

Session 1A: DATA  
Ground-based observations

## Photometric observations of pulsating stars (ground-based)

S. O. Kepler<sup>1</sup>

<sup>1</sup> Instituto de Física, Universidade Federal do Rio Grande do Sul, 91501-970 Porto Alegre, RS, Brazil

### Abstract

The study of pulsating stars through photometric observations, specially time series photometry, has grown from visual to single channel photometry, double and triple channel and finally CCD photometry. The continuous measurement of the pulsating star, simultaneously with accurate sky measurements and several comparison stars, has allowed a huge increase in the detectability of low amplitude pulsations, and the possible correction of thin cloud and atmospheric variability, which can occur at timescales of minutes, due to g-modes on the Earth atmosphere. It has also been crucial to be able to use comparisons brighter than the target star and less than a few arcminutes from the pulsating star, decreasing the noise introduced in the differential photometry due to noise in the comparisons. On 4m class telescopes, and prime focus on 2m class telescopes, we can routinely achieve 1 mmag precision up to 19th mag stars, allowing the study of distant stars and possibly different populations. To be able to measure multiple periods present in non-radially pulsating stars, it is necessary to observe the star for several beat periods, and multi-site campaigns, with networks such as the Delta Scuti Network and the Whole Earth Telescope, for example, have allowed such long observations, lasting of the order of two to five months. On the data analysis side, corrections of the observations times to the barycenter of the solar system became necessary to join long data sets, and Monte Carlo simulations of the time series allowed an efficient way to estimate the detection limits for time series with gaps and multiperiodic, where the noise distribution is not Poissonic. The discovery of many pulsation modes in nonradially pulsating stars, as Delta Scuti, roAp, the Sun and white dwarf stars, has allowed seismological studies measuring accurately several internal properties of these pulsating stars, as each mode of pulsation is an independent measurement of the stellar structure, and both g-modes and p-modes in general sample a large fraction of the star. It has become evident that most types of pulsators show amplitude variations on timescales of weeks to years, even when we can untangle the individual modes, i.e., correct by the beating of nearby modes. These changes are most likely on timescales comparable to the growth timescales of the different modes and should carry detailed information on the instability mechanism. White dwarf pulsators show the largest number of pulsation modes detected after the Sun. Their study has allowed a strong test on stellar evolution and high density physics, including their secular time change rate, placing these stars in levels comparable to large collider experiments.

Individual Objects: GD 358, PG 1159-035, G 117-B15A, FG Vir

### Introduction

Delta Scuti, roAp (e.g., Kurtz et al. 2005), sdBs, ZZ Ceti, DBVs, DOVs, Herbig Ae stars (e.g., Bernabei et al. 2007), and several other classes of pulsators show multiperiodic nonradial pulsations that carry information on the stellar structure.

The study of variable stars outgrew the single channel photometry to two channels, where a star plus a nearby comparison star were observed simultaneously to allow the detection of variability due to the Earth's atmosphere, and therefore not intrinsic to the star (Nather 1973). Later three channel photometers were introduced, where in addition to the variable star plus comparison, a sky channel is measured continuously and simultaneously (Nather et al. 1990), as the Earth's atmosphere also undergoes g-modes, on timescale around a few hundred seconds and longer, comparable to the stellar pulsations we aim to detect.

More recently, the readout noise reduction and improvements in blue sensitivity in CCDs has allowed star, several comparison stars, and sky measurements simultaneously, improving the detection limits (e.g., O'Donoghue 1995, Nather & Mukadam 2004). To achieve 1 mma (fraction intensity variation) detection level, it is recommended to obtain flat field measurements with at least a signal-to-noise ratio of  $S/N=1000$  at 1% linearity, which in general requires 100 flat field exposures, keeping the counts at a fraction of the full well capacity to assure such linearity. The routine use of autoguiders, maintaining the stellar image in a few fixed pixels and the use of at least two comparison stars -preferably brighter than the target star, the use of frame transfer, low duty cycle or windowing and precise timings have allowed the detection of low amplitude variability (e.g., Castanheira et al. 2007) for stars previously reported as stable. Note that the use of CCDs with different quantum efficiencies and different observatory altitudes affects the measured amplitudes and even phases, caused by chromatic effects. Most variable stars exhibit chromatic amplitude and phase changes, which can be used for mode identification (e.g., Kepler et al. 2000).

For data reduction, it is necessary to include leap second corrections and convert the timings to the barycenter of the solar system in order to prevent the introduction of timescale variability caused by the Earth's orbit (e.g., Kepler et al. 2005). The optimum extraction techniques, aperture or profile fittings with addition of residuals have been discussed, for example, by Kjeldsen & Frandsen (1992), Kanaan et al. (2000), and Handler (2003a). I have a preference for weighted apertures. Care must also be taken with the extinction correction, as the colors of the nearby comparison stars, in general, cannot be chosen to match the color of the target star. For eclipsing pulsators, data reduction must account for the change in surface area during ingress and egress (e.g., Vuckovic et al. 2007).

The recent development of fast readout CCDs has allowed the search for variability on timescales much shorter than one second, for example with the Ultracam (Dhillon et al. 2007, Silvotti et al. 2007a).

## Multisite campaigns

To detect multiperiodicities closely spaced in frequency and separate real amplitude variations from beating, continuous data sets, and therefore network observations, are necessary. Examples are: (i) The DSN (Delta Scuti Network) which started in 1983, with at least 29 campaigns to date. The DSN 25 campaign for FG Vir in 2004 detected a total of 79 frequencies (Breger et al. 2005, Breger & Pamyatnykh 2006); (ii) Stephi, a 3-site Delta Scuti network which started in 1987 and reached 15 campaigns in 2006 (Michel et al. 2000); (iii) The Whole Earth Telescope (WET), started in 1988 and in 2008 reaching 26 campaigns, with repeated observations of GD 358 (Winget et al. 1994, Vuille et al. 2000, Kepler et al. 2003 and Provencal et al. 2008) and PG 1159-035, for which a total of 198 independent frequencies have been detected, of which 29 are triplets and 46 are quintuplets (Winget et al. 1991, Costa et al. 2008), the largest number of modes detected after the Sun. WET has also been used to study Delta Scuti stars (e.g., Breger & Handler 1993, Handler et al. 1997) and roAp stars (e.g., Kurtz et al. 2005). In fact, all networks found that repeat observations are necessary, as the detected pulsation modes in general change from year to year (e.g., Kleinman et al. 1998, Vuille 2000, Breger et al. 2005, Kurtz et al. 2005). Handler (2003b) discusses the application of statistical weights when combining data from telescopes with different apertures and noise distribution.

## Fourier Transforms

Considering the noise distribution is not Poissonic due to the multiperiodicities, and the data are not equally spaced, it is necessary to perform Monte Carlo simulation, shuffling the data in the time domain to estimate the false alarm probability and subsequent identification the multiple modes through pre-whitening in the light curve domain, fitting the light curves with non-linear least square algorithms. With the advances of fast computers, discrete Fourier transforms have become the norm, instead of the fast Fourier algorithms that require equally spaced data (e.g., Kepler 1993).

## Amplitude Changes

Most pulsators show amplitude changes on timescales of days to years, for example GD 358 (Kepler et al. 2003, Provencal et al. 2008) and other DBVs (Handler et al. 2003). The DOV PG 1159-035 also show amplitude variations, but no harmonics or combination modes were detected and the models show no significant convection zone (Costa et al. 2008). Several Delta Scuti stars (e.g., Breger & Lenz 2008, Breger, Davis & Dukes 2008) and Cepheids (e.g., Breger 2006) are also observed to show amplitude variations.

Several pulsators show combination frequencies (e.g., Vuille et al. 2000, Kepler et al. 2003, Breger & Kolenberg 2006), which can be used to study convection (e.g., Montgomery 2005, 2008a), mode identification (e.g., Yeates et al. 2005), and the amplitude limitation mechanism (e.g., Montgomery 2008b).

