Radial and Nonradial Pulsations as Probes of Stellar Physics
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Nonradial Pulsations in Classical Pulsators

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Abstract. Recent analyses of photometric data on globular clusters and galaxies enabled us to study more closely the long-periodic amplitude/phase modulation (Blazhko effect) in classical variables. In the frequency spectra of these stars we see either a doublet or an equally-spaced triplet with a very small frequency separation close to the main component. None of the available theoretical models are able to explain this behavior without invoking some form of nonradial pulsation. In this review we describe the observational status of the Blazhko variables, and discuss the limits of the applicability of the current models to these stars.

1. Introduction

The long-term periodic phase modulation of the RR Lyrae star RW Dra was discovered almost one hundred years ago by Blazhko (1907). Therefore, this phenomenon is called *Blazhko effect* (for the nomenclature see also the comment of Szeidl & Kolláth, 2000).

Long-term amplitude/phase modulation is quite common in the case of multimode pulsators (e.g., δ Scuti stars, white dwarfs), where the effect of close excited normal modes can also be viewed as an amplitude modulation. What makes Blazhko-type stars particularly interesting and important is that they have high pulsation amplitudes, and therefore there is no doubt that their main pulsation component is basically a radial mode. Since the long-term amplitude/phase modulations are exhibited in the frequency spectra as closely spaced components, and the eigenspectrum of the radial modes is too sparse, we are left with the following two possibilities to explain the Blazhko effect:

- amplitude/phase-modulated pulsation of a purely radial mode,
- basically radial pulsation, contaminated by nonradial component(s) either through mode coupling, or through the distortion of the radial eigenfunction by a large-scale magnetic field.

Convection can be considered also in the above scheme, because (at least in the first approximation) it can be treated as a large set of nonradial modes of high spherical harmonic order. Of course, if any form of convection is responsible for the amplitude modulation, the interaction with the radial normal mode should lead to a genuine amplitude modulation which is independent of the aspect angle, because the averaging effect is certainly overwhelming in this case.

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In the following we will give an account of the observed properties of the Blazhko variables and describe the ability of the current models to explain the observations. We will see that, according to our current understanding, it is very difficult to escape the possibility that nonradial pulsations play a significant role in these variables.

2. Data analysis

Because of the long modulation periods, identification of Blazhko variables requires sufficiently long data coverage and proper analysis. While in the case of old photographic data the high noise level is the most serious problem, the photoelectric observations, made on individual variables during the past decades, suffer from another problem. Besides the daily alias in the sampling of these data there is another artificial periodicity due to the high concentration of data points on the rising branches. This observation technique was justified because of the input data required by the $O - C$ analyses, most frequently used in the past to study these stars. The sampling periodicity with the pulsation period makes it very difficult/impossible to perform a Fourier analysis and correctly identify the modulation components around the harmonics.

Data supplied by the microlensing surveys and observations made on individual globular clusters suffer from problems, too. Microlensing data have rather low sampling rate and usually high noise (at least at the brightness level of the RR Lyrae stars). Although individual cluster data have much higher sampling rate, and, in general, are more accurate, they are far less extended. Nevertheless, analysis of the above types of data during the last few years has led to significant progress in the study of these stars.

As an example of the data quality and types of frequency patterns obtained in the recent analysis of the MACHO database on the Large Magellanic Cloud (LMC) fundamental mode RR Lyrae (RRab) stars (Welch et al., these proceedings), we show the result for five representative variables in Fig. 1. Each row in the figure represents different objects as given by the first item on the left in the corresponding header. From left to right we have: first column: folded light curves, second column: amplitude spectra of the original data, third column: amplitude spectra of the prewhitened data, and insets in the upper right corners: blow-ups of the neighborhood of the fundamental frequency in the prewhitened spectra. Light curves, frequency spectra of the original data and those in the insets are normalized independently. Prewhitened spectra are normalized by the highest amplitude in the corresponding spectra of the original data.

