Project closing report, K-068626

Unresolved problems of the modulation properties of pulsating variable stars

The scientific results of the team members have been published in 21 high impact factor scientific papers, in 8 other communications and in 10 conference poster/talk presentations. There are already 134 independent citations of these articles in the literature. Without a complete list, the most successful papers of the project with the number of the independent citations are listed bellow.

Jurcsik, J.; Sódor, Á., Szeidl, B. et al, 2009, MNRAS, 400, 1006; *The Konkoly Blazhko Survey: is light-curve modulation a common property of RRab stars?* CIT:**18**

Jurcsik, J., Sódor, Á., Hurta, Zs. et al., 2008, MNRAS 391, 164; *An extensive photometric study of the Blazhko RRLyrae star MWLyr - I. Light-curve solution* CIT:**17**

Hurta, Zs.; Jurcsik, J.; Szeidl, B.; Sódor, Á. 2008, AJ, 135, 957; *First Quintuplet Frequency Solution of a Blazhko Variable: Light Curve Analysis of RV UMa* CIT:**12**

Jurcsik, J.; Hurta, Zs.; Sódor, Á. et al., 2009, MNRAS, 397, 350; *An extensive photometric study of the Blazhko RR Lyrae star DM Cyg* CIT:**11**

Szeidl, B.; Jurcsik, J., 2009, CoAst., 160, 17; *The frequency spectrum of periodically modulated sinusoidal oscillation* CIT:**9**

Kolláth, Z.; Oláh, K. 2009, A&A, 501, 695; *Multiple and changing cycles of active stars. I. Methods of analysis and application to the solar cycles* CIT:**8**

Oláh, K.; Kolláth, Z.; Granzer, T. et al., 2009, A&A, 501, 703O; *Multiple and changing cycles of active stars. II. Results* CIT:**8**

Jurcsik, J.; Sódor, Á.; Szeidl, B. et al., 2009, MNRAS, 393, 1553; *An extensive photometric study of the Blazhko RR Lyrae star MW Lyr - II. Changes in the physical parameters* CIT:**7**

Sódor, Á.; Jurcsik, J.; Szeidl, B. 2009, MNRAS, 394, 261; *A new method for determining physical parameters of fundamental mode RR Lyrae stars from multicolour light curves* CIT:**6**

Szeidl, B.; Hurta, Zs.; Jurcsik, J.; Clement, C., Lovas, M. 2011, MNRAS, 411, 1763; *Long-term photometric monitoring of Messier 5 variables - I. Period changes of RR Lyrae stars* CIT:**5**

Scientific results published in high impact factor journals and in other periodicals:

- Corrected archive photometric data of RV UMa, an RRab star showing regular large-amplitude light-curve modulation have been presented with additional, previously unpublished measurements. The re-analysis of the combination of the corrected and supplemented observations has led to the discovery that the appropriate mathematical model of the light curve is, in fact, a quintuplet frequency solution, rather than a triplet. No quintuplet structure was detected in any of the observations previously. This finding has crucial importance in the interpretation of the Blazhko phenomenon, as a triplet (doublet) is the preferred structure in resonance models, while magnetic models predict quintuplet structure.

  Period changes of both the pulsation and modulation light variations of RV UMa have

been detected based on its century-long photometric observations. An overall anti-correlation between the pulsation and modulation period changes can be defined by $\mathrm{d}P_{\mathrm{Bl}}/\mathrm{d}P_0 = -8.6 \times 10^4$ gradient, i.e., the modulation period of RV UMa is longer if the pulsation period is shorter. Between 1946 and 1975, the pulsation and modulation periods showed, however, parallel changes, which points to that there is no strict relation between the changes in the periods of the pulsation and modulation.