## Rate of Change with Time

With repeat observations over up to 34 years, it has been possible to detect the secular rate of period change. For example, for G 117-B15A (Kepler et al. 2005), the most stable optical clock known, it was possible to measure the timescale for evolution and infer the core composition. For PG 1159-035, Costa, Kepler, & Winget 1999, and Costa & Kepler (2008) report a measurement of  $dP/dt$  for multiple modes, allowing an estimation of  $dP_{\text{rotation}}/dt$ ,  $dR/dt$ ,  $dT/dt$ , and even  $d^2P/dt^2$ . Althaus et al. (2008a) used the multiple  $dP/dt$  to demonstrate that the star has a thin He envelope.

## Conclusions

It is important to note that rotation causes multiplets to have different amplitudes, and amplitude changes possibly caused by energy exchange with rotation. Gough (2007) points out the following: "No matter what the distortion of the eigenfunction, and from no matter what source it arises, nonrotating stars don't know the difference between their left and their right. Left - right is the only property that distinguishes between  $m = +1$  and  $m = -1$ , but the latter is a matter of one's choice of coordinate axis, which a star cannot know. Only when the star is rotating, there is a physically real principal axis, an axis which we are forced to adopt for describing eigenmodes; that axis has a well-defined directed orientation, and therefore can tell the star which is the left and which is the right. It is quite different from the principal axis of the distortion caused by any other, axisymmetric, force, such as a magnetic field, for example, which has direction, of course, but is not orientated. So if there is an  $m = +1$ ,  $m = -1$  asymmetry, whether it be in photometric or in spectroscopic data, it has to be a consequence of rotation."

Considering that white dwarf pulsations are global and sample almost the whole interior of white dwarf stars, seismologically determined masses (e.g., Winget et al. 1991, 1994, Costa et al. 2008, Córscico et al. 2008, Althaus et al. 2008b) can be more accurate than those

obtained from binary solutions. Asteroseismology is the only tool to measure the surface layer masses, which are determined from the up-to-now not accurately modeled mass loss through stellar evolution. For example, Castanheira & Kepler (2008) measured the hydrogen layer mass for a set of ZZ Ceti stars.

The rates of change of the pulsation periods are measurable and can be used to precisely measure the evolutionary rates of these stars, to detect planets around them (e.g., Silvotti et al. 2007b), and to probe for exotic particles that are strong candidates for dark matter (e.g., Winget et al. 2004, Kepler 2004).

On mode properties, there are still several unanswered questions, as pointed out by Winget & Kepler (2008): what is (are) the driving, mode selection, and amplitude limiting mechanism(s)? Are they the same for all instability strips and throughout each strip? Are the amplitude and phase changes on timescales from days to years due to the different growth timescales? What is the origin, role, and nature of mode coupling? What is the role of inclination in *m*-selection, considering we see the amplitude of different *m* components change with time in a few stars? Are there pulsations with higher values of the spherical harmonic degree? Can we identify the modes with chromatic amplitude and combination peaks?

Ground-based photometry continues to be the fundamental tool for the study of pulsating stars, and improvements in instrumentation and analysis tools have allowed continuous progress.

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## DISCUSSION

**Dziembowski:** Is the total pulsational energy conserved when the dramatic changes in oscillation spectrum occur?

**Kepler:** In general terms, yes. For PG1159.035 and GD358, when we consider the total energy in pulsations, it is the same within a factor 2 over the years. This is within our uncertainties, as the amplitude uncertainties for each mode is of the order of 20%.

**Breger:** The  $\delta$  Scuti stars may be different: for amplitude changes, the energy is not conserved among visible modes.

**Guzik:** What does the second time derivative of period tells you about the star physically?

**Kepler:** Pre-white dwarfs are cooling rapidly. Also, the cooling rate is changing rapidly.

## Spectroscopic observations of pulsating stars

C. Aerts<sup>1,2</sup>, M. Briquet<sup>1</sup>, F. Carrier<sup>1</sup>, M. Desmet<sup>1</sup>, and W. Zima<sup>1</sup>

<sup>1</sup> Instituut voor Sterrenkunde, Celestijnenlaan 200D, B-3001 Leuven, Belgium

<sup>2</sup> Department of Astrophysics, IMAPP, Radboud University Nijmegen, PO Box 9010, 6500 GL, Nijmegen, the Netherlands

### Abstract

During the past three decades, astronomers have been gathering extensive time series of high-precision spectroscopy of pulsating stars. In contrast to one-shot spectra, which provide the fundamental parameters, time-resolved spectroscopy offers a much broader variety of input for asteroseismology. The most important applications encompass the determination of the radial-velocity amplitudes and phases of the modes, the detection of modes that are invisible in photometry, the identification of the azimuthal orders through specialised methodology, the unravelling of pulsational and orbital motions, and, since a few years, the detection of solar-like oscillations in various types of stars. We discuss the input that spectroscopic time series can provide for asteroseismic modelling, for various types of pulsators. We end with some future prospects of how spectroscopy can help to push seismic applications beyond the present achievements.

Individual Objects:  $\beta$  Cep,  $\beta$  CMa,  $\nu$  Eri,  $\theta$  Oph,  $\delta$  Cet, FG Vir, Procyon,  $\eta$  Boo,  $\alpha$  Cen A,  $\beta$  Hyi

### Spectra for fundamental parameter determination

Time-resolved spectroscopy alone usually does not yet imply sufficient information to interpret the oscillation spectra of stars. The limited number of detected frequencies and lack of unambiguous mode identification on the one hand, and the limitations of the validity of the theoretical models on the other hand, require us to consider additional information to limit the grids of models for seismic tuning. This additional information usually consists of the fundamental parameters of the star, such as its effective temperature, gravity, luminosity, rotation velocity and abundances. A high-precision determination of the fundamental parameters of asteroseismic targets remains of importance. This can be achieved partly through photometric data, but the abundances and rotation information must come from high-resolution spectroscopy. Large systematic differences occur when comparing quantities derived from photometric calibrations and from spectroscopic diagnostics (e.g., De Ridder et al. 2004). It is obvious that photometric data, even for well-calibrated narrow filter systems, can never deliver the same accuracy as high signal-to-noise high-resolution spectroscopy. On the other hand, uncertainties in atmosphere model computations (e.g. in terms of atomic data, non-LTE effects, line blocking, mass loss effects, etc.) along with imperfect continuum normalisation imply systematic uncertainties.

Modern applications of spectroscopic fundamental parameter determination for various pulsators are available in, e.g., Gillon & Magain (2006), Morel et al. (2006), Lefever et al. (2007), Bruntt et al. (2008). These works all show that such type of classical work remains of importance, since more precise results are found each time the data

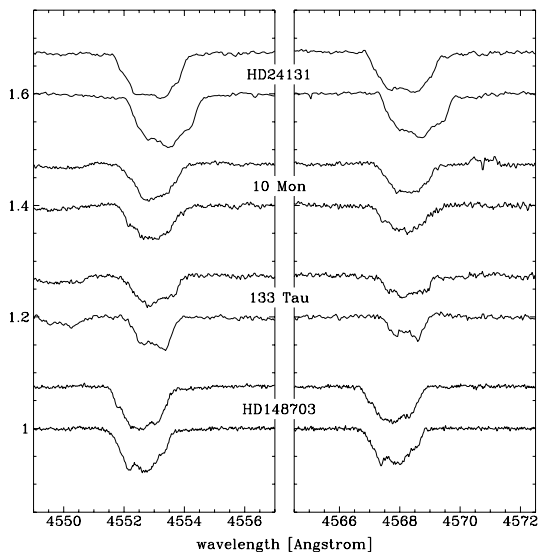


Figure 1: Snapshot spectra from the line-profile survey of bright B-type stars by Telting et al. (2006).

quality and model atmosphere computations improve. In particular, the addition of polarimetric information besides classical spectroscopy has revealed a number of surprises, such as the discovery of magnetic fields in hot Be stars (e.g., Neiner 2007 for a review) and in half of the slowly pulsating B stars (Hubrig et al. 2006).