The top panel is only to demonstrate that for single mode variables, the prewhitened spectrum is completely featureless, presuming that a sufficient number of harmonics (in this case three) are subtracted from the signal. In the next two panels from the top we show cases when only one side component is seen after prewhitening, whereas the lower two panels are examples when both modulation components are clearly visible. These types of frequency spectra have also been observed in the first overtone RR Lyrae (RRc) stars (see Alcock et al., 2000; Cseresnjes, 2001; Olech et al., 2001, and references therein). In this paper variables displaying *any* of the above types of frequency patterns are called Blazhko (BL) variables, because at the time of this writing it is not entirely

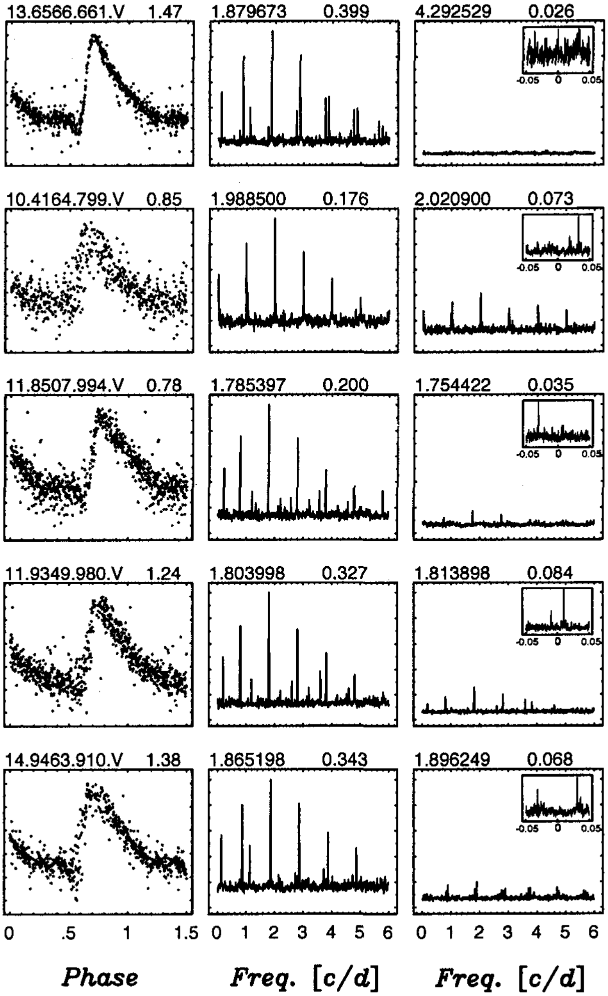

Figure 1. Selected samples of light curves and frequency spectra of the MACHO fundamental mode RR Lyrae star inventory in the LMC. In the headers from left to right are shown: MACHO identifier, total V amplitude, fundamental frequency [d^{-1}] and its amplitude, peak frequency and its amplitude in the prewhitened spectra. For further explanation: see text.

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clear if there is an abrupt or continuous transition between the cases of strongly asymmetric and single modulation components.

Although additional analyses of new and already existing data will continuously increase the number of Blazhko stars with reliably identified frequency patterns, we think it is useful to present the number statistics available for us at this moment. Several comments should be added to the numbers displayed in Table 1. For the RRab-BL stars in the Galactic field, we rely on the review of

Table 1. Number of known Blazhko variables in various stellar systems.

Cluster/Galaxy	$N_{RRab-BL}$	N_{RRc-BL}	Source
Galactic field	37	8	1, 5
Galactic Bulge	35	2	6
Globular clusters	?	7	2, 3, 4
LMC	149	52	7, 8
Sgr dwarf gal.	?	5	5

References: (1) Szeidl (1988); (2) Olech et al. (1999a); (3) Olech et al. (1999b); (4) Olech et al. (2001); (5) Cseresnjes (2001); (6) Moskalik & Poretti (these proceedings); (7) Alcock et al. (2000); (8) Welch et al. (these proceedings)
Note: See text for the discussion of the incompleteness of the above statistics.

