collection of time series data still has a wide usage, and in some cases, the nature of the flux variation itself takes a back seat to help solve different questions. A prominent example is the numerous extragalactic Cepheid light curves obtained with the Hubble Space Telescope that were used to pin down the value of H_0, the Hubble constant (Riess et al., 2016). Here we shall discuss missions that study stars via space-based, (quasi-)continuous time-series photometry, with emphasis on some particular subgroup of stars: the most classical of classical pulsators, RR Lyrae and Cepheid stars.

The missions. The story of space-based, continuous time-series photometry of stellar targets goes back a long way. One early prediction was that the eventual discovery of small, rocky planets around other stars through their transits would need photometric precision that is only achievable from space, to avoid the effects caused by the atmosphere (Borucki & Summers, 1984). These initial findings eventually developed into a proposed NASA mission called *FRESIP* (FRequency of Earth-size Inner Planets), but later renamed to *Kepler* (Borucki, 2016).

Meanwhile, other missions were also in development, to pursue slightly different goals. Photometric stability and extended observations that circumvent the night-day cycles of ground-based observations are a necessity not only for transits but for stellar astrophysics too. Solar-like oscillations, in particular, were long sought-after,

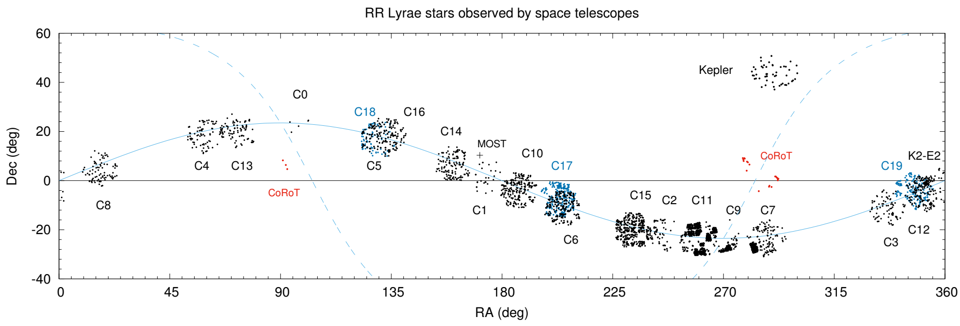

Fig. 1: RR Lyrae stars observed by various space missions. Black and blue points show targeted and proposed *Kepler* and *K2* observations, red points are *CoRoT* targets, and cross marks the single *MOST* target.

promising to extend the toolkit of helioseismology to stars other than the Sun. Even before the *FRESIP/Kepler* proposals, European researchers were already pursuing to fly an instrument dedicated to stellar activity and variability as a standalone mission or as a secondary payload (Roxburgh, 2006). These efforts culminated in two projects that left the Earth. One was *EVRIS* (Etude de la Variabilité, de la Rotation et des Intérieurs Stellaires), a 9 cm telescope that was supposed to observe bright stars on board the Russian *Mars–96* spacecraft en route to Mars (Baglin, 1991). Unfortunately, the mission never left low-Earth orbit and burned up in the atmosphere. The first successful European space-photometric mission came a decade later, with the launch of *CoRoT* (Convection, Rotation and planetary Transits), a 24 cm telescope in polar Earth orbit that executed a program shared between asteroseismology and exoplanets until 2012 (Baglin et al., 2002).

In the US and Canada, while successive *Kepler* proposals got rejected, other photometric missions emerged. The Canadian *MOST* (Microvariability and Oscillations of Stars), a small satellite with a 15 cm telescope was launched in 2003 to execute a one-year asteroseismic mission (Walker et al., 2003). The sturdy satellite is still functional at the time of writing, 14 years later. In the US, the malfunction of the main instrument of the *WIRE* (Wide-field Infrared Explorer) space telescope in 1999 led to the unexpected possibility to use the 5 cm optical star tracker telescope for asteroseismology for several years (Buzasi, 2002). Further contributions to the field include the *SMEI* (Solar Mass Ejection Imager) all-sky camera on the *Coriolis* satellite that observed between 2003–11 (Hick et al., 2007), and the High-Resolution Imager on the *Deep Impact* space probe that was utilized to measure transiting exoplanets in 2008 (Ballard et al., 2011; Christiansen et al., 2011).