Precise abundance determinations are also relevant in the context of the discovery of massive pulsators in the Magellanic Clouds (e.g. Kołaczowski et al. 2006, Karoff et al. 2008, Sarro et al. 2008). For the modes in such stars to be excited, a higher-than-average SMC metallicity is needed (Miglio et al. 2007). This implies that the opacities are still too low and/or atomic diffusion processes (Montalbán & Miglio 2008) are not yet well included in the models.

## Spectroscopic surveys to discover pulsators from line features

While large-scale photometric searches for new pulsators have been ongoing since the 1950s, we had to await for improvements in the efficiency of high-resolution spectroscopic instrumentation, which was achieved only since the mid 1980s, to start systematic searches for line-profile variables. At first this was done in a biased way, in the sense that the results from photometric surveys were used for the target selection of the spectroscopic surveys, e.g., Solano & Fernley (1997) for  $\delta$  Sct stars, Aerts et al. (1999) for slowly pulsating B stars, Mathias et al. (2004) and De Cat et al. (2006) for  $\gamma$  Dor stars, Kurtz et al. (2006) for roAp stars, Lefever et al. (2007) for hot supergiants, etc.

Unbiased high-resolution spectroscopic surveys are scarce and still limited to bright stars. A notable achievement was the long-term survey assembled by Telting et al. (2006) who took spectra for an almost complete sample of stars with spectral type between B0 to B3 and with visual magnitude below 5.5. They discovered that line-profile features occur in 65% of their 171 monitored stars. Examples are shown in Fig. 1. While not necessarily all of



them are pulsators, this is a much higher percentage of variability than the one found from photometric surveys. The explanation is that most line-profile variables turn out to have bumpy line features, which points to modes of degree above 2, which have amplitudes too low to be detected in ground-based photometry. This result is in full agreement with the survey of 27 monitored bright southern early-type Be stars by Rivinius et al. (2003), who find 25 of them to be nonradial pulsators.

As a side result, spectroscopic binaries were discovered from these spectroscopic surveys. Each of the discovered line-profile variables is in principle suitable for seismic tuning. This requires dedicated long-term follow-up spectroscopy as described below, but with the additional challenge that we cannot rely on photometric time series to deliver the mode degrees.

## Time series for radial-velocity variations of solar-like pulsators

The oscillations of the Sun are caused by turbulent convective motions near its surface. Such oscillations are thus expected to occur in all stars with outer convection zones. The first firm detection of individual frequencies was achieved from time-resolved spectroscopy of the G5IV star  $\eta$  Boo (Kjeldsen et al. 1995). Even though Brown et al. (1997) could not establish a confirmation of this detection, the result was confirmed by Kjeldsen et al. (2003) and Carrier et al. (2005). Solar-like oscillations were also definitely established in Procyon (Martić et al. 1999), in the G2IV star  $\beta$  Hyi (Bedding et al. 2001) as well as in the G2V star  $\alpha$  Cen A (Bouchy & Carrier 2001).

With the availability of high-precision spectrographs, built mainly for planet hunting, more discoveries were made. Several review papers on this topic already exist, so we refer the reader to those rather than repeating them here (e.g., Bedding & Kjeldsen 2007). Meanwhile, solar-like oscillations have been firmly established in some 30 stars. Their position in the HR Diagram is provided in Aerts et al. (2008). Their frequency separations behave as expected from theoretical predictions and scaling relations based on extrapolations from helioseismology (e.g., Kjeldsen & Bedding 1995, Samadi et al. 2005).

The level of sophistication in the seismic modelling of solar-like oscillators is still far from the one in helioseismology. However, given that the detections were established only recently and that the space missions CoRoT and Kepler will add numerous cases of stars with uninterrupted photometry, we expect a breakthrough in the near future.

## Time series for mode identification of classical pulsators

Pulsators excited by the  $\kappa$ -mechanism usually do not give rise to many detected frequencies, nor to frequency separations. Before seismic modelling can be attempted for such stars, it is necessary to achieve empirical mode identification based on data. The gathering and interpretation of time-resolved high-resolution spectroscopy for mode identification was pioneered in the 1980s by M. Smith and his collaborators as well as by D. Baade. These teams obtained such type of data with the very first high-resolution spectrographs for various types of pulsating stars along the main sequence and compared these with theoretical predictions through line-profile fitting (e.g., Campos & Smith 1980a,b; Baade 1982, 1984; Smith 1983, 1985a,b, 1986; Smith et al. 1984).

To make the mode identification more objective, quantitative spectroscopic mode identification methods have been developed meanwhile. The idea is to compute carefully defined diagnostics from the observed line profiles and compare them with theoretical predictions based on the theory of stellar oscillations. One such method is based on the moment variations of the spectral lines and was first introduced by Balona (1986a,b, 1987) and further developed by Aerts et al. (1992), Aerts (1996), Cugier & Daszyńska (2001) and Briquet & Aerts (2003). This method has meanwhile been applied to many different types of pulsators along the

Table 1: Comparison of the results for the mode identification of the  $\delta$  Sct star FG Vir, as available in the literature. Whenever more than one value for  $\ell$  or  $m$  is given in a column, discrimination among them was impossible.

| Frequency<br>$\text{d}^{-1}$ | Viskum<br>et al.<br>(1998) | Breger<br>et al.<br>(1999) | Daszyńska-<br>Daszkiewicz<br>et al. (2005b) | Zima et al. 2006 |             |
|------------------------------|----------------------------|----------------------------|---|------------------|-------------|
| 9.199                        | $\ell = 2$                 | $\ell = 2$                 | $\ell = 2$                                  | $\ell = 1, 2, 3$ | $m = +1$    |
| 9.656                        | $\ell = 2$                 | $\ell = 1, 2$              | $\ell = 2$                                  | $\ell = 0, 1, 2$ | $m = 0$     |
| 12.154                       | $\ell = 0$                 | $\ell = 0$                 | $\ell = 0$                                  | $\ell = 0, 1, 2$ | $m = 0, +1$ |
| 12.716                       | $\ell = 1$                 | $\ell = 1$                 | $\ell = 1$                                  | $\ell = 1$       | $m = 0$     |
| 12.794                       | –                          | –                          | $\ell = 2, 1$                               | $\ell = 2, 3, 4$ | $m = -2$    |
| 16.071                       | –                          | –                          | $\ell = 0$                                  | –                | –           |
| 19.227                       | –                          | –                          | $\ell = 2, 1, 0$                            | $\ell = 1, 2$    | $m = +1$    |
| 19.867                       | $\ell = 2$                 | $\ell = 2$                 | $\ell = 2, 1$                               | $\ell = 0, 1, 2$ | $m = 0$     |
| 20.287                       | –                          | –                          | $\ell = 0, 1$                               | $\ell = 1, 2, 3$ | $m = -1$    |
| 20.834                       | –                          | –                          | –   | $\ell = 2, 3, 4$ | $m = +1$    |
| 21.051                       | $\ell = 2$                 | $\ell = 2$                 | $\ell = 1, 0$                               | $\ell = 0, 1, 2$ | $m = 0$     |
| 23.403                       | $\ell = 0$                 | $\ell = 0, 1$              | $\ell = 2, 1$                               | $\ell = 2$       | $m = 0$     |
| 24.227                       | $\ell = 1$                 | $\ell = 1, 2$              | $\ell = 1$                                  | $\ell = 0, 1$    | $m = 0$     |

main sequence (Aerts & De Cat 2003). It is very powerful for low-degree modes ( $l \leq 4$ ) in slow rotators ( $v \sin i \leq 50 \text{ km s}^{-1}$ ). Another quantitative method was introduced by Gies & Kullavanijaya (1988) and further developed by Kennelly & Walker (1996), Telting & Schrijvers (1997), Mantegazza (2000) and Zima (2006). Applications are available in, e.g., Telting et al. (1997) for the star  $\beta$  Cephei and in Zima et al. (2006) for the  $\delta$  Sct star FG Vir. Its strength is the relatively easy application to fast rotators ( $v \sin i \geq 50 \text{ km s}^{-1}$ ) with high-degree modes ( $l \geq 4$ ). Both methods were integrated in the software package FAMIAS (Zima 2008). We refer to the review paper by Telting (2008, these proceedings) for illustrations and more details on their use. Examples were presented during the workshop by Pollard et al., Castanheira et al., Lehmann et al., Oreiro et al., Østensen et al., Vučković et al., Wright et al., Tkachenko et al., illustrating the need of, and interest in empirical mode identification for asteroseismology of classical pulsators.

