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Investigation of RV Tauri-type pulsating variable stars in the era of space telescopes

PhD thesis statements

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Scientific background

After central helium burning, stars of Population II with masses higher than 0.5 $M_\odot$ evolve from the horizontal branch (HB) towards the asymptotic giant branch (AGB). During the numerous thermal pulses that occurs during their evolution away from the HB, the stars may cross the instability strip and start pulsating. Such stars are called type II Cepheids or Population II Cepheids. Their periods range from 1 d for stars to about one month at higher luminosities (Aerts, Christensen-Dalsgaard & Kurtz, 2010).

The longer period Population II Cepheids were originally also discovered by Henrietta Leavitt early in the 20th century; they have been called the W Virginis stars for a long time. Today, the Type II Cepheids are divided in groups by period, such that the stars with periods between 1 and 5 d (BL Her class), 10 to 20 d (W Virginis class), and longer than 20 d (RV Tauri class) have differing evolutionary histories (Wallerstein, 2002). This division is actually completely arbitrary.

The RV Tauri variables constitute a small group of pulsating stars with some dozen known members in the Milky Way and a similar number of variables in the Magellanic Clouds. They are low metallicity, low mass ($\sim$0.5-0.8 $M_\odot$), F-, G-, and K-type supergiants with an average effective temperature of 5000-6000 K. They form the high-luminosity extension of Population II Cepheids near the cooler edge of the classical instability (IS). They are rapidly evolving through the post-RGB/AGB IS to become planetary nebulae (Manick et al., 2018, Kamath, Wood & Van Winckel, 2015, 2014, Jura, 1986).

Among the post-AGB variables, the most regular, Cepheid-like pulsations, belong to the RV Tauri stars. The main characteristics of the light curve is the presence of alternating minima (i.e., every second minimum is shallower). The observed periods usually fall between 20 and 90 days. The periodicity is not strict, as the cycle-to-cycle variations can be quite significant. Some RV Tau stars show long-term modulation of the mean brightness with periods of 700–2500 days. For decades, the phenomenon has been associated with dust surrounding the stars, during which obscuration is caused by the pulsating star orbiting in a binary surrounded by a large opaque screen; during long-term minima, the pulsating component is hidden by the dust screen, during maxima the star becomes visible (Fokin, 1994, Pollard et al., 1996, Van Winckel et al., 1999, Fokin et al., 2001, Maas, Van Winckel & Waelkens, 2002, Gezer et al., 2015). The absence or presence of the slow modulation is the basis for classifying the stars into the RVa and RVb photometric subclasses, respectively.

Previous studies on the period–luminosity (PL) relations of RV Tauri stars were almost exclusively based on various samples of Population II Cepheids in the Magellanic Clouds or in globular clusters. There were hints of a different slope for longer-period Type II Cepheids (McNamara, 1995), which was found to depend on the wavelength of the observations, with negligible effects in the JHK_S bands (Matsunaga et al., 2006). Recent results (Groenewegen & Jurković, 2017, Manick et al., 2017) presented supporting indications of a steeper RV Tau PL relation for the dusty objects in the Magellanic Clouds and the Milky Way, respectively.

Until now, no PL relation has been published for nearby, bright, and, in all other aspects, well-observed Galactic RV Tauri stars. *Gaia* Data Release 2 (DR2) has opened, for the first time, the possibility of a geometric distance measurement of Galactic RV Tau stars.

Research methods

During my doctoral research, for the first time, I have been studying in details the RV Tauri-type star, DF Cygni, using the most accurate photometric measurements ever obtained. I supplemented the measurements of the *Kepler* space telescope, which provided extremely accurate data, with visual observations collected by amateur astronomers for decades and analyzed them using Fourier- and wavelet-analysis and the traditional O–C method. Using the results of the latest hydrodynamic models, I drew conclusions about sudden changes in the light curve. Based on the several decade long measurements, I studied the stability of the high-amplitude long-term variation, from which important constraints could be drawn on the possible physical explanations of the brightness changes of the star.

Although, due to their rapid evolution (i.e. their short lifetime), we only know a few RV Tauri-type stars, after studying single objects I studied the brightness variation of several stars collectively. The goal was to reveal the relationship between the periodic changes of the RVb sub-type on longer (several-hundred-day) and shorter (few-ten-day) timescales, thereby supporting the dust obscuration model. For the analysis, I determined the local average brightness (in flux units) and the brightness difference between the minimum and maximum light caused by pulsation (i.e. the local pulse amplitude), also in flux units, for each pulsation cycle of each star. My results suggest that previous authors have failed to notice that the data actually supports the expected pulsation amplitude changes due to the dust obscuration. To recognize this, it was necessary to use the measurements in flux units, which is naturally supported by the *Kepler* space telescope, since all *Kepler* data is available in flux units.

