RR Lyrae Stars: Cosmic Lighthouses With a Twist

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Abstract Since their discovery over a century ago, RR Lyrae stars have proven to be valuable objects for the entire field of astrophysics. They are used as standard candles and witnesses of galactic evolution. Though the pulsations that cause their light variations are dominated by relatively “simple” radial modes, some aspects of RR Lyrae pulsation remain enigmatic. Besides the visual, photographic, and photometric observations of these stars that span several decades, spectroscopic data provide an in-depth view on the pulsations. In the past decade, particularly since the launch of the satellite missions with asteroseismology as part of their program (for example, MOST, CoRoT, and Kepler), several findings have helped us better understand the structure and pulsations of RR Lyrae stars. Nevertheless, ground-based observations and long-term monitoring of RR Lyrae stars, as done by the AAVSO members, remain of utmost importance.

1. A century of RR Lyrae studies

The story of the discovery of the RR Lyrae stars starts at the end of the 19th century with the globular cluster studies initiated by Harvard astronomer Solon I. Bailey, rendering many variable stars. Those variables that were seen in large numbers, with short periods of under a day and photographic amplitudes of about one magnitude, were called cluster variables. Soon thereafter, similar variables were found in the field. Initially, the “cluster variables” were put in the same basket as the Cepheids because of the similarities in their light curves. When it was recognized that there are notable differences between the two types of stars (period, location, population type, kinematical properties), RR Lyrae itself, the brightest field star of this type discovered by Williamina Fleming in 1899, became the eponym of the class.

Both Cepheids and RR Lyraes were first thought to be variable due to a binary nature. The foundations for stellar pulsation theory that explains the light variations in RR Lyrae stars were laid by Eddington (1926).

2. What are they and why do we care about them?

RR Lyrae stars are pulsating low-mass stars that have evolved away from the main sequence and are burning Helium in their core. In the Hertzsprung-Russell diagram (HRD) they are located on the horizontal branch and its intersection with the so-called instability strip (see Figure 1). In this strip, crossing the HR diagram nearly vertically, pulsations are driven by the kappa (κ) mechanism. Kappa stands for the opacity of a stellar layer, its capacity to block incoming radiation. In most of the inside of stars, the opacity of stellar gas decreases as its temperature increases. However, there are some regions where this tendency gets weak, or even reversed. For example, in the hydrogen and helium partial ionization zones, connected to specific temperatures, the opacity increases as the temperature increases, that is, with compression. These zones, especially the helium partial ionization zones, are considered to be the regions for pulsation excitation in classical Cepheids and RR Lyrae stars. At compression, ionized material increases the opacity and the layer is pushed upwards by radiation pressure. When the layer moves up and reaches lower temperatures, recombination happens, the opacity decreases, the layer falls back, and the cycle is repeated. In order to be efficient drivers of pulsation, these partial ionization zones should be located at a critical depth in the star. For this, a suitable combination of stellar properties is needed, which is why the κ mechanism driven pulsations are confined to specific regions in the HRD, such as the instability strip.

RR Lyrae stars have typical periods of ~0.2 to ~1 day, amplitudes in the optical of 0.3 up to 2 magnitudes, and spectral types of A2 to F6. Most of them pulsate in the radial fundamental mode (called Bailey type RRab stars), the radial first overtone (Bailey type RRc stars), and, in some cases, in both modes simultaneously (RRd stars), see Figure 2. Type RRab stars have the larger light curve amplitudes (around 1 magnitude) and longer periods (~0.35–1 day); type RRc stars generally have more sinusoidal light curves with lower amplitudes (around 0.5 magnitude) and shorter periods (~0.2–0.45 day), though the period ranges overlap. The RRd stars pulsate in both radial modes simultaneously and hence have more complex light curves.

Since the large scale surveys and the satellite missions, higher-order radial overtone modes have been detected in RR Lyrae stars (Olech and Moskalik 2009; Benkő *et al.* 2010).