One of the problems that occurred in the past for empirical mode identification was the inconsistency in the results derived from photometric observables (see review talk by Handler 2008) and spectroscopy. Recent studies have shown, however, that fully consistent solutions are found if one uses data from multisite multitechnique campaigns (e.g., De Ridder et al. 2004, Zima et al. 2006), pointing out that the previous discrepancies were probably due to unresolved beating phenomena and/or too uncertain amplitudes. Zima et al. (2006) succeeded to identify twelve modes for the  $\delta$  Sct star FG Vir (Table 1).

Whenever modes are detected in both multicolour photometry and high-resolution spectroscopy, one can do better than simply compare the mode identification results by exploiting the data simultaneously. Daszyńska-Daszkiewicz et al. (2005a) added the amplitude and phase of the first moment to the multicolour amplitudes and phases in order to obtain a safer mode identification for the  $\beta$  Cep stars  $\delta$  Ceti and  $\nu$  Eridani. For such an application, the data should be taken quasi-simultaneously to avoid different beat patterns to occur in the two types of data. Daszyńska-Daszkiewicz et al. (2005a) also derived information on the most appropriate opacities to explain the modes. Mazumdar et al. (2006) and Briquet et al. (2007) used a different integration of both types of data, by imposing the identified degree  $\ell$  from photometric amplitude ratios into the spectroscopic mode identification, leading to secure identification of the azimuthal order  $m$ . It is this combined method that led to successful seismic modelling of the  $\beta$  Cep stars  $\beta$  CMa and  $\theta$  Oph.

## Future improvements

The examples discussed above show how to pave the way to seismic modelling of classical pulsators: perform multisite and/or space photometric observations along with spectroscopic campaigns that cover the beat patterns of the oscillations. This is why a large programme of spectroscopy has been set up to accompany the CoRoT space photometry (e.g., Uytterhoeven et al. 2008).

Besides such long-term spectroscopic campaigns, one can gain from an integrated spectroscopic/interferometric approach. Cunha et al. (2007) provided a list of bright stars for which a direct radius estimate with a relative precision better than a few % can be obtained from VLTI/AMBER. Similarly, the masses of SB2 binaries with a pulsating component can be derived with a precision of only a few % by combining interferometric and spectroscopic monitoring (e.g., Aussenloos et al. 2006). The future upgrades of VLTI should also allow, in principle, the modes to be identified from spectro-interferometric data (e.g., Jankov et al. 2001). Finally, the Gaia space mission will deliver us accurate distances and, by implication, luminosities and radii of a vast amount of pulsators too faint to be analysed with VLTI.

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## DISCUSSION

**Kovács:** What are expected photometric amplitudes for spectral line variables based on their observed spectroscopic data?

**Aerts:** From the mode identification and velocity amplitudes derived from spectroscopy, we find typically modes with degrees  $\ell > 2$  and these would result in photometric amplitudes typically below 1 and occasionally a few mmag. You can thus see them in a quite long photometric time series or not at all. This is in agreement with time series assembled by the WIRE and MOST which reach lower amplitudes than typical ground-based photometric campaigns.

## Multi-wavelength photometric variation of PG 1605+072

S. Schuh<sup>1</sup>, S. Dreizler<sup>1</sup>, U. Heber<sup>2</sup>, C.S. Jeffery<sup>3</sup>, S.J. O'Toole<sup>2,4</sup>, O. Cordes<sup>5</sup>, T. Stahn<sup>1,6</sup>,  
R. Lutz<sup>1,6</sup>, A. Tillich<sup>2</sup>, and the WET and MSST collaborations

<sup>1</sup>Institut für Astrophysik, Georg-August-Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen,  
Germany

<sup>2</sup>Dr. Reimis-Sternwarte Bamberg, Universität Erlangen-Nürnberg,  
Sternwartstraße 7, Germany

<sup>3</sup>Armagh Observatory, College Hill, Armagh BT61 9DG,  
Northern Ireland, United Kingdom

<sup>4</sup>Anglo-Australian Observatory, P.O. Box 296, Epping, NSW 1710, Australia

<sup>5</sup>Argelander-Institut für Astronomie, Universität Bonn,  
Auf dem Hügel 71, 53121 Bonn, Germany

<sup>6</sup>Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Straße 2,  
37191 Katlenburg-Lindau, Germany

### Abstract

In a large coordinated attempt to further our understanding of the p-mode pulsating sdB star PG 1605+072, the Multi-Site Spectroscopic Telescope (MSST) collaboration has obtained simultaneous time-resolved spectroscopic and photometric observations. The photometry was extended by additional WET data which increased the time base. This contribution outlines the analysis of the MSST photometric light curve, including the four-colour BUSCA data from which chromatic amplitudes have been derived, as well as supplementary FUV spectra and light curves from two different epochs. These results have the potential to complement the interpretation of the published spectroscopic information.

Individual Objects: PG 1605+072

### Multi-Site Spectroscopic Telescope for PG 1605+072

#### Introduction and MSST overview

PG 1605+072 is a pulsating subdwarf B star evolving off the EHB. Observationally, it may be considered a sibling among sdBs of the even brighter star Balloon 090100001; both stars are multiperiodic and pulsate each with the largest amplitude among the sdBs of  $\approx 6\%$  in the strongest mode. Just as more recently for Balloon 090100001, the rich frequency spectrum has triggered extended photometric monitoring campaigns in the optical as well as the gathering of time-resolved colour and spectral information. The resulting literature that has been published, from the initial discoveries and campaigns all the way to the work in progress on analysing the repeated coordinated observational efforts, is too numerous to be cited comprehensively in this context.

The Multi-Site Spectroscopic Telescope (MSST) project in particular combined the following observational ingredients in order to simultaneously sample PG 1605+072's intensity and radial velocity variations: white light and multicolour light curves; low-resolution time-resolved spectroscopy (O'Toole et al. 2005, Tillich et al. 2007); and high-resolution time-resolved spectroscopy.

This report primarily makes mention of the photometric analysis, and furthermore discusses PG 1605+072 as observed with FUSE: light curves, radial velocities, and especially chromatic amplitudes as presented by Stahn (2005) and Lutz (2007).

In the spirit of this workshop, the focus is on the variety of data sets available and how to treat and potentially combine this data. For published results (in numbers) the relevant work is referenced; here we note that the immediate aim of MSST is mode identification ( $l$ ) to complement future asteroseismic modelling. The changing power in the pulsation spectrum of PG 1605+072 may make this difficult, but may also hold clues to the details of the driving mechanism. The long-term motivation remains the clarification of the evolutionary status and origin of PG 1605+072 as one representative of the subdwarf B stars.