And then *Kepler* was launched in 2009. But let us first summarize the discoveries made by the missions before that.

The first discoveries. The missions until *Kepler* were limited to a few weeks of observations (extending to 150 d with the long runs of *CoRoT*), and to relatively bright targets. Nevertheless, the combination of stable, precision photometry with extended coverage, led to discoveries in RR Lyrae and Cepheid stars. While these stars have been studied extensively for more than a century now, they still hold

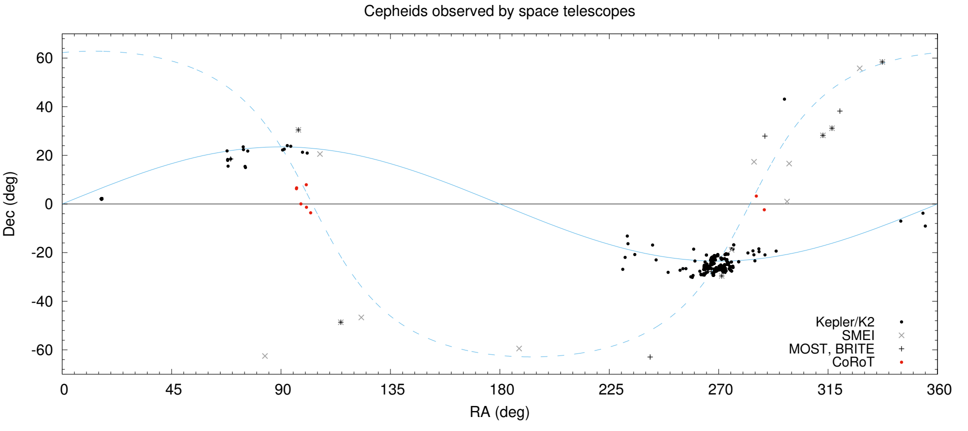

Fig. 2: Cepheid stars observed by various space missions. Notation is similar to Fig. 1. The only target missing from this map is Polaris.

mysteries and convey valuable information for both stellar astrophysics and near-field cosmology. The first RR Lyrae, AQ Leo, a representative of the RRd (double-mode) subclass was observed from space by *MOST*. Gruberbauer et al. (2007) discovered low-amplitude additional signals in the star that were attributed to non-radial modes, the first clear detection of such additional modes in RR Lyrae stars.

In parallel, Bruntt et al. (2008) combined the extended, but low-precision *SMEI* data with the shorter, but much more dense and precise *WIRE* observations, and with additional radial-velocity data for the Cepheid star Polaris (α UMi). The observations showed that the pulsation is, in fact, not switching off in the star, as it was assumed before, but instead its amplitude started to increase after reaching minimum in the years around 2000. They also detected some small power excess in the low-frequency end of the *WIRE* data that they tentatively interpreted as granulation noise in the star.

Interestingly, the pioneering observations were not followed up with other targets by those missions. Instead, the thread was picked up by the *CoRoT* mission that started to accumulate longer light curves for multiple objects. With 143 days of continuous observations collected for the short-period, fundamental-mode star V1127 Aql, we had the best picture of the Blazhko effect (Chadid et al., 2010). The star also showed various additional modes, whose origins were quite mysterious at the time. Recently, similar signals were found in multiple short-period RRab stars among the OGLE Bulge stars (Prudil et al., 2017).

Variations or multiple periodicities in the Blazhko effect, the amplitude and phase modulation of the pulsation, were long suspected (see, e.g., Sódor et al., 2006). Another RR Lyrae, CoRoT 105288363, showed us that consecutive Blazhko cycles can, indeed, have different shapes and amplitudes (Guggenberger et al., 2011).