As the RR Lyrae stars are indeed occupying a small range in *V* magnitude on the horizontal branch (see Smith 1995), they qualify as excellent distance indicators. When we know their luminosity or absolute magnitude, this can be of great help in estimating the distances (and hence the ages) of globular clusters, and to galactic and extragalactic (local group) locations. Moreover, as an old stellar population and found in large numbers, the RR Lyrae stars can be used as witnesses of chemical and dynamical galactic evolution.

They also serve as test objects for low-mass stellar evolution and radial pulsation theory.

A frequency spectrum of an RR Lyrae star will typically show the main pulsation frequency (corresponding to the radial fundamental mode or the first overtone) as well as its harmonics (double, triple, quadruple frequency, and so on). Especially for the RRab stars, pulsating with higher amplitudes reflected in their non-sinusoidal light curves, the harmonics will be very prominent.

3. So we know what they are all about?

Despite their numerous applications in various fields of astrophysics, several aspects of RR Lyrae pulsation remain not fully understood.

One not completely resolved issue concerns the *Oosterhoff dichotomy* (Oosterhoff 1939). RR Lyrae-rich globular clusters can be divided into two groups on the basis of the properties of their RR Lyrae stars. Oosterhoff type I clusters, such as M3 and M5, contain many more RRab stars than RRc stars. The mean periods of both types of pulsators are 0.55 day for RRab stars and 0.32 day for RRc stars, respectively. Oosterhoff type II clusters, such as ω Cen, M15, and M53 have more nearly equal numbers of RRab and RRc stars and longer mean periods of 0.64 day and 0.37 day, respectively. There is a correlation with metallicity: Oosterhoff type II are more metal-poor than their Oosterhoff type I counterparts.

The most popular theoretical explanation for this phenomenon relies on a so-called "hysteresis mechanism" (van Albada and Baker 1973). There is an "either-or" region in the middle of the RR Lyrae instability strip where the pulsation mode is determined by the star's previous evolutionary path. RR Lyrae stars in Oosterhoff type II clusters are evolved from a position on the blue horizontal branch, whereas those in Oosterhoff type I globulars contain a mix of evolved and unevolved stars.

The existence of the Oosterhoff gap at $< P_{\mathrm{ab}} > = 0.60$ day, among the halo clusters, and its absence among the galaxy's satellite systems, indicates that the halo could not have been built through the merger of systems exactly like the early counterparts of the Milky Way's current satellite galaxies (Catelan 2006).

I will now focus on one of the most stubborn and long-standing mysteries in stellar pulsation theory, the so-called *Blazhko effect*, since it is a phenomenon that observers of RR Lyrae stars are likely to encounter.

In 1907, Sergei Nicolaevich Blazhko reported on the periodic variations in the timing of maximum light for the star RW Dra (Blazhko 1907). Soon after that, it was realized that other, similar stars showed modulations of their light curve shape over time scales of weeks or even months. In 1916 Harlow Shapley reported on the changes in the spectrum, period, and light curve of the prototype RR Lyr itself. The Blazhko effect, as this periodic amplitude and phase modulation is called nowadays, turned out to be rather common in

RR Lyrae stars. Previously reported galactic occurrence rates were 20–30% for Galactic RRab stars and a few percent for RRc stars (Szeidl 1988), and somewhat lower in the LMC: 12% RRab and 4% RRc (Alcock *et al.* 2000, 2003). The most recent surveys, however, both from the ground (Jurcsik *et al.* 2009b) and from space (Szabó *et al.* 2009; Benkő *et al.* 2010), seem to indicate that close to 50% of the fundamental mode RR Lyrae pulsators show the Blazhko effect (Figure 3).

In the frequency spectra of Blazhko stars we will see multiplets with equidistant spacing (equal to the Blazhko frequency) around the main frequency and its harmonics (some schematic examples are shown in Figure 4). These reflect the amplitude and phase modulation happening in the star (see also Benkő *et al.* 2011).