#### MSST and WET optical light curve, Fourier transforms and frequency fitting

The optical light curve consists of a total of 96 individual data sets, combining white light data from the MSST photometry and the WET Xcov22 campaign. The frequency solution for the white light curve has been obtained in an iterative manner. First of all, overlapping data sets were cross-correlated to check the timing and quality. On a trusted subset of the data obtained by bootstrapping from the overlapping data sets, first a four-, later an eleven-frequency model was constructed. The initial model was cross-correlated with all observations to uncover and correct for remaining timing errors, improved using the provisionally corrected full data set, and the procedure repeated with the second, more complex model. Finally, a 55-frequency model was fitted to the corrected data, using a non-linear least squares sine fit as in the steps before.

The final light curve documents this procedure by providing, for each data point, the time as raw truncated Julian Date, followed by the value of the barycentric correction, the time in BJD, the value of the corrections derived from the cross correlation, and finally the corrected time in BJD. This is followed by the modulation intensity with a mean value of zero, and an observation ID unique to each of the 96 data sets.

#### Chromatic amplitudes

##### MSST: BUSCA multicolour light curve

Tremblay et al. (2006) have compiled and analysed the optical multicolour photometry available for pulsating sdB stars at the time. This included the measurements by Falter et al. (2003) obtained in 2001 for PG 1605+072. Figure 1 shows the five nights of multicolour photometry obtained in 2002 with the BUSCA instrument at the Calar Alto 2.2m telescope. To construct the overplotted model, the BUSCA colours were first collapsed into one "white" light curve, which was fitted with a reduced set of frequencies from the simultaneous, more extended white light MSST photometry. The reduction of the number of frequencies was done by merging close frequencies, not resolved in the BUSCA data subset, assuming they belong to the same  $l$ . This may not be correct; if so, the chromatic amplitudes derived for these merged frequencies will be meaningless. Chromatic amplitudes were obtained by fixing the 30 frequencies fitted to the BUSCA "white" light curve and re-determining amplitudes and phases on the individual  $uv$ ,  $b$ ,  $r$ , and  $nir$  light curves. The result for the twelve strongest frequencies is shown in Fig. 2. In a plot where the chromatic amplitudes are normalised to the  $uv$  amplitude (not shown), the curves roughly fall into three groups with different slopes, indicative of the expected grouping according to common  $l$  values.

##### FUSE far-UV light curve

As shown by Fontaine & Chayer (2006), far-UV light curves for PG 1605+072 may be obtained by collapsing FUSE spectra extracted in bins from time-tagged data producing a time series.

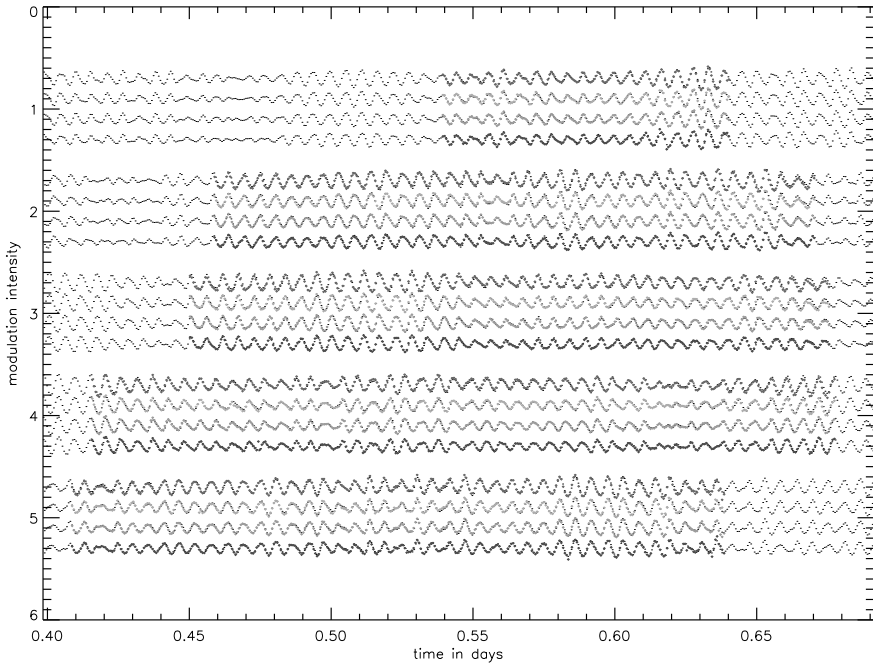


Figure 1: Five nights of multicolour photometry obtained in (2002) with the BUSCA instrument attached to the Calar Alto 2.2m telescope. The data points in the top four curves correspond (in descending order) to the unfiltered *uv*, *b*, *r*, *nir* light curves of May 14, followed by the data sets corresponding to May 18, 19, 20, and 21. A continuous model light curve containing 30 frequencies is overplotted.

If the collapsing process is applied to a subset of wavelength bins, chromatic amplitudes for the far-UV spectral range can be determined from the resulting individual intensity time series. This has been done by Stahn (2005) for the 07/2001 data (see also Lutz (2007) for the 04/2004 data). Again, a smaller subset of merged frequencies was used when deriving the chromatic amplitudes, with close frequencies not resolved in the FUSE Fourier spectrum merged together. The observed wavelength dependency of the pulsation amplitudes was compared to model predictions, but did not allow a reliable mode identification.

## Radial velocities and spectroscopic parameters

### FUSE radial velocities

The time series of uncollapsed FUSE spectra can be subjected to a cross-correlation analysis which yields pulsational radial velocities. The 07/2001 radial velocity curve has been analysed by Stahn (2005) in a similar way to the analysis done on the FUV intensity. In a direct comparison of the full curves, Stahn (2005) finds that the light to radial velocity phase shift amounts to  $\pi/3$ , a result which differs from that published by Kuassivi et al. (2005) who find  $\pi/2$ . When the comparison is done for individual frequencies, Stahn (2005) notices that the  $\pi/3$  phase shift basically reflects the value corresponding to the strongest frequency, and derives differing values for two further frequencies. These results are indicative of a non-adiabatic pulsational behaviour of PG 1605+072.

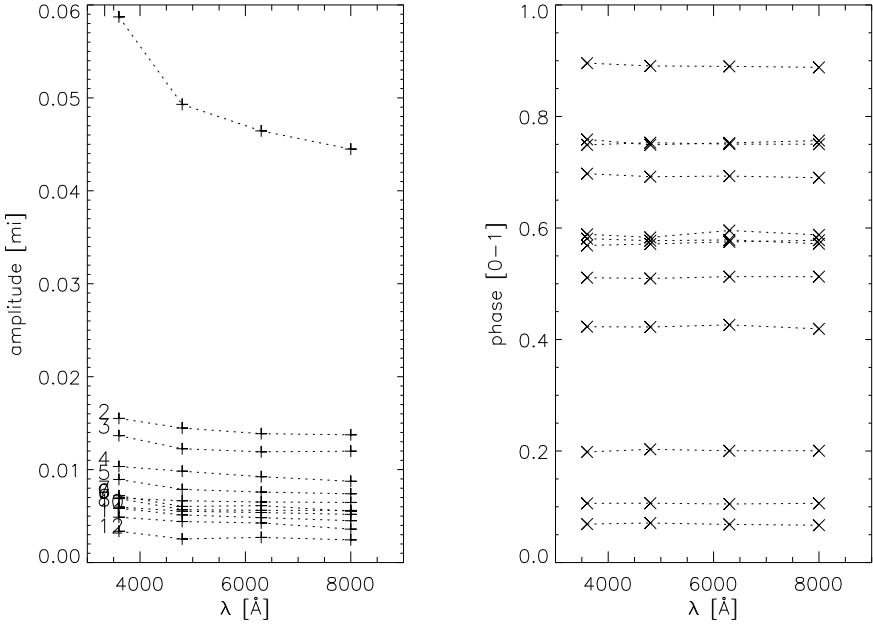


Figure 2: *Left panel:* Chromatic amplitudes derived from the 2002 BUSCA data shown in Fig. 1 for the twelve strongest frequencies in the model light curves. The error bars correspond roughly to the symbol size; beyond the 12th strongest frequency, error bars are larger than the measurable slope. *Right panel:* A quality check of the fit is obtained by inspecting the stability of the phase (free parameter; arbitrary zero point).