2 Enter *Kepler*

While these missions provided a new look into variable stars, the field has been revolutionised by the *Kepler* mission. A large, 95 cm aperture telescope, with a huge field-of-view spanning about 100 square degrees, in an Earth-trailing orbit far from the planet, and an observing mode that provided multi-year coverage, made *Kepler* vastly superior to its predecessors. And the mission was put to good use. It gathered 4 years of continuous observations in a very wide brightness range that will not be surpassed for many years to come. But then, in 2013, the telescope was left with one reaction wheel short to continue its mission. Soon an ingenious plan called the *K2* mission was devised to reorient *Kepler* towards the Ecliptic to follow a step-and-stare approach and to look at a new field of view at about every three months (Howell et al., 2014). It is now clear that this massive hack to save a crippled space telescope has evolved into a hugely successful and versatile astrophysical mission.

The power of continuous data. The first *Kepler* light curves of RR Lyrae stars were simply shocking: multiple stars, including RR Lyr itself, showed clearly alternating cycle amplitudes in the pulsation (Szabó et al., 2010; Kolenberg et al., 2011). These variations, called period doubling (since the repeating pattern is now two cycles long) should have been clearly detectable from the ground. That they were not can be traced back to a simple cause: the typical half-day-long pulsation periods of these stars make it virtually impossible to observe consecutive cycles with the same telescope.

Nevertheless, period doubling was not the only new signal found in RR Lyraes. The *Kepler* data revealed additional frequency components below the millimagnitude level in fundamental-mode stars (Benkő et al., 2010, 2014; Molnár et al., 2012). While most of these signals can be grouped into three main categories (near the expected ranges of first and second overtones, plus the half-integer peaks of period doubling), they spread out in the Petersen-diagram, indicating that many of them must be non-radial modes (Molnár et al., 2017a). Interestingly, all of these modes were identified in modulated stars, while all non-Blazhko RRab stars appeared to be monoperiodic, down to sub-millimag amplitudes, suggesting some connection between the two phenomena. However, it is not always easy to separate modulated and non-modulated stars from each other. While the presence of amplitude modulation is obvious in most *Kepler* Blazhko targets, some stars needed careful processing and analysis to detect small changes in the light curves (Nemec et al., 2011; Benkő & Szabó, 2015). In these cases, phase variation and changes in the relative Fourier coefficients are better indicators for modulation than the pulsation amplitude itself. The light curves also revealed that the majority of modulated stars have either multiperiodic or changing modulation cycles (Benkő et al., 2014). Plachy et al. (2014) investigated if the modulation could be chaotic, but even the 4-year-long *Kepler* data covered too few modulation cycles for a conclusive answer.

Analysis of the four known RRc stars led to similar discoveries. All four stars show various additional modes, including the so-called $f_{\rm x}$ mode or 0.61-mode that has been detected in a large number of RRc and RRd stars, both from space and from the ground (Moskalik et al., 2015; Netzel et al., 2015a). The first additional frequencies found in AQ Leo also fit into this pattern. Similar signals were found in overtone Cepheids as well, highlighting the peculiarity of these modes and their connection to the first overtone (Moskalik & Kołaczkowski, 2009). Yet another group of modes in RRc stars fall below the (expected) frequency of the fundamental mode (Netzel et al., 2015b).

The *Kepler* field-of-view included only a single Cepheid, V1154 Cyg, but 4 years of continuous observations revealed even the smallest details about this fundamental-mode star. While the pulsation period was found to be stable in the long term, fluctuations in the cycle shape and length were clearly detectable (Szabó et al., 2011; Derekas et al., 2012). Moreover, a low-level modulation is also present in the pulsation, on top of the fluctuations. Then a further signal was found, hiding behind the pulsation: the first clear detection of granulation noise in a Cepheid. It was even more intriguing that solar-like oscillations were not seen in the star, suggesting that they are either strongly suppressed, or absent altogether (Derekas et al., 2017).

Advances in understanding. These discoveries have presented new challenges to our understanding of stellar pulsation. Model calculations soon revealed that period doubling is caused by non-linear interactions between pulsation modes. The 9th radial overtone may become trapped between the surface and the partial ionization zone and turn into a so-called strange mode. This mode then can lock into a strong resonance with the fundamental mode with a period ratio of $P_0/P_9 = 9/2$ (Kolláth et al., 2011). When that happens, we are not simply observing two modes anymore, but instead, the fundamental mode bifurcates into a period-doubled limit cycle, repeating two pulsation cycles with different amplitudes. These resonances could potentially lead to modulation in some calculations, suggesting that mode resonances and interactions could be behind the Blazhko effect (Buchler & Kolláth, 2011). We emphasize here that the mode resonance hypothesis is currently the only model that is not in contradiction with the observations.