After several decades of dedicated studies of Blazhko stars, a variety of behavior is observed in these stars: changing Blazhko cycles, additional longer cycles, multiple modulation periods, complex multiplet structures in the frequency spectra, additional frequencies corresponding to higher overtone modes.

3.1. Multicolor data and spectroscopy

Early studies of RR Lyrae variables, including Blazhko variables, were based on photographic and photometric data of the stars, often focusing around maximum light for the purpose of O–C ("observed minus calculated," comparing expected with observed times of maximum light). From complete light curves of the stars we can get much more information on their pulsation properties.

For a real in-depth study of RR Lyrae stars, however, multicolor and spectroscopic data are the way forward.

Approaches to derive atmospheric parameters of RR Lyrae stars through multicolor photometry and/or spectroscopy, such as applied by De Boer and Maintz (2010), Sódor *et al.* (2009), Kolenberg *et al.* (2010a), and For *et al.* (2011), allow us to connect the complex atmospheric variations with the pulsation patterns, and even their modulations.

Sódor *et al.* (2009) devised an inverse photometric Baade-Wesselink method for determining physical parameters of RRab variables exclusively from multicolor light curves. Its application to the Blazhko star MW Lyr (Jurcsik *et al.* 2009a) shows how the mean global parameters, such as the radius, luminosity, and surface effective temperature of a modulated star vary over the Blazhko cycle. As a consequence, the instantaneous period varies over the Blazhko cycle. This modulation of the stellar parameters throughout the modulation is a very important result for the further development of Blazhko models.

RR Lyrae stars have rather tumultuous atmospheres due to high pulsation velocities in the outer layers of the star. This gives rise to shock waves in particular pulsation phases, reflected in spectral line broadening and doubling

(Gillet and Crowe 1988). Moreover, there is a gradient in velocity between different layers in the star, the so-called Van Hoof effect (Mathias *et al.* 1995).

In addition, new and exciting findings such as the occurrence of Helium emission (Preston 2009) and neutral line disappearance (Chadid *et al.* 2008) would be very interesting to study as a function of the Blazhko phase. These methods, and their extensions, in combination with high-precision and/or long-term photometric data, allow us to perform (literally) in-depth studies of the Blazhko phenomenon. As pointed out by Kovács (2009), accurate time-series spectral line analysis is needed to reveal any possible non-radial components.

3.2. Models for modulation

More than a century after the discovery of the Blazhko effect, we still are at a loss for a definitive explanation. But we are narrowing down the possibilities.

Until recently, the nonradial resonance model (Van Hoolst *et al.* 1998; Dziembowski and Mizerski 2004, and references therein) and the magnetic model (Shibahashi and Takata 1995; Shibahashi 2000, and references therein) were most commonly quoted. They both rely on the excitation of nonradial pulsation mode components in the modulated star, and state a connection between the modulation period and the rotation period. They provide predictions for the appearance of the Fourier spectra of modulated stars. The magnetic model for the Blazhko effect received some blows when spectropolarimetric observations indicated that a strong kiloGauss-order dipole field, a premise in the model (Shibahashi 2000), is not present in the prototype RR Lyr (Chadid *et al.* 2004) nor in a sample of seventeen selected modulated and non-modulated RR Lyrae stars (Kolenberg and Bagnulo 2009).

As neither of both models could explain the variety of observed behavior in Blazhko stars, an alternative idea was (re-)proposed by Stothers (2006, 2010). In this scenario, the amplitude and phase (period) modulation is caused by the cyclical weakening and strengthening of the convective turbulence in the star. The variations in convective turbulence can be caused by a transient magnetic field in the star. The presence of such a field, however, would be very hard to demonstrate. What makes the Stothers (2006) idea attractive is that it does not require the presence of nonradial modes, nor a clockwork regularity in the Blazhko cycles. Also, the variations of the mean parameters of the star, as mentioned above, are a consequence of the modulation of turbulent convection in this model. The Stothers model was recently challenged by the findings by Molnár and Kolláth (2010) and Smolec *et al.* (2011) that the modulation of the convective strength should be unphysically large to cause the observed modulation.