- We presented a new method for determining physical parameters of RRab variables exclusively from multicolour light curves. This method is the only possibility today to derive the variations of the physical parameters of a Blazhko star throughout the modulation cycle. The Inverse Photometric Method (IPM), using a nonlinear least squares algorithm, searches for the effective temperature (T_{eff}) and pulsational velocity (V_{p}) curves and other physical parameters that best fit the observed light curves, utilising synthetic colours and bolometric corrections from static atmosphere models. The T_{eff} and V_{p} curves are initially derived from empirical relations then they are varied by the fitting algorithm. The method yields the variations and the absolute values of the radius, the effective temperature, the visual brightness, and the luminosity of individual objects. The method has been tested on 9 RRab stars subjected to Baade-Wesselink analyses earlier by several authors. The physical parameters derived by our method using only the light curve data of these stars are well within their possible ranges defined by direct Baade-Wesselink and other techniques. A new empirical relation between the I_{C} magnitude and the pulsational velocity has also been presented, which allows to construct the V_{p} curve of an RRab star purely from photometric observations to an accuracy of about 3.5 km/s.

- We have obtained the most extensive and most accurate multicolour photometric data of a large modulation amplitude Blazhko variable MW Lyrae during the 2006–2007 observing seasons. The data within each 1/20 phase bin of the modulation period ($P_{\mathrm{m}} = 16.55\,\mathrm{d}$) cover the entire light cycle of the primary pulsation period ($P_0 = 0.39767\,\mathrm{d}$), allowing a very rigorous and complete analysis. Besides the main modulation frequency, (f_{m}), sidelobe modulation frequencies around the pulsation frequency and its harmonics appear at $\pm 2f_{\mathrm{m}}$, $\pm 4f_{\mathrm{m}}$ and $\pm 12.5f_{\mathrm{m}}$ separations as well. Residual signals in the pre-whitened light curve larger than the observational noise appear at the minimum-rising branch-maximum phase of the pulsation, which most probably arise from some stochastic/chaotic behaviour of the pulsation/modulation. A new phenomenological description of the light-curve variation is defined that separates the amplitude and phase (period) modulations utilizing the phase coherency of the lower order Fourier phases.

- The analysis of the multicolour photometric observations of MW Lyr utilizing the IP method, have been revealed for the first time how the mean global physical parameters of the star vary during the Blazhko cycle. About 1–2 percent changes in the mean radius, luminosity and surface effective temperature have been detected. We interpret the phase modulation of the pulsation to be a consequence of period changes. Its magnitude corresponds exactly what one expects from the detected changes of the mean radius assuming that the pulsation constant remains the same during the modulation. Our

results indicate that during the modulation the pulsation remains purely radial, and the underlying mechanism is most probably a periodic perturbation of the stellar luminosity with the modulation period.

- DM Cyg, a fundamental mode RRab star was observed in the 2007 and 2008 seasons in the frame of the Konkoly Blazhko Survey. Very small amplitude light curve modulation was detected with 10.57 d modulation period. The maximum brightness and phase variations do not exceed 0.07 mag and 7 min, respectively. In spite of the very small amplitude of the modulation, beside the frequency triplets characterizing the Fourier spectrum of the light curve, two quintuplet components were also identified. Utilizing the IP method, we could detect very small systematic changes in the global mean physical parameters of DM Cyg during its Blazhko cycle, too. The detected changes are similar to what we have already found in a large modulation amplitude Blazhko variable MW Lyr but on a 10 % smaller scale, in accordance with its modulation amplitude being about one tenth of the modulation amplitude of MW Lyr.

- The mathematical model of periodically amplitude and phase modulated sinusoidal oscillation was studied, and its Fourier spectrum was given analytically. The Fourier spectrum of the model explained the main features of the frequency spectrum of RR Lyrae stars showing the Blazhko effect: among others the appearance of multiplets, the rapid decrease of their amplitudes in increasing orders, the asymmetry of the amplitudes of the side frequency pairs, and the possibility of the occurrence of frequency doublets instead of triplets in the spectrum. The good agreement of the results of this mathematical model with observational facts favours those physical models of the Blazhko effect which explain the phenomenon as a modulation of the oscillation with the modulation frequency, $f_{\rm m}$.

- Complete pulsation multicolour light curves of 16 short-period RRab stars ($P < 0.5$ d) have also been obtained with the 60-cm telescope. The light curves were covered by observations from about 10–20 nights spanning over 50–100 days in order exclude light curve modulation with amplitude larger than 0.01–0.02 mag in these stars.

