László Molnár

Dynamical phenomena in RR Lyrae stars

Theses of dissertation

Supervisor: Prof. Zoltán Kolláth
DSc, research advisor
Konkoly Observatory, MTA CSFK
Institute of Mathematics and Physics,
University of West Hungary

Scientific advisors:
Dr. Róbert Szabó, PhD, senior research fellow
Dr. László Szabados, DSc, research advisor
Konkoly Observatory, MTA CSFK

Eötvös Loránd University, Faculty of Science
PhD School of Physics – PhD Program in Particle Physics and Astronomy
Head of School: Prof. László Palla
Head of Program: Prof. Ferenc Csikor

2013

1 Background

RR Lyrae stars are well-known, important celestial objects in the field of astrophysics. They represent one of the first steps of the cosmic distance ladder as distance indicators and can be used to determine the distances of globular clusters and nearby galaxies. Moreover, being population II objects they trace old stellar populations and can be used to map galactic halos.

Until recently, pulsations of RR Lyrae stars were considered to be fairly simple. According to the classical paradigm, these stars pulsate in a radial mode, either in the fundamental mode, or in the first overtone, or both. The most important issue in this picture has been the Blazhko effect: the modulation or cyclic variation of the pulsation amplitude and period in about half of the fundamental-mode and at in least ten percent of the first-overtone stars. Several hypotheses were put forward to explain this phenomenon but none of them has been able to provide satisfactory results so far. Some concepts propose geometric effects, tying the modulation to the rotation of the star; others consider physical effects like changes in the stellar structure or interaction of pulsation modes to explain the modulation.

2 Scientific goals

At the start of my PhD work, we initially planned to investigate the dynamics, interactions and appearances of processes that happen on different timescales in pulsating variables, such as pulsation, modulation, mode interaction and entering or leaving the instability strip. As a first step, I started a detailed investigation on Stothers' convective-cycle model, a new proposal for the Blazhko effect.

The *Kepler* space telescope was launched around the same time. Several RR Lyrae stars lie in the *Kepler* field of view and the very first observations revealed new phenomena: period doubling and the existence of very-low-amplitude additional modes in the stars. These discoveries led me to focus my research on the questions of mode interaction and modulation. Beside the analysis and description of the new phenomena I also used hydrodynamic models to understand their origins.

3 Methods

I used both observational data and model calculations in my research. Models were computed with the Florida–Budapest hydrodynamic code. The code calculates one-dimensional, turbulent convective stellar models. It can derive the linear oscillation periods and mode growth rates of the equilibrium models, nonlinearly iterate the perturbed models in time and converge them into a limit cycle solution and determine their stability. I compared the hydrodynamic results to amplitude equation calculations: this method allows for much faster calculation of mode amplitude variations but the values of the coefficients have to be determined first. If hydrodynamic models were calculated, amplitude equations can be fitted to them. Once the coefficients have been determined, the parameter space can be explored much faster this way.

I mainly used the photometric measurements of the *Kepler* space telescope for data analysis. *Kepler* delivered micromagnitude-level precision that exceeded any previous measurements while maintained 90% or higher duty cycle. The telescope was able to follow up to 170 000 stars among which about 40 RR Lyrae stars are known.

I also used ground-based measurements beside the space-based ones: I compiled observations of V473 Lyrae from several sources into a homogeneous data set that spans several decades.

4 Theses

Analysis of the Stothers model

1. The convective cycle model connects the Blazhko effect to changes in the convective envelope of the star. According to the proposal, a periodically strengthening and weakening turbulent magnetic field changes the properties of the convective layer sufficiently to cause observable

changes in the pulsations of the star. However, I showed that drastic changes are required in the convective parameters of the hydrodynamic models to achieve the level of change in linear periods as expected from observational data.

2. I investigated the efficiency of the mechanism on different time scales using nonlinear hydrodynamic models and amplitude equations. Based on my results, because of the small growth rate of the pulsation mode, convective cycles are capable to generate large amplitude variations only on modulation periods longer than about 150 days. Hence the mechanism is not able to explain the strong and fast (few weeks long) Blazhko effect observed in many stars.

Models of period doubling

3. I detected period doubling both in radiative and convective RR Lyrae models. The phenomenon may undergo additional bifurcations, I identified four- and eight-fundamental-period-long limit cycles too. Period doubling only appeared when I tuned the convective parameters of the models away from their classical values and towards the radiative limit. RR Lyrae stars observed by *Kepler* show the same phenomenon, hence the models were vital in the understanding of the measurements.