### Optical radial velocities and spectroscopic parameters

O'Toole et al. (2005) derived the radial velocity variation from MSST low-resolution spectra. These results were used by Tillich et al. (2007) to produce RV-corrected, phase-resolved summed spectra for the strongest pulsation frequencies from the same optical spectroscopy. From these the variation in effective temperature and surface gravity corresponding to the individual pulsations could be determined. Phase relations were obtained for the photospheric parameters radial velocity versus  $\log g$  and radial velocity versus temperature variation. As expected from geometrical considerations, the radial velocity versus  $\log g$  variation results in a shift of  $\pi/2$ . The shift in radial velocity versus temperature variation of  $\pi/3$  is fully consistent with the FUSE results if the intensity variation is assumed to be primarily due to changes in the effective temperature. Again, this points to the presence of non-adiabatic pulsational behaviour.

### Challenges

To fully exploit the available observations briefly presented above, the following exercises remain to be carried out on the data. First, an in-depth analysis of the white light curve should be able to discriminate from the behaviour of phases if either genuine amplitude variations or instead unresolved modes are seen. This will also be of relevance for justifying the merging of frequencies when determining chromatic amplitudes; here the 2002 BUSCA



optical chromatic amplitude results need still to be compared to Falter et al. (2003) (2001 data). The same argument holds for the analysis of the short FUSE data sets that do not fully resolve the pulsation spectrum; some improvement can be expected when adding in the second (2004) FUSE data set. The challenge will then be to bring together the non-simultaneous optical and FUV chromatic amplitudes; the latter can in principle provide a very significant lever.

The next interesting step will be to bring together the optical light curves and the spectroscopy: will the same phase lags as found in the FUV, and similarly indicated by the variation in the spectroscopic parameters, be directly evident there? It also remains to be seen if the overall line profile variations will be matched by modelling attempts. Finally, it will be interesting to find out if the mode identification with these methods continues to remain a fundamental challenge despite the encouraging intermediate results.

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## Radial-velocity observations of pulsating stars with a new Poznań Spectroscopic Telescope

W. Dimitrow

Adam Mickiewicz University, Poland

### Abstract

We present results of radial velocity measurements of classical cepheids,  $\delta$  Scuti and  $\beta$  Cephei stars. The spectra were obtained with Poznan Spectroscopic Telescope (PST). The telescope has been operating since August 2007. The PST is equipped with two 40cm diameter mirrors of Newtonian focus, connected by an optic fiber with an echelle spectrograph. The PSTs design aimed at the best cooperation with the spectrograph as well as limiting light losses. It allows us to measure radial velocity of stars as faint as 11.5 magnitudes. The peltier-liquid cooled CCD camera covers 64 echelle orders with spectral range from 4480 to 9250Å. The dispersion of the obtained radial velocity measurements is on the level of 150 m/s. Echelle spectra reduction and RV measurements are performed with Image Reduction and Analysis Facility (IRAF). We have achieved sufficient phase coverage for 28 And,  $\gamma$  Peg, Polaris and V440 Per. Further data acquisition for other pulsating stars is currently held.



Wojciech Dimitrow, Olivera Latković and Géza Kovács

## Detecting pulsating variable stars from OGLE survey

I. Soszyński<sup>1</sup>, A. Udalski<sup>1</sup>, M. K. Szymański<sup>1</sup>, M. Kubiak<sup>1</sup>, G. Pietrzyński<sup>1,2</sup>,  
Ł. Wyrzykowski<sup>1,3</sup>, O. Szewczyk<sup>1,2</sup>, K. Ulaczyk<sup>1</sup>, and R. Poleski<sup>1</sup>

<sup>1</sup> Warsaw University Observatory,

Al. Ujazdowskie 4, 00-478 Warszawa, Poland

<sup>2</sup> Universidad de Concepción, Departamento de Física,  
Casilla 160-C, Concepción, Chile

<sup>3</sup> Institute of Astronomy, University of Cambridge,  
Madingley Road, Cambridge CB3 0HA, UK

### Abstract

The Optical Gravitational Lensing Experiment (OGLE) regularly observes about 200 million stars in the Magellanic Clouds and Galactic bulge searching for gravitational microlensing events. Since 2001, when the third phase of the OGLE survey started, about  $10^{11}$  individual high precision photometric points have been collected. This huge database provides us with the ideal material for selecting and studying hundreds of thousands of variable stars, which will be the basis of the OGLE-III Catalog of Variable Stars. Here, we report preliminary results of this analysis, describing the samples of classical Cepheids and other pulsating stars detected in the Large Magellanic Cloud. We also describe the plans for future expansion of the OGLE project.

Individual Objects: Magellanic Clouds

### Introduction

The Optical Gravitational Lensing Experiment is a long-term sky survey with the main goal of searching for gravitational microlensing events. Every clear night about 100 images of the most crowded parts of the sky are collected with the Warsaw Telescope located at Las Campanas Observatory, Chile (operated by Carnegie Institution of Washington). Inspired by the Paczyński (1986) idea, OGLE started its operation in 1992. In the same year, two other large photometric surveys – MACHO (Alcock et al. 1993) and EROS (Aubourg et al. 1993) – began their operations.

Historically, the OGLE survey can be divided into three phases. The first phase lasted from 1992 to 1995 and was conducted with the 1-m Swope Telescope at Las Campanas Observatory. This part of the project contributed in several thousands of newly discovered variable stars in the Galactic bulge, globular clusters and dwarf galaxies. The second stage of the project began in January 1997 when 1.3-m Warsaw Telescope at Las Campanas Observatory started its operation. The OGLE-II project, together with other microlensing surveys, revolutionized the studies of variable stars. Hundred of thousands of variables have been discovered in the Magellanic Clouds and Galactic bulge. In 2001, the Warsaw Telescope was equipped with the  $8192 \times 8192$  pixel mosaic CCD camera, increasing the observing capabilities of the project by a factor of ten. Since that time, the third phase of the project is conducted (OGLE-III).

The OGLE-III photometry constitutes a unique data set covering the Magellanic Clouds, Galactic bulge and Galactic disk fields monitored regularly every clear night since 2001. The

project collected a database of 200 million light curves spanning 7 years. With the earlier OGLE-II photometry some of the observed fields have now 12-year long photometric coverage. This huge database is an ideal material for selection and analysis of variable stars. Here we describe the first results of our ongoing project of preparation of the OGLE-III Catalog of Variable Stars (OIII-CVS).

## The OGLE-III Catalog of Variable Stars

We plan to catalog all variable sources in the OGLE-III photometric database. All objects will be classified and cross-identified with previously known stars of the given type. Various methods will be applied to identify variable stars: variability searching in the images subtracted with the Difference Image Analysis (Alard and Lupton 1998, Woźniak 2000), searching for enormously scattered light curves, derivation of periods for all stars in our database, automated analysis of light curve shapes. However, all methods of the variability selection and classification will be controlled by a human – the final decision about including a star in the particular group of variables will be done after careful visual inspection of the light curve.

The first part of the OIII-CVS has already been published (Soszyński et al. 2008b). It presents classical Cepheids in the LMC. In total, 3361 such objects were identified, which is the largest sample of classical Cepheids found not only in the LMC, but also in any other environment. About 1000 objects are identified for the first time. The large sample probes uncommon pulsation modes. The catalog includes the enormous number of 266 double-mode Cepheids, which is a few times larger sample than any other known before. Among these objects there are two Cepheids of a new type – with the first and the third overtones simultaneously excited (Soszyński et al. 2008a).