- A systematic survey to establish the true incidence rate of Blazhko modulation among short-period, fundamental-mode, Galactic field RR Lyrae stars has been carried out. The Konkoly Blazhko Survey (KBS) was initiated in 2004. Between 2004 and 2009, more than 750 nights of observation was devoted to this project. A sample of 30 RRab stars was extensively observed, and light-curve modulation was detected in 14 cases. The 47 per cent occurrence rate of the modulation is much larger than any previous estimate. The significant increase of the detected incidence rate is mostly a result of the discovery of small-amplitude modulation. Half of the Blazhko variables in our sample show the modulation with such a small amplitude that would definitely have been missed in previous surveys. We have found that the modulation can be very unstable in some cases; for example, RY Com showed regular modulation during only one part of the observations, and had a quasi-stable light curve with abrupt, small changes in the pulsation amplitude during two observing seasons. This type of light-curve variability

is hard to detect in the data of other surveys. The higher frequency of the light-curve modulation of RRab stars makes it even more important to find an explanation for the Blazhko phenomenon.

- The validity of the [Fe/H](P, φ_{31}) relationship using the mean light curves of Blazhko variables has been checked in our sample. We have found that the formula gives accurate result for small-modulation-amplitude Blazhko stars, and this is also the case for large-modulation-amplitude stars if the light curve has complete phase coverage. However, if the data for large-modulation-amplitude Blazhko stars are not extended enough, the formula may give false result owing to the distorted shape of the mean light curve used.

- A thorough analysis of the multicolour CCD observations of the RRab-type variable, CZ Lacertae, has been published. The observations were carried out in two consecutive observing seasons in 2004 and 2005 within the framework of the Konkoly Blazhko Survey of bright, northern, short-period RRab variables. The $O - C$ variation of CZ Lac indicated that a significant period decrease took place just around the time of the CCD observations. Our data gave a unique opportunity to study the related changes in the pulsation and modulation properties of a Blazhko star in detail. Two different period components ($\approx$ 14.6 and $\approx$ 18.6 d) of the Blazhko modulation have been identified. Both modulation components had similar strength. The periods and amplitudes of the modulations changed significantly from the first season to the next, while the mean pulsation amplitude decreased slightly. The modulation frequencies were in a 5:4 resonance ratio in the first observing season, and then the frequencies shifted in opposite directions, and their ratio was close to the 4:3 resonance in the next season. The interaction of the two modulations caused beating with a period of 74 d in the first season, which resembled the 4-yr-long cycle of the $\approx$ 40-d modulation of RR Lyr. The mean values of the global physical parameters and their changes with the Blazhko phase of both modulation components have been determined by the inverse photometric method.

- The period changes of 86 RR Lyrae stars in the globular cluster M5 have been investigated on a one hundred-year time base. 21 RR Lyrae stars have increasing, 18 decreasing and 16 constant period. The mean rates of period change of these variables are: $-0.006 \pm 0.16\,\mathrm{d\,Myr^{-1}}$ or -0.021 ± 0.31 $\mathrm{Myr^{-1}}$. Ten RR Lyrae stars show fast period decrease with $\mathrm{d}\,P/\mathrm{d}\,t < -0.10\,\mathrm{d\,Myr^{-1}}$. At least some of these variables may be in the pre-zero age horizontal branch (ZAHB) evolutionary stage. The variables on the long-period sequence of the period-amplitude diagram are brighter than the other RR Lyrae stars of M5 and are in an advanced evolutionary stage moving off from the HB redward. More than one third of the M5 RR Lyrae stars investigated have irregular period change. The irregular period behaviour is relatively more frequent among the RRc (RR1) stars (50 %) than among the RRab (RR0) stars (34 %). A strict relationship has been found between the irregular period change and Blazhko effect of M5 RRab stars. This fact indicates a common origin for these phenomena. It is remarkable that, if the RRab stars showing Blazhko effect are omitted from the sample, the mean rates of the period change have small positive values ($0.012 \pm 0.15\,\mathrm{d\,Myr^{-1}}$ or $0.013 \pm 0.28\,\mathrm{Myr^{-1}}$) in excellent agreement with HB evolutionary model predictions.