Szeidl (1988), who listed 'RRab stars with known or presumed Blazhko period' in his Table 3. We note that there are stars (mentioned also by Szeidl) which might not be Blazhko variables, because they do not show definitive change in the shape of their light curves in the contemporary observations, whereas the old photographic data might indicate such changes. Furthermore, partially because of the problems due to the biased sampling as mentioned at the beginning of this section, only a few of these stars have been frequency analyzed (Borkowski, 1980; Smith et al., 1994; Kovács, 1995; Nagy, 1998; Smith et al., 1999; Szeidl & Kolláth, 2000; Lee & Schmidt, 2001, and references therein).

In the case of globular clusters, we included only those variables which have been discovered from the frequency analysis of current CCD observations. Unfortunately, none of these analyses were extended to RRab stars. Therefore, we did not include any data for the RRab-BL stars. For these variables we refer the interested reader to the statistics based mostly on the visual inspection of photographic data as presented by Szeidl (1988).

We also do not have complete information on the statistics of the Blazhko phenomenon for the Sagittarius dwarf galaxy. This is because the analysis of the RRab stars was dropped due to the short time span of the observations.

Periodic amplitude/phase variation among Cepheids must be very rare. The only known Blazhko variable in the Galactic field classified as a Cepheid is HR 7308 (Burki et al., 1986; see also Van Hoolst & Waelkens, 1995). A preliminary analysis of the MACHO database of the Magellanic Clouds suggests an incidence rate of $0.5 - 1.0\%$ (Welch, 2001, private communication). Our own

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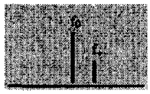
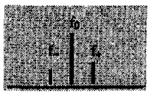


- f_- , f_0 is also possible
- $|f_\pm - f_0| < 0.1$ c/d
- $0.15 < A_\pm/A_0 < 0.7$
- 80% of this type of RRab stars in the LMC have A_+ component



- $f_+ - f_0 = f_0 - f_-$
- $f_+ - f_0 < 0.07$ c/d
- $0.1 < A_\pm/A_0 < 0.5$
- Asymmetry in the modulation amplitudes < 50%

— No preferred period range
— Modulation periods can be very large
— There are also other types of frequency patterns

Figure 2. Main properties of the Blazhko variables.

analysis of some 1400 Cepheids in the same system from the OGLE database (Udalski et al. 1999), has led basically to a null result. Considering that the Blazhko Cepheids identified so far have short periods and our analysis covered a wide range of periods, these results seem to suggest an incidence rate lower than 1% for these variables. This is an order of magnitude lower than the recent estimate of the incidence rate of the Blazhko RR Lyrae stars in the LMC (Welch et al., these proceedings).

3. Observed properties

As we mentioned in the previous section, the statistics of the Blazhko stars is incomplete in many systems. The only exception is the LMC, where, due to the analysis of several thousands stars, we have a sample of $\approx$ 200 Blazhko stars (RRab & RRc). Based mainly on these stars, we summarize the properties obtained from frequency analyses in Fig. 2.

First of all, we have to point out that, although the data strongly suggest the existence of two main classes, the noise level is still too high to separate clearly the class of variables with two modulation components (BL2-type) from the ones which apparently have only one such a component (BL1-type). Significant doublets rarely appear with an asymmetry larger than 50% in the prewhitened spectra of the BL2 variables. However, less significant peaks are sometimes observable at the equally spaced frequency position in the case of variables classified as BL1-type. Even though we cannot exclude the existence of BL2 variables with strongly asymmetric modulation components, we think that it is safe to state that in the large majority of BL2 stars this asymmetry cannot be larger than 70%.

Modulation periods are larger than $\approx$ 20 days for the RRab stars whereas for the RRc stars they can be even shorter than 10 days. For the upper limit of the modulation periods we may not have such a relatively firm statement. The longest modulation periods observed in the MACHO database are comparable

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with the length of the total time span of the observations, which is 7.5 years. The modulation periods for the RRc-BL stars are distributed roughly uniformly with some preference toward longer periods. For the RRab-BL stars, modulation periods shorter than ≈ 40 days are not frequent, but above this value the distribution is reasonably uniform.