Nonlinear asteroseismology

4. I identified sections in the short cadence *Kepler* data of RR Lyrae where a pattern of six different-amplitude pulsation cycles repeated quasi-regularly instead of simple period doubling. The phenomenon is caused by the combination of period doubling and the beating between the the fundamental mode and the first overtone whose frequency ratio is close to 3:4. The intermittent nature of the phenomenon suggests that amplitudes and perhaps the phases of not only the fundamental mode but the first overtone change over time as well.

5. I confirmed that RR Lyrae is very likely to have three different excited radial modes: the fundamental mode, the first overtone and the ninth overtone which is responsible for period doubling. Hydrodynamic models that fall into the classical RRab (fundamental-mode) regin but show period doubling and a very-low-amplitude first overtone and the *Kepler* observations of RR Lyae display a very high degree of similarity. This makes RR Lyrae the first member of its own class where three radial modes have been identified.

Analysis of V473 Lyrae

6. I demonstrated that not only the amplitude but the phase of the pulsation of the Cepheid V473 Lyrae is modulated with a period of 1205 ± 3 days. However, neither the amplitude nor the phase varies strictly regularly and the phase displays few-modulation-cycles long additional variations too. According to the results, the properties of light variations are analogous to the Blazhko effect.

5 Conclusions

The scientific goals of my PhD work were to better understand the time scales and dynamical phenomena related to stellar pulsations. These goals were successfully achieved.

The seemingly diverse results can be connected to a central theme. The new phenomena identified in RR Lyrae stars, the period doubling and the additional modes revealed that important dynamical processes happen in the pulsation of these stars. The discoveries led to a new proposal for the Blazhko effect. The mode resonance model invokes the interaction of the excited modes in the star to explain the modulation. My results, including the critique of the Stothers model and the analysis of period doubling and additional modes, confirm that the mode resonance is a valid explanation for the Blazhko effect – in fact it is the only model that is not in contradiction with the observations.

The detection of three radial modes in RR Lyrae foreshadows the application of nonlinear asteroseismology, the direct comparison of amplitudes and frequencies of modes excited in stars and in hydrodynamic models.

The mode resonance model can be extended to Cepheid stars too. Although their evolution is very different, the pulsation of RR Lyrae and Cepheid stars show many similarities. Hence amplitude modulation by mode interaction is a plausible explanation for the few modulated Cepheids, including V473 Lyrae, and it can be modeled with the same tools I applied to RR Lyrae stars.

6 Fundamental publications of the theses

- Molnár, L; Kolláth, Z.: *Linear period dependencies from free parameters in RR Lyrae models*, 2010, JPhCS, 218, 012027

- Kolláth, Z., Molnár, L., Szabó, R.: *Period doubling bifurcation and high-order resonances in RR Lyrae hydrodynamical models*, 2011, MNRAS, 414, 1111

- Molnár, L., Kolláth, Z., Szabó, R.: *Can turbulent convective variations drive the Blazhko cycle? Dynamical investigation of the Stothers idea*, 2012, MNRAS, 424, 31

- Molnár, L.; Kolláth, Z.; Szabó, R.; Bryson, S.; Kolenberg, K., Mullally, F., Thompson, S. E.: *Nonlinear Asteroseismology of RR Lyrae*, 2012, ApJ, 757, L13

- Molnár, L.; Kolláth, Z.; Szabó, R.; Plachy, E.: *New results in RR Lyrae modeling: convective cycles, additional modes and more*, 2012, AN, 333, 950

- Molnár, L.; Szabados, L.; Dukes, R. J., Jr.; Győrffy, Á.; Szabó, R.: *Analysis of the possible Blazhko-effect Cepheid V473 Lyrae*, 2013, AN, accepted

7 Other related publications

- Molnár, L., Benkő, J. M., Szabó, R., Kolláth, Z.: *Kepler RR Lyrae stars: beyond period doubling* 2013, IAUS, accepted

- Plachy, E.; Kolláth, Z.; Molnár, L.: *Low-dimensional chaos in RR Lyrae models*, 2013, MNRAS, 433, 3590

- Szabó, R.; Kolláth, Z.; Molnár, L. és mtsai: *Does Kepler unveil the mystery of the Blazhko effect? First detection of period doubling in Kepler Blazhko RR Lyrae stars*, 2010, MNRAS, 409, 1244

- Molnár, L.; Kolláth, Z.; Szabó, R.: *Uncovering hidden modes in RR Lyrae stars*, Proceedings of the "20th Stellar Pulsation Conference Series", 2013, ASSP, 31, 185

- Jurcsik, J.; Sódor, Á.; Szeidl, B.; Hurta, Zs.; Váradi, M.; Posztobányi, K.; Vida, K.; Hajdu, G.; Kõvári, Zs.; Nagy, I.; Molnár, L.; Belucz, B.: *The Konkoly Blazhko Survey: Is light-curve modulation a common property of RRab stars?*, 2009, MNRAS, 400, 1006