Further calculations revealed that the period-doubled fundamental mode can become unstable against the first overtone too, outside the classical RRd regime. The appearance of a low-amplitude first overtone in RRab stars could explain at least some observations of additional modes (Molnár et al., 2012; Kolláth, 2016). Detailed analysis of these three-mode hydrodynamic models showed that they can become chaotic, an unexpected result from stellar models with relatively low mode growth rates (Plachy et al., 2013).

The presence of other additional modes has been also intriguing, especially the abundance of f_x-type modes in overtone stars. There is no plausible explanation in our current framework for their appearance. However, Dziembowski (2016) suggests that we actually observed a harmonic of non-radial $\ell = 8, 9$ modes (also $\ell = 7$ for Cepheids), and the intrinsic pulsation frequency at $f_\mathrm{x}/2$ is observed, in the majority of cases, with smaller amplitudes due to cancellation effects.

It has been long known that the shape of RR Lyrae light curves is affected by their chemical composition. The photometric metallicity relation has been calibrated for the *Kepler* passband based on high-resolution spectra (Nemec et al., 2013). This semi-empirical relation is accurate to about ± 0.1 dex in [Fe/H], except for stars with the strongest modulation. However, it is important to keep in mind that Fourier parameters can change drastically in some Blazhko stars, which could affect the derived photometric metallicities too (Bódi et al., these proceedings).

3 After *Kepler*

The *Kepler* mission has transformed stellar astrophysics, but it was nevertheless limited to a single patch of sky, with a limited stellar sample. Therefore, other missions were utilized in new ways, either by mining their archives or by proposing new observations. The *CoRoT* light curves also revealed period doubling and additional modes in multiple RR Lyrae stars (Szabó et al., 2014; Benkő et al., 2016). No significant period fluctuations were found in the Cepheids observed by the mission, but one double-mode star exhibited the same, low-frequency additional mode that was detected in RRc stars too (Poretti et al., 2014, 2015).

Many Cepheids are bright enough to be detected even by the smallest-aperture missions. The *BRITE* fleet of satellites observed multiple targets, but unfortunately only those gathered with the red-filter satellites turned out to be useful. Possible detection of modulation and additional modes in some targets were reported by Smolec et al. (2017). The venerable *MOST* satellite also observed some Cepheids. It detected slight differences between the stability of pulsation in fundamental-mode and overtone stars as well as period doubling in the peculiar, modulated Cepheid, V473 Lyr (Evans et al., 2015; Molnár et al., 2017b).

Meanwhile, the saga of *Kepler* itself was far from over. *K2*, the new mission, opened up many new fields for observation, from the halo to the Sagittarius stream and the Galactic Bulge. Although campaigns are limited to 70–80 days, the fields amassed thousands of RR Lyrae and hundreds of Cepheid observations (Figs 1–2, Plachy et al. 2016). These included lesser-studied subtypes like RRd stars, including a modulated one, as well as variables in globular clusters and nearby galaxies, but the processing of the light curves is still ongoing (see, e.g., Molnár et al., 2015; Kurtz et al., 2016; Kuehn et al., 2017; Plachy et al., 2017a). Type II Cepheids of the W Vir subclass showed clear cycle-to-cycle variations (Plachy et al., 2017b).

The *K2* goldmine will serve us with wonderful discoveries for years to come, but we cannot rest: new missions will provide even more data. The European *Gaia* spacecraft does not fit into our description of continuous photometry, but it is nevertheless collecting sparse observations for the entire sky. Many new variable stars are expected to come from the photometry and the extremely precise astrometry will undoubtedly mean another revolution for stellar astronomy (Clementini et al., 2016). And then, from 2018, the American *TESS* mission will produce proper light curves for almost the whole sky – although not quite to the same depth as *Kepler* and *Gaia* may reach (Ricker et al., 2014). And with all these missions at full swing, the photometric revolution may enter a new phase, where synergies between missions, such as combination of photometry with astrometry, or revisits by successive missions and spectroscopic follow-up will become just as important as the light curves themselves.

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