The latest development in the models for the Blazhko effect were triggered by uninterrupted, high-precision observations of Blazhko stars, as described in the next section.

4. Progress: expected and serendipitous

Several space telescopes have asteroseismology (or the study of pulsating stars) as an important part (or prime by-product) of their mission and have performed high-precision observations of RR Lyrae stars: the Canadian suitcase-sized MOST telescope (Gruberbauer *et al.* 2007), the French-led ESA space mission CoRoT (Chadid *et al.* 2010), and NASA's Kepler mission (Kolenberg *et al.* 2010b). These space missions deliver high-precision data and are not disturbed by daily and weather gaps, typical for Earth-based observations.

The new data on Blazhko stars reveal complex multiplet structures in the Fourier spectra and additional frequency peaks of which some can be explained in terms of radial overtones, and others not (Chadid *et al.* 2010, Benkő *et al.* 2010). The Kepler data allow us to find the smallest detectable amplitude and phase modulation values. However, still about half of the RR Lyrae stars do turn out to be unmodulated (see, for example, Nemec *et al.* 2011).

By a fortunate coincidence, the star RR Lyr itself, the prototype of the class and a Blazhko variable studied for over a century, is located in the Kepler field. Though initially thought to be too bright to be observed successfully with Kepler, the flux of the star can be recovered thanks to a custom aperture especially devised for the star (Kolenberg *et al.* 2011). In RR Lyr we detected a new phenomenon, reflected in alternatingly high and low maxima (Kolenberg *et al.* 2010b). This effect can be rather large, regularly 0.05 magnitude in RR Lyr. In the frequency spectrum, these variations with the double period result in the appearance of so-called half-integer frequencies. This phenomenon, called period doubling, was reported in models of Cepheids, stars that undergo radial pulsations just like RR Lyrae stars (Moskalik and Buchler 1990). It had, however, never been observed before in observational data of Cepheids or RR Lyrae stars. Szabó *et al.* (2010) find that a 9:2 resonance between the fundamental radial mode and the 9th overtone might be responsible for period doubling. The fact that period doubling was also found in a few other Blazhko stars, and not in non-modulated stars, revealed a possible connection between period doubling and modulation (Figure 5).

Period doubling does not occur at all phases in the Blazhko cycle. It can be very obvious in some phases, and invisible in others. And just like sometimes there is no strict repetition from one Blazhko cycle to the next, period doubling does not repeat in the same Blazhko phases for consecutive cycles.

Why was period doubling not detected earlier in ground-based data, particularly for a star as well-studied as RR Lyr? Besides the fact that period doubling does not always occur, the main reason is undoubtedly that RR Lyrae stars have periods of around half a day, and, when observing from one site on Earth, consecutive pulsation maxima are usually missed.

The observation of period doubling sparked new modelling efforts (Szabó *et al.* 2010; Kolláth *et al.* 2011), and recently a new model for the Blazhko effect was proposed by Buchler and Kolláth (2011). Using the amplitude equation formalism to study the nonlinear, resonant interaction between the two modes, they showed that the (9:2) radial resonance can not only cause period doubling, but it may also lead to amplitude modulation. Moreover, in a broad range of parameters the modulations can be irregular, just like recent observations show.

Therefore, we are now left with a new hierarchy for the models for explaining the Blazhko effect (Figure 6).

5. Pro-Am observations and RR Lyrae stars

Their large pulsation amplitudes, their pulsation periods, and their characteristic light curve shapes make the RR Lyrae stars easily distinguishable from other variables and gratifying targets for amateur observations.

