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# Period doubling in *Kepler* RR Lyrae stars

R. Szabó, Z. Kolláth, L. Molnár, K. Kolenberg, D. W. Kurtz and WG#13 members

**Abstract** The origin of the conspicuous amplitude and phase modulation of the RR Lyrae pulsation – known as the Blazhko effect – is still a mystery after more than 100 years of its discovery. With the help of the Kepler space telescope we have revealed a new and unexpected phenomenon: period doubling in RR Lyr – the eponym and prototype of its class – as well as in other Kepler Blazhko RR Lyrae stars. We have found that period doubling is directly connected to the Blazhko modulation. Furthermore, with hydrodynamic model calculations we have succeeded in reproducing the period doubling and proved that the root cause of this effect is a high order resonance (9:2) between the fundamental mode and the 9<sup>th</sup> radial overtone, which is a strange mode. We discuss the implications of these recent findings on our understanding of the century-old Blazhko problem.

## 1 Period doubling in pulsating variable stars

Period doubling (PD) bifurcation is a well-known dynamical effect. In the parlance of dynamical systems a new limit cycle emerges from an existing limit cycle with a period twice as long as the old one. In the case of a pulsating star we observe alternating cycles in the time domain, in the frequency domain PD manifests itself as half-integer frequencies (the  $f/2$  subharmonic and its odd integer multiples). In stellar astrophysics the heyday of period doubling occurred more than two decades

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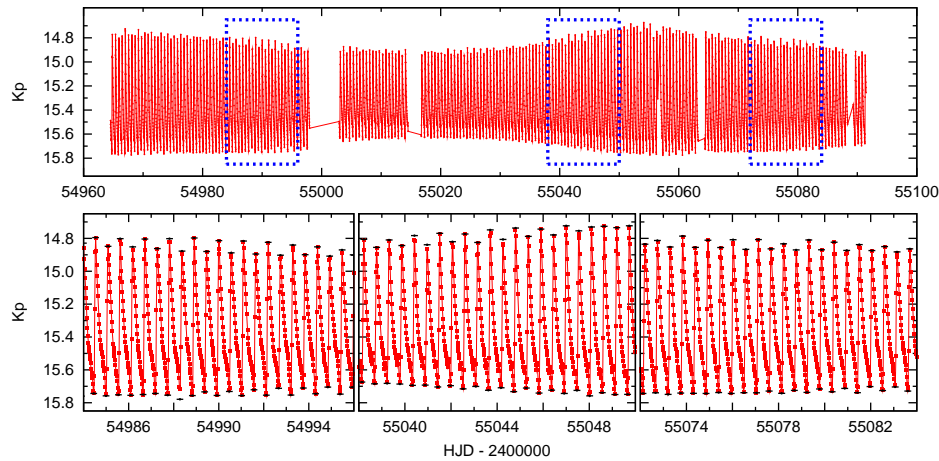
R. Szabó, Z. Kolláth, L. Molnár  
Konkoly Observatory of the Hungarian Academy of Sciences, H-1121 Budapest, Konkoly Thege  
Miklós út 15-17., Hungary, e-mail: rszabo@konkoly.hu

K. Kolenberg  
Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge MA 02138 USA  
Instituut voor Sterrenkunde, Celestijnenlaan 200D, 3001 Heverlee, Belgium

D. Kurtz  
Jeremiah Horrocks Institute, University of Central Lancashire, Preston PR1 2HE, UK

ago when it was discovered in one-dimensional hydrodynamic models of Cepheids [12], [13], [5] and Type II Cepheids [4], [10] by J. R. Buchler and his collaborators. The cause of PD was found to be a low-order resonance between the fundamental mode and a low radial overtone. In the hydrodynamic model calculations mentioned usually the 3:2 or the 5:2 resonances were acting [12]. One of the main reasons to study the phenomenon is that a star can go from regular pulsations to chaos through a PD bifurcation cascade (known as a Feigenbaum cascade). Buchler et al. [2] proved that the characteristic light variations of RV Tauri stars, which show alternating deep and shallow minima, can be interpreted as a result of deterministic chaos of low dimension.