Three new triple-mode Cepheids were identified (Soszyński et al. 2008a), what increased the number of known objects of that type to five. Such stars are particularly interesting, because three periods associated with the radial pulsations strictly constrain stellar parameters. It is worth noting that our preliminary analysis of these stars did not confirm the theoretical prediction that triple-mode Cepheids with the three lowest overtones excited are on the first crossing of the instability strip (Moskalik & Dziembowski 2005). We measured no secular changes of periods at all, or the rates of period changes had opposite sign than expected from the theoretical models. The conclusion from this analysis is ambiguous. Derived ratios of period changes cannot be explained by the evolutionary models. It seems that there is other than evolutionary mechanism causing changes of periods in Cepheids.

The search for multi-modal Cepheids resulted in the detection of considerable number of Cepheids with the secondary periods very close to the primary ones. Such a behavior is often connected with changes of amplitudes of pulsations, sometimes very prominent. We also found about 30 double-periodic Cepheids with the period ratios between 0.60 and 0.63 and the longer period (always related to the first overtone mode) in the range 1.7–2.6 days. These objects seem to follow two parallel sequences in the Petersen diagram. The origin of these secondary variations is unknown.

Our analysis also revealed a sample of 14 firm candidates for single-mode second-overtone Cepheids in the LMC. This is a very homogeneous group of stars with nearly sinusoidal light curves, small amplitudes and colors placing them in the blue edge of the instability strip. These objects follow the period–luminosity law located above the relation for the first-overtone Cepheids.

Large samples of particular type of stars are not only a source of uncommon cases, but also allow to study global properties of these objects. Sometimes interesting features of variable stars become visible when hundreds or thousands of such objects are studied simultaneously. For example, we noticed a new feature in our group of Cepheids pulsating in the first overtone. For stars with periods of about 0.35 days the amplitude ratio  $R_{21}$  has the local minimum, while the phase difference  $\phi_{21}$  is close to zero. In analogy to similar behavior at  $P \approx 3$  days for

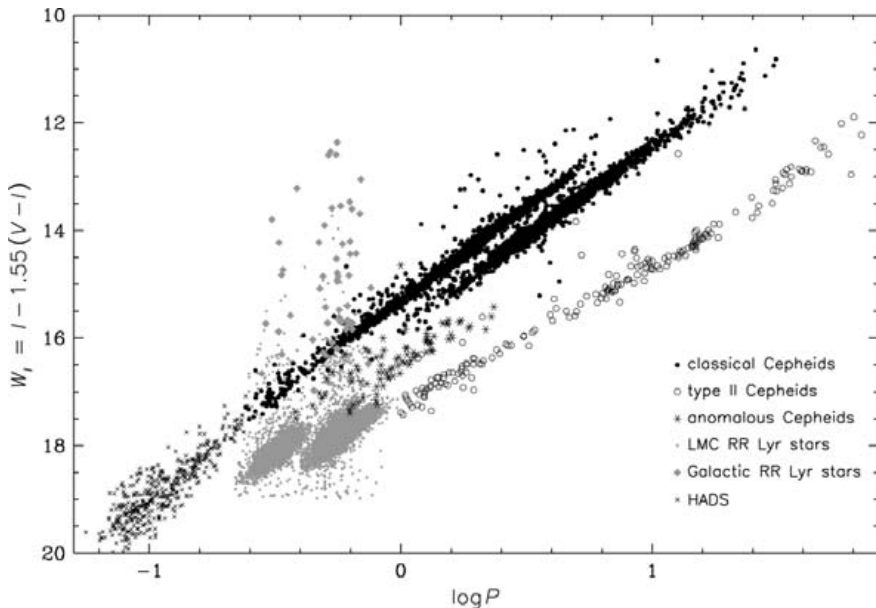


Figure 1: Period–luminosity diagram for pulsating stars in the LMC. Different points show classical Cepheids, type II Cepheids (including RV Tau stars), anomalous Cepheids, RR Lyr stars from the LMC and Galaxy, and HADS.

first-overtone Cepheids, and at  $P \approx 10$  days for fundamental-mode Cepheids, we interpret this new feature as a signature of an internal resonance between two radial modes. A preliminary analysis (Dziembowski, private communication) shows that the sharp feature for 0.35 days is caused by a presence of 2:1 resonance between the first and fifth overtones.

During the selection process we found not only classical Cepheids, but also a large number of other pulsating variables crossing the classical instability strip: type II Cepheids, anomalous Cepheids, Galactic and LMC RR Lyr stars and High Amplitude  $\delta$  Sct stars (HADS). Distinguishing between all these classes of pulsating variables is a rather difficult task. For the first approach, we relied on the position of star in the period–luminosity diagram (Fig. 1). However, the OGLE fields are usually very crowded, and many stars are strongly blended with other objects, what increases the apparent luminosity of stars.

Thus, the final classification was performed using the shapes of the light curves of the stars. In Fig. 2 we show several light curves of various types. Each column contains stars with similar periods. One can notice the different shapes of the light curves in different types of variables. Using this method we found a group of peculiar W Vir stars (the example labeled “?” in Fig. 2) with different light curves, somewhat different colors and located slightly above typical W Vir stars in the  $\log P$ – $I$ -band diagram.

Pulsating stars are an excellent tool to study the inner structure of the galaxies. Fig. 3 shows the spatial distribution of classical Cepheids (upper panel) and RR Lyr stars (lower panel) in the LMC. The candidates for RR Lyr stars were selected automatically using their luminosities and Fourier parameters. One can easily notice the difference in distribution of the two types of variables.

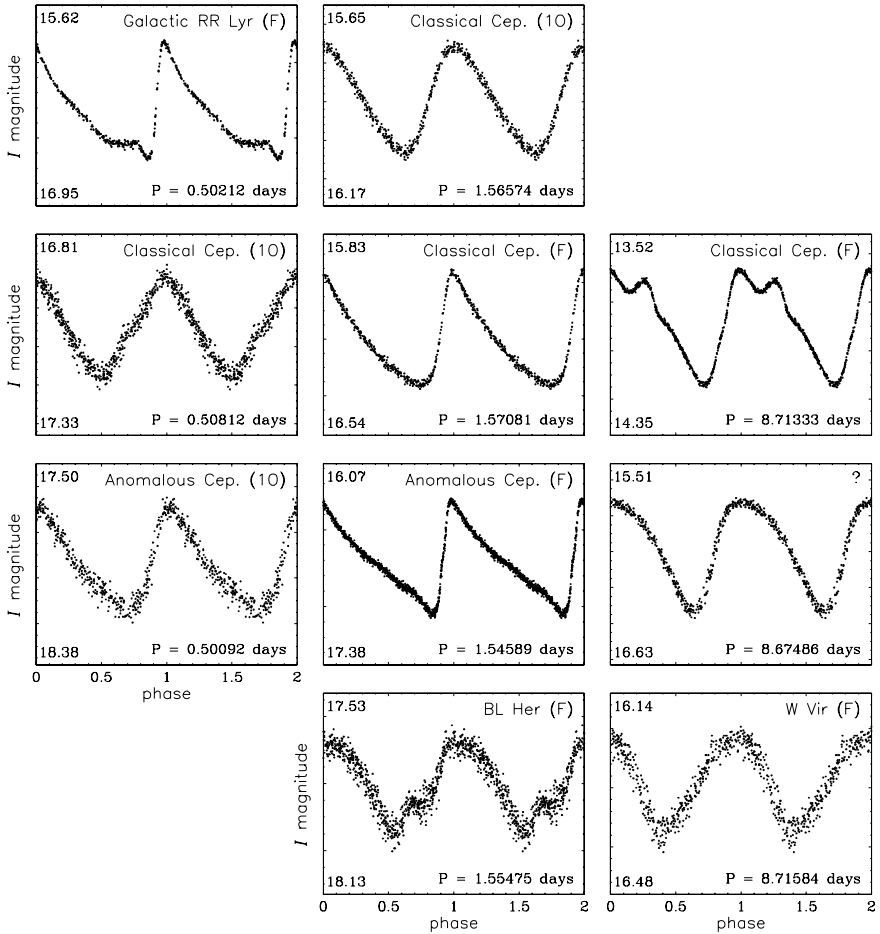


Figure 2: Phased light curves of various pulsating stars in the LMC. Left column shows stars with periods of about 0.5 days, middle column – about 1.55 days, and right column – about 8.7 days. Types of variables and modes of pulsations are provided in the panels.