- The light curves of 50 RRab stars in M5 have been investigated to detect Blazhko modulation. 18 Blazhko stars have been identified and modulation is suspected in two additional cases. The mean pulsation period of Blazhko stars is 0.04 d shorter than the mean period of the entire RRab sample in M5. Among the RRab stars with periods shorter than 0.55 d, the incidence rate of the modulation is as high as 60 %. The mean $B-V$ colours of Blazhko stars overlap with the colours of first overtone RRc pulsators. The mean V magnitudes of Blazhko stars are, on the average, 0.05 mag fainter than those of the RRab stars with stable light curves. Blazhko stars tend to be situated close to the zero age horizontal branch at the blue edge of the fundamental mode instability strip in M5. We speculate that this specific location hints that the Blazhko effect may have an evolutionary connection with the mode switch from fundamental to overtone mode pulsation.

- We have derived the basic physical parameters of the double-mode field RR Lyrae star, BS Com, from its observed periods and the requirement of consistency between the pulsational and evolutionary constraints. By using the current solar-scaled horizontal branch evolutionary models and our linear non-adiabatic purely radiative pulsational models, we get $\mathrm{M/M_\odot} = 0.698 \pm 0.004$, $\log(L/L_\odot) = 1.712 \pm 0.005$, $\mathrm{T_{eff}} = 6840 \pm 14\,\mathrm{K}$, $[\mathrm{Fe/H}] = -1.67 \pm 0.01$ for the physical parameters of BS Com.

- Double-mode nature of three pulsating variables has been revealed. HD 190336 (B0.7 II-III) has been shown to be a multiperiodic β Cep variable based on the publicly available HAT-5, Integral/OMC, and Hipparcos data.

- Long-term observational data have information on the magnetic cycles of active stars and that of the Sun. The changes in the activity of our central star have basic effects on Earth, such as variations in the global climate, so that understanding the nature of these variations is extremely important. The observed variations related to magnetic activity cannot be treated as stationary periodic variations, therefore, methods like Fourier transform or different versions of periodograms only give partial information on the nature of the light variability. We have demonstrated that time-frequency distributions provide useful tools for analysing the observations of active stars. We tested and used different methods, such as short-term Fourier transform, wavelet, and generalised time-frequency distributions, for analysing temporal variations on timescales of observational data. With test data, we have demonstrated that the observational noise has practically no effect on the determination in the long-term changes of time-series observations of active stars. The rotational signal may modify the determined cycles, therefore it is advisable to remove it from the data. Wavelets are less powerful in recovering complex long-term changes than other distributions discussed. By applying our technique to the sunspot data, we have found a complicated, multi-scale evolution in the solar activity.

- We studied the time variations in the cycles of 20 active stars based on decade-long photometric or spectroscopic observations. A new method of time-frequency analysis was applied to the data. We have found that fifteen stars definitely show multiple cycles, but the records of the rest are too short to verify a timescale for a second cycle.

The cycles typically show systematic changes. For three stars, we found two cycles in each of them that are not harmonics and vary in parallel, indicating a common physical mechanism arising from a dynamo construct. The positive relation between the rotational and cycle periods is confirmed for the inhomogeneous set of active stars. We conclude that stellar activity cycles are generally multiple and variable.

- We have investigated the fast rotating ($P_{\rm orb} = P_{\rm rot} = 0.465\,{\rm d}$) active dwarf binary V405 And (M0V+M5V) using photometric $BV(RI)_{\rm C}$ and optical spectroscopic data. The light variation is caused by the combined effect of spottedness and binarity with a small eclipse. From the available light and radial velocity curves we estimate the system parameters. Three flare events occurred during the observations: two were found in the spectroscopic data and one was observed photometrically in $BV(RI)_{\rm C}$ colours. An interesting eruptive phenomenon emerged from the photometric measurements which can be interpreted as a series of post-flare eruptions lasting for at least 3 orbits (rotations) of the system, originating from trans-equatorial magnetic loops, which connect the active regions in the two hemispheres. The two components of V405 And have masses well over and below the theoretical limit of full convection. This rare property makes the binary an ideal target for observing and testing models for stellar dynamo action.

- We presented more than 1000-day long photometry of EY Draconis in $BV(RI)_{\rm C}$ passbands. The changes in the light curve are caused by the spottedness of the rotating surface. Modelling of the spotted surface revealed that there are two large active regions present on the star on the opposite hemispheres. The evolution of the surface patterns suggests a flip-flop phenomenon. We detect a rotation period of $P_{\rm rot} = 0.45875\,{\rm d}$, and an activity cycle with $P \sim 350\,{\rm d}$. This cycle is the shortest one ever detected on active stars. Two bright flares are also detected and analysed.