In the last phase of my research, I used the data of the astrometric satellite *Gaia*, launched by the European Space Agency in December 2013, to study several RV Tauri stars collectively. The second data release, published in April 2018, also contains a large number of high-precision parallaxes for pulsating stars. Using statistical methods, with these data complemented with ground-based photometric and spectroscopic measurements, I have been able to determine the distances, luminosities and radii of several galactic RV Tauri stars. I have established the strict relationship between the pulsation period and luminosity, which has been known for the population of Magellanic Clouds, stellar associations, and globular clusters, for the galactic stars as well. Based on their position on the Hertzsprung–Russell diagram and stellar evolutionary models, I have drawn conclusions on the evolutionary history of RV Tauri stars.

Results

1. I have combined almost 50 yr of visual observations from the American Association of Variable Star Observers and about four years of *Kepler* data to perform the most detailed light curve analysis of an RV Tau-type variable star, DF Cyg, ever obtained.
(Bódi, Szatmáry, Kiss, 2016, A&A, 504, 24)

1.a I showed that the bright RVb-star, which is a typical member of the class, showing a prominent long-period mean brightness change and Cepheid-like pulsations that change constantly in amplitude and phase.

1.b In the Fourier spectrum of the *Kepler* data, I revealed a characteristic set of subharmonics, which indicate the presence of a complex period-doubling pattern. I clearly showed that the time-frequency distributions show the non-repetitive variations of the amplitudes.

1.c In the *Kepler* light curve, I detected some transients, during which the anti-correlated period and amplitude variations could be an indication of emerging non-linear effects.

1.d The long-term coherence of the RVb modulation is consistent with binary motion, and I noted some similarities with the long secondary periods of the pulsating red giants.

2. I have compiled the most complete sample of RVb-type variables, using visual observations, ground-based CCD photometric measurements, and ultra-precise data from the *Kepler* space telescope.
(Kiss, Bódi, 2017, A&A, 608, 99)

2.a I found a ubiquitous linear correlation between the pulsation amplitude and the mean brightness, when both are measured in flux units. There is a one-to-one correspondence between their relative changes, meaning that the pulsation amplitude actually remains constant throughout the RVb cycle, when measured relative to the system flux level.

2.b The properties of the correlation can be naturally explained by a mechanism that equally affects the mean flux and the apparent amplitude, meaning that the whole light curve is scaled by a time-dependent factor.

Periodically variable obscuration by a large opaque screen, presumably corresponding to a circumbinary dust disk, provides the required mechanism.

2.c According to my conclusions the light variations of RVb-type stars can be fully explained phenomenologically by the combination of time-dependent non-linear pulsations and the dust obscuration model of the RVb phenomenon. There is no need to assume any further exotic interactions and complicated phenomena.

3. To compare the RV Tau populations of the Milky Way and the Magellanic Clouds and the universality of their PL relations, I have compiled the most reliable, high-confidence collection of galactic RV Tauri stars complete with well-determined *Gaia* DR2 distances.
(Bódi, Kiss, 2019, ApJ, 872, 60)

3.a I showed that *Gaia* DR2 effective temperatures for RV Tau-type stars deviate significantly from the spectroscopically determined values. They are lower with a mean shift of $\sim$436 K. The reason for this systematics is the lack of reddening correction for stars that lie in the location of RV Tau-type stars in the Hertzsprung–Russell diagram.

3.b I discussed the evolutionary status of galactic RV Tau-type stars, which is fairly ambiguous. The most luminous ones that are brighter than the tip of the red giant branch of 1 $M_\odot$ model are presumably post-AGB objects that are descendants of stars with masses higher than 1 $M_\odot$. Fainter ones are probably post-AGBs if they have an initial mass between $\sim$2-4 $M_\odot$. Otherwise, they likely were formed from lower-mass binary post-RGB progenitors. Others are probably post-RGB binary stars with lower progenitor masses.

3.c From the position of stars in the Hertzsprung–Russell diagram, I came to the conclusion that the IS of RV Tauri stars has a broader extension in the cooler range than the classical IS of classical Cepheids.

3.d I derived parallax-based period–luminosity and period–radius relations for galactic RV Tauri-type variable stars. These stars follow steeper period–luminosity and period–radius relations than those of the Population

II Cepheids with shorter pulsation periods.

3.e For the first time, I derived a period–absolute magnitude relation between the period of the mean-brightness variation of RVb stars and their V-band absolute magnitude. However, this relation is based on a very low number of stars; further observations will be needed to confirm this correlation.

3.f I found that the median mass of RVa stars is around 0.45–0.52 $M_\odot$, which is in agreement with Type II Cepheid model calculations. The mass distribution of our very small sample of RVb stars is sort of bimodal, with masses around $\sim$0.7 $M_\odot$ and $\sim 1.8_\odot$.

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Publications

Publications associated with the thesis

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1. **Bódi, A.**, Kiss, L. L.: *Physical properties of galactic RV Tauri stars from Gaia DR2 data*, 2019, Astrophysical Journal, 872, 60
2. Kiss, L. L., **Bódi, A.**: *Amplitude variations of modulated RV Tauri stars support the dust obscuration model of the RVb phenomenon*, 2017, Astronomy & Astrophysics, 608, 99
3. **Bódi, A.**, Szatmáry, K., Kiss, L. L.: *Periodicities of the RV Tauri-type pulsating star DF Cygni: A combination of Kepler data with ground-based observations*, 2016, Astronomy & Astrophysics, 596, 24

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