## Summary and Future Plans

OGLE produced a wealth of stellar photometry in the most crowded parts of the sky what will be a baseline of a new catalog of variable stars. The huge number of variables expected in the OIII-CVS will be ideal material for both statistical analysis and the search for unique objects. The homogeneous OGLE photometry allows us to perform comparative studies between various types of variable stars in the Galaxy, LMC and SMC.

In 2009, the Warsaw Telescope will be upgraded again. The eight-chip mosaic CCD camera will be replaced by the new generation camera consisting of 32 chips. Such an instrument will practically entirely fill the field of view of the Warsaw Telescope increasing the observing capabilities of the OGLE project by another order of magnitude.

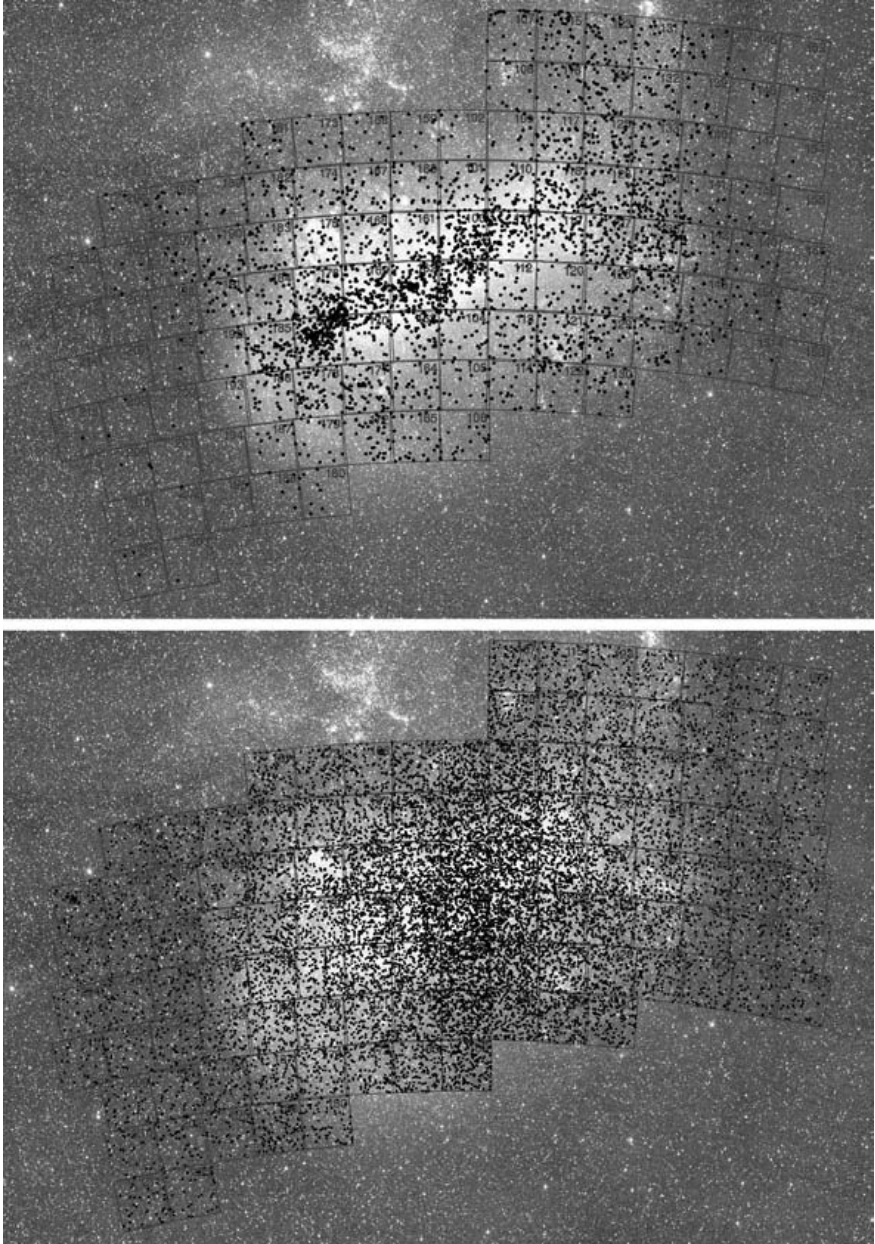


Figure 3: Spatial distribution of classical Cepheids (upper panel) and RR Lyr stars (lower panel) in the LMC. The picture of the LMC is originated in the ASAS project.

**Acknowledgments.** We thank Prof. M. Breger and Prof. W. Dziembowski for their helpful comments. This work has been supported by the Foundation for Polish Science through the Homing Program and by MNiSW grants: NN203293533 to IS and N20303032/4275 to AU.

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## DISCUSSION

**von der Lühe:** How often is a particular field revisited? What is a typical cadence?

**Soszyński:** In the Magellanic Clouds, we observe a particular field once per night. In the Galactic Bulge the selected fields are monitored a few times per night.

**Kovács:** Did you reach the white noise level in your analysis? At what level the systematics were filtered out by your reduction pipeline?

**Soszyński:** We have not filtered out photometry for systematic effects. The OGLE III data are very stable. However, the filtering can, of course, increase the accuracy of detailed analyses.

**Schwarzenberg-Czerny:** What kind of compression are you using?

**Soszyński:** We use the RISE compression, decreasing the size of the FITS file by factor two.

**Castanheira:** What is the integration plus readout time of the observations?

**Soszyński:** The integration time is 180s and the readout time is 120s. The readout time will be down to few seconds for OGLE IV.

**Kepler:** What is the magnitude limit of the OGLE III data?

**Soszyński:** The magnitude limit for the selection of variable stars is about 20.5 mag in the I band.



## Discovery of non-radial pulsations in the spectroscopic binary Herbig Ae star RS Cha

T. Böhm<sup>1</sup>, W. Zima<sup>2</sup>, C. Catala<sup>3</sup>, E. Alecian<sup>4</sup>, K. Pollard<sup>5</sup>, and D. Wright<sup>5</sup>

<sup>1</sup> LATT, Université de Toulouse, CNRS, 14 avenue Edouard Belin,  
F - 31400 Toulouse. (boehm@obs-mip.fr)

<sup>2</sup> Instituut voor Sterrenkunde, K.U. Leuven, Celestijnenlaan 200D, B - 3001 Leuven

<sup>3</sup> LESIA, Observatoire de Paris-Meudon, 5 place Jules Janssen, F - 92195 Meudon

<sup>4</sup> Dept. of Physics, Royal Military College of Canada, PO Box 17000,  
Stn Forces, Kingston, Canada K7KK 7B4

<sup>5</sup> Dept. of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, NZ

### Abstract

The spectroscopic binary Herbig Ae star RS Cha was monitored in quasi-continuous observations during 14 observing nights (2006) at the 1m Mt John telescope (New Zealand) with the Hercules high-resolution echelle spectrograph. For the first time, we discovered by direct observational means non-radial oscillations in a binary Herbig Ae star using high echelle spectroscopy. A preliminary mode identification was performed yielding strong constraints on