Even a Mira star, (R Cyg), was observed to show this phenomenon [7], and quite recently BL Herculis stars with PD were discovered in the OGLE-III data [16], confirming earlier theoretical predictions. RR Lyr stars, on the other hand, have been thought to pulsate quite regularly without low order resonances. This belief was based on decades-long observations and hydrodynamic models, with the only disturbing fact being the perplexing presence of amplitude and phase modulation (known as the Blazhko effect) in an increasing number of these stars. Therefore, the discovery of PD in the *Kepler* data was a surprise, forcing us to overhaul existing models and theories of RR Lyr pulsation.



**Fig. 1 Top:** A *Kepler* light curve of the Blazhko star V808 Cygni (KIC 4484128) in quarters Q1 and Q2 showing 133 d of observations. Gaps in the data are due to safe mode events of the spacecraft and planned data download periods. The Blazhko cycle is around 90 d. **Bottom:** Magnification of three 12-d sections of the light curve highlighted by rectangles in the upper panel showing the characteristic period doubling behaviour. Polynomial fitting of the maxima and minima are also plotted for better visibility.

## 2 Discovery of period doubling in RR Lyrae stars

*Kepler* is a NASA Discovery mission to find Earth-like planets in the habitable zones of solar-like stars using the transit method [1]. It provides incredibly high-precision, quasi-continuous observations of a  $115 \text{ deg}^2$  swath of the sky. The currently known sample of RR Lyr stars in the *Kepler* field consists of some 40 members, the majority of which are RRab stars, and half of which show Blazhko modulation. The field contains RR Lyrae itself, and despite of its brightness, hence heavy saturation on the CCD, we managed to get extremely precise photometry for this important target with *Kepler* [18].

We found PD in the first release of data for RR Lyrae itself (KIC 7198959) [8], then subsequently in two other *Kepler* Blazhko RR Lyr stars: V808 Cyg (Fig.1) and V355 Lyr (KIC 4484128 and KIC 7505345, respectively), both of which are much fainter than RR Lyrae itself [18]. The strength of the PD is variable; at the strongest phase the difference between subsequent maxima can be as large as 0.1 magnitude in RR Lyrae. We found that PD is stronger in certain Blazhko phases. There are hints in another four modulated stars of half-integer frequencies [18], which means that at least half of the modulated RRab stars show PD as well. After monitoring our RR Lyr star sample with *Kepler* for years we expect to see PD in more stars.

Interestingly, non-Blazhko stars do not show PD down to the precision of the *Kepler* measurements [18], [14]. Despite close monitoring of RR Lyr stars it was not possible to detect PD previously, partly because the consecutive cycles rarely can be observed from one geographical location, while the usually low amplitude of the phenomenon and its non-stationary nature also add to the difficulties.

## 3 Period doubling and the Blazhko effect

The PD phenomenon is intimately connected to the Blazhko cycle. Therefore by studying it, we may gain new insights into the intricacies of the Blazhko effect. Importantly, we succeeded in reproducing PD in hydrodynamic models [18], and unambiguously traced its cause back to a 9:2 resonance between the fundamental mode and the 9<sup>th</sup> overtone, which is a strange mode [9], [11].

Based on resonant amplitude equations accounting for the 9:2 resonance between the fundamental mode and the 9<sup>th</sup> (strange) overtone, Buchler & Kolláth [3] have found that this resonance may give rise not to only period doubled solutions, but irregularly (chaotic) modulated solutions as well. This is important, since recent observations proved that the Blazhko effect is not a clockwork precision process: both long-term and cycle-to-cycle variations are frequently found in the modulation (see, e.g., [6]). Further investigations should clarify whether these amplitude equations can describe state-of-the-art hydrodynamic model calculations and, ultimately, real RR Lyr stars. If that turns out to be the case, then this elegant prediction may be the long-sought explanation of the mysterious Blazhko effect. Additional complicating effects can also contribute to the whole picture, like resonances involving nonradial

modes [15], three-mode resonances [11] and magneto-hydrodynamic dynamo-like processes [17]. Beyond doubt, the discovery of period doubling in the *Kepler* data has opened a whole new avenue in the research of RR Lyr stars.

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