- $BV(RI)_{\rm C}$ and JHK photometry and low- and high-resolution spectroscopy of the 11th mag G-type star TYC 2627-638-1 have been obtained. The target is separated into two young, early-G-type main-sequence (or late pre-main-sequence) stars, which are most probably bound and form a wide binary system. A substellar body orbits the brighter component as implied by radial velocity variations. The brighter component possibly also has a faint, later type stellar companion. A few hundredths of a magnitude amplitude rotational modulation is detected, which is most likely due to cool starspots. The spectral energy distribution shows a strong near-infrared excess in the fainter component of the wide binary.

- We analyzed the H_α spectral variability of the rapidly-rotating K1-dwarf LQ Hya using high-resolution H_α spectra recorded during April-May 2000. Chromospheric parameters were computed from the H_α profile as a function of rotational phase. We find that all these parameters vary in phase, with a higher chromospheric electron density coinciding with the maximum H_α emission. We find a clear rotational modulation of the emission that is better emphasized by subtracting a reference photospheric template built up with a spectrum of a non-active star of the same spectral type. A geometrical plage model applied to the H_α variation curve allows us to derive the location of the active

regions that come out to be close in longitude to the most pronounced photospheric spots found with Doppler imaging applied to the photospheric lines in the same spectra. Our analysis suggests that the H_α features observed in LQ Hya in 2000 are a scaled-up version of the solar plages as regards dimensions and/or flux contrast.

- The results of contemporaneous spectroscopic and photometric monitoring of the young solar-type star HD171488 ($P_{\rm rot} \sim 1.337\,$d) that aimed at studying surface inhomogeneities at photospheric/chromospheric levels have been published. Spectral type, rotational velocity, metallicity, and gravity were determined using a code developed by us. The active regions of the rapidly rotating star HD171488 are similar to the solar ones in some respect, because the spot temperature is close to that of sunspot umbrae and the plage flux-contrast is consistent with the average solar values.

The $O-C$ analysis of the RRab variables in M3 has been completed based on archive and recent CCD data obtained with the 60/90/180 Schmidt telescope of the Konkoly Observatory. We concluded that the period changes of many variables in M3 are in conflict with theoretical expectations; either the observed period changes do not reflect evolutionary changes, or theory does not interpret the HB evolution accurately enough. The paper is being submitted to MNRAS in August, 2011.

We have also completed the second part of the Konkoly Blazhko Survey, focusing on RRab stars in the 0.55–0.60 d period range. A large sample of these stars were observed between 2007–2011 with the 60-cm and 1-m telescopes of the Konkoly Observatory. The data release of the SuperWASP, our cooperation with the HAT project, the continuation of the ASAS observations, and literature information made it possible to study the complete sample of Northern RRab stars brighter than $K = 13$ mag in this period range. These data enabled us to study the incidence rate of the modulation ($\sim 50\,\%$) and the modulation properties of these stars in comparison with the results of the short-period sample of the KBS-I. The results of the KBS-II survey are planned to be published in the second part of 2011.

Extended multicolour data of 8 RR Lyrae stars showing the Blazhko effect have been obtained with the 60-cm telescope during the past years. The analysis of these data is in progress, the results are planned to be published in separate papers in the next year.

Most of our scientific achievements based fully or partly on the observations obtained with the 60-cm telescope with the assistence of graduate and undergraduate students. The continuous observations with the 60-cm telescope serve as an ideal training possibility for astronomy students from ELTE and SZTE, to learn observation and photometric data reduction. The senior members of the group are supervising several PhD, MSc and BSc work.
PhD: Á. Sódor completed (J. Jurcsik); K. Vida in progress (K. Oláh); Zs. Hurta in progress (B. Szeidl, J. Jurcsik)
MSc: G. Hajdu completed (B. Szeidl, J. Jurcsik), E. Kun in progress (J. Jurcsik), Á. Dózsa in progress (J. Jurcsik), P. Smitola in progress (J. Jurcsik)
BSc: P. Smitola completed (J. Jurcsik)

Budapest, July 29, 2011.