The pulsation periods cover almost the total range of that of the monoperiodic variables. For the RRab- and RRc-BL stars we have $0\overset{d}{.}35 < P_0 < 0\overset{d}{.}7$ and $0\overset{d}{.}23 < P_0 < 0\overset{d}{.}46$, respectively. There are a few RRc-BL stars with very strong modulation ($A_{\pm}/A_0 > 0.7$). In about two third of the BL2 stars (both among the RRab and RRc stars) the modulation component with the larger frequency has also larger amplitude. In 80% of the RRab-BL1 variables the modulation component has larger frequency than the pulsation component. There is no such trend among the RRc-BL1 stars.

To estimate the incidence rate of the Blazhko phenomenon, we turn to the MACHO data set which contains enough variables to yield reliable figures. According to Alcock et al. (2000) and Welch et al. (these proceedings), the incidence rates of the BL1 & BL2 phenomena in the LMC are about 10% and 4% among the RRab and RRc variables, respectively. Based on the analysis of 214 stars from the OGLE data set, Moskalik & Poretti (these proceedings) get rates of 23% and 3% for the Galactic Bulge. We think that these results clearly show that, in general, the Blazhko phenomenon has at least a three times higher incidence rate among RRab stars than among RRc stars. However, the actual value of this ratio depends on the system studied.

4. Physical modelling

The reasons why all current models include some form of nonradial pulsations in explaining the Blazhko effect are the following:

- Previous attempts in using only radial mode interactions have failed (nonresonant modes – Buchler & Kovács, 1986; 2:1 resonance – Moskalik, 1986; noise induced transitions – Kovács, 1994; no reports from past and current hydrodynamical simulations – Kolláth, 2001, private communication).

- Linear models suggest excitation of nonradial modes (Cepheids – Osaki, 1977; RR Lyrae stars – Dziembowski, 1977; Cox, 1993; Dziembowski & Cassisi, 1999; beyond the blue edge – Shibahashi & Osaki, 1981).

- Observed frequency patterns are compatible with the assumption of nonradial pulsation (equidistant triplet, closely spaced frequencies).

We show a schematic representation of the two currently competing models in Fig. 3. Both in the Oblique Rotating Magnetic Pulsator (ORMP, see Shibahashi, 2000) and in the Rotating Resonant Pulsator (RRP, see Nowakowski & Dziembowski, 2001) models the pulsation amplitudes are *constant*. The observed modulation of the light curve is a consequence of *rotation*, and the modulation period is directly related to it. The degree of modulation is strongly *aspect-dependent* in both cases. Another peculiarity of these models is that they predict modulation components of *equal amplitudes*, which is in sharp contrast to most

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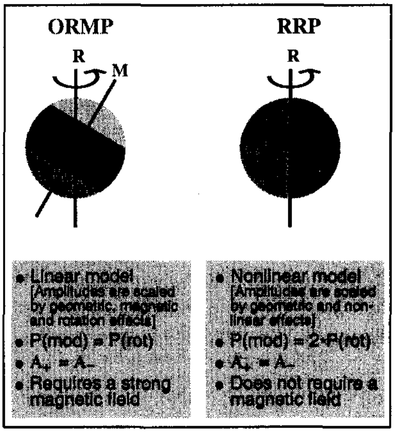

Figure 3. Comparison of two models of the Blazhko effect.

of the frequency patterns observed, especially to those which are of BL1-type. A further question to deal with is the reason why RRc-BL variables show significantly lower incidence rates than their fundamental mode counterparts. This question has not yet been dealt with in the ORMP model, but the RRP model does show such an effect, although still not in the degree observed. Finally, it is important to mention that deviations from strict amplitude/phase modulations might occur in Blazhko stars (e.g., Szeidl, 1988; Smith et al., these proceedings) which should be explained by future modelling.