Several groups worldwide have carried out observations of RR Lyrae stars. GEOS (Groupe Européen d'Observations Stellaires) is a European group of variable star observers with nearly eighty active members (of which ten are professionals). The GEOS RR Lyrae database (http://dbrr.ast.obs-mip.fr/) is intended to help observations and studies on RR Lyrae stars. It contains the times of light maximum of RR Lyrae stars obtained either visually, with electronic devices, or photographically. The data are collected in the literature (dating back to the end of the 19th century) or are submitted by the observers themselves (since 2004 also through automated observations). This database is a useful resource for the study of period changes in RR Lyraes, as well as the Blazhko effect.

The AAVSO has an impressive database of observations dating back more than a century. This database is a treasure chest for variable star research (including RR Lyrae stars) and part of these observations remain unpublished to date. Observations of RR Lyrae stars are gathered in the framework of the AAVSO's Short Period Pulsation Section. From time to time there are organized efforts focusing on legacy stars that have a Blazhko effect (see, for example, the AAVSO's "Variable Star of the Season Archive," http://www.aavso.org./vsots_archive).

Although the satellite missions deliver data with unprecedented precision on RR Lyrae stars, long-term monitoring of RR Lyrae stars is most valuable. Only such data can reveal phenomena happening on time scales of years, decades, or even longer, such as period changes due to stellar evolution, long-term changes in the Blazhko effect, and additional cycles with periods of years or longer. Sometimes sudden changes and transient phenomena can be observed in stars that have been followed for decades. Satellite missions and dedicated campaigns are limited in time. Moreover, the number of RR Lyrae stars observed with the satellite missions is limited, and generally the brighter stars, those that also can be followed more easily through spectroscopy, are not observed by the space missions. Nowadays, amateur observers play a very important role in contributing to the data that allow these discoveries. For these endeavors to be satisfying and optimally useful, interaction between professionals and amateurs is important, clarifying what kind of observations (of which targets) are needed.

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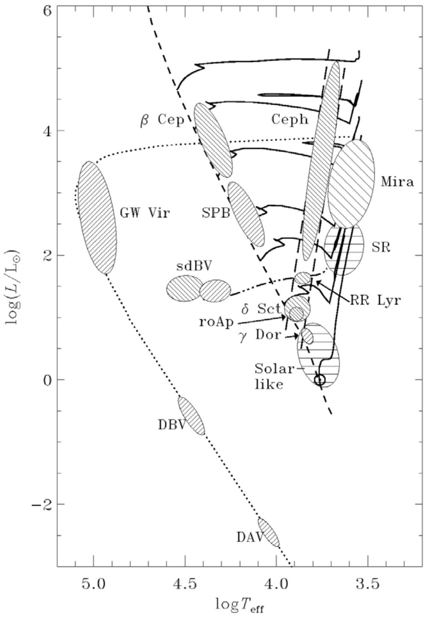

Figure 1. Stellar pulsations across the Hertzsprung-Russell diagram. Dashed line: zero-age main sequence; continuous lines: selected evolutionary tracks; triple-dot-dashed line: horizontal branch; dotted line: white dwarf cooling curve. The RR Lyrae stars are located on the horizontal branch in the instability strip. The hatching in the zones of pulsating stars represents the type of mode and the excitation mechanism: up-left for opacity-driven acoustic modes, up-right for opacity-driven internal gravity modes, and horizontal for stochastically excited modes. (From Christensen-Dalsgaard *et al.* 2004)

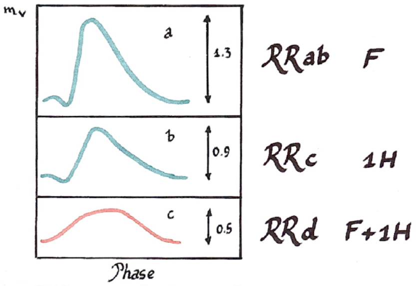

Figure 2. RR Lyrae Bailey subtypes. F: radial fundamental mode; 1H: radial first overtone.