5. Problems and prospects

In spite of the progress made during the last few years both in the observations and modelling, the basic physical understanding of the Blazhko phenomenon is still missing. Posed by the observations, here is a (probably incomplete) list of problems to be dealt with: – uneven modulation components; – incidence rates (high for RRab, much lower for RRc and almost zero for Cepheids); – deviations from strictly periodic modulations; – magnetic field (spectroscopic detection and its relation to the Blazhko effect); – surface velocity field (spectroscopic detection of the nonradial component). Present models are still not the results of direct hydrodynamical simulations, but rely either on linear pulsation (OMRP) or on the amplitude equation formalism, using some numerical estimates of the coupling coefficients. Further progress in this field requires substantial efforts. From the observational side, disentangling the radial and nonradial components of the surface velocity field and detecting/studying a magnetic field would be of prime importance. From the theoretical side, a full scale hydrodynamical simulation is still a formidable task. Therefore, additional work within the framework of amplitude equations seems to be the most promising. Considering the fundamental importance of RR Lyrae stars in various fields of astronomy, we think that it is very much worthwhile to put substantial efforts in understanding this long-standing problem.

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References

Alcock, et al. (the MACHO collaboration) 2000, ApJ, 542, 257

Blazhko, S. 1907, Astr. Nachr., 175, 325

Borkowski, K.J. 1980, Acta Astron., 30, 393

Buchler, J.R. & Kovács, G. 1986, ApJ, 308, 661

Burki, G., Schmidt, E.G., Arellano Ferro, A., et al. 1986, A&A, 168, 139

Cox, A.N. 1993, in New Perspectives on Stellar Pulsation and Pulsating Variable Stars, eds. J. Nemec & J. Matthews, (Cambridge Univ. Press), 409

Cseresnjes, P. 2001, A&A, 375, 909

Dziembowski, W. 1977, Acta Astron., 27, 95

Dziembowski, W.A. & Cassisi, S. 1999, Acta Astron., 49, 371

Kovács, G. 1994, Annals of the New York Acad. Sci., 706, 70

Kovács, G. 1995, A&A, 295, 693

Lee, K.M. & Schmidt, E.G. 2001, PASP, 113, 1140

Moskalik, P. 1986, Acta Astron., 36, 333

Nagy, A. 1998, A&A, 339, 440

Nowakowski, R.M., & Dziembowski, W.A. 2001, Acta Astron., 51, 5

Olech, A., Kaluzny, J. & Thompson, I.B., et al. 1999a, AJ, 118, 442

Olech, A., Woźniak, P.R. & Alard, C., et al. 1999b, MNRAS, 310, 759

Olech, A., Kaluzny, J. & Thompson, I.B. 2001, MNRAS, 321, 421

Osaki, Y. 1977, PASJ, 29, 235

Shibahashi, H. 2000, in ASP Conf. Ser., Vol. 203, The Impact of Large-Scale Surveys on Pulsating Star Research, eds. L. Szabados & D. Kurtz, (San Francisco ASP), 299

Shibahashi, H. & Osaki, Y. 1981, PASJ, 33, 427

Smith, H.A., Matthews, J.M. & Lee, K.M., et al. 1994, AJ, 107, 679

Smith, H.A., Barnett, M. & Silbermann, N.A. 1999, AJ, 118, 572

Szeidl, B., 1988, in Multimode Stellar Pulsations, eds. G. Kovács, L. Szabados, & B. Szeidl, (Konkoly Observatory – Kultúra, Budapest), 45

Szeidl, B. & Kolláth, Z. 2000, in ASP Conf. Ser., Vol. 203, The Impact of Large-Scale Surveys on Pulsating Star Research, eds. L. Szabados & D. Kurtz, (San Francisco ASP), 281

Udalski A., Szymański M. & Kubiak M., et al. 1999, Acta Astron., 49, 201

Van Hoolst, T. & Waelkens, C. 1995, A&A, 295, 361