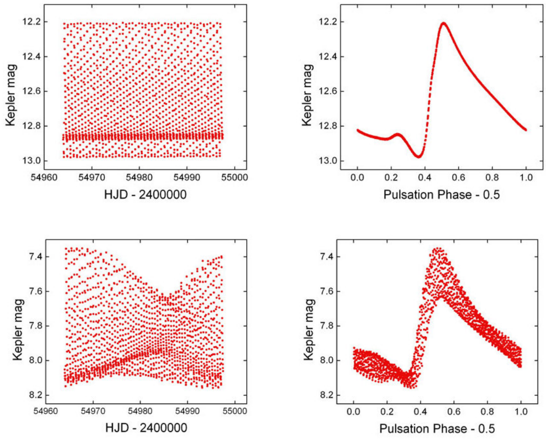

Figure 3. Kepler observations of a non-mdulated RR Lyrae star (top pair) and a Blazhko star (bottom pair). Left: 30-minute cadence data; right: folded light curve.

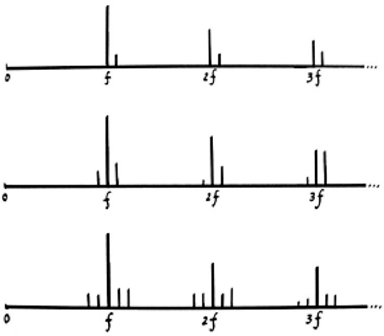

Figure 4. Typical frequency spectra for a Blazhko-modulated RR Lyrae star, showing multiplets. They can get even more complex than the schematic representations given here.

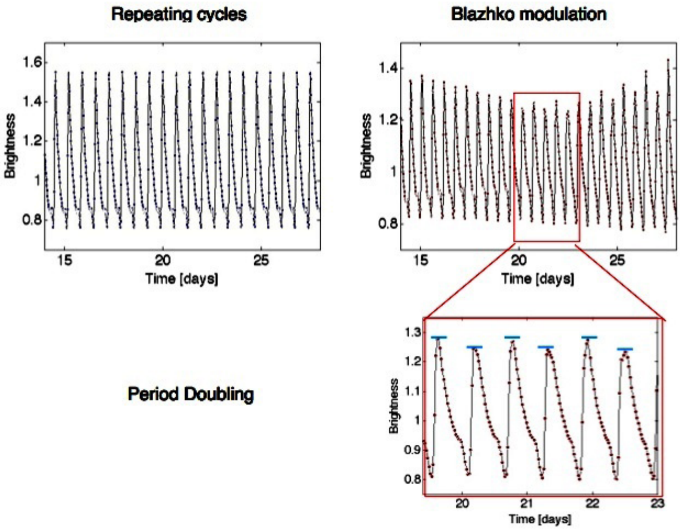

Figure 5. Period doubling manifesting in alternatingly higher and lower maxima, as seen in a star with Blazhko modulation (RR Lyr itself, top right panel). Period doubling is not seen in non-modulated stars (top left panel).

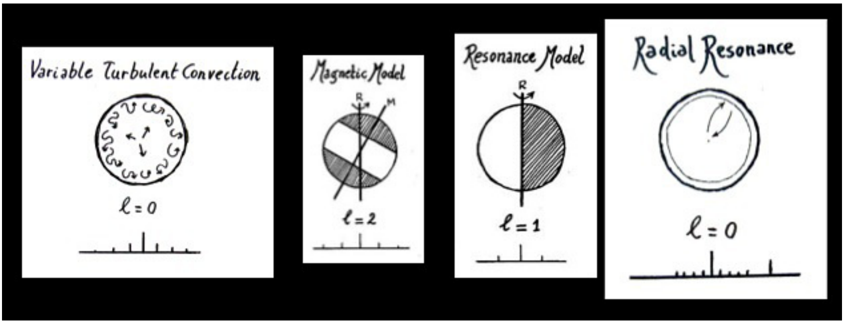

Figure 6. Models for the Blazhko effect: the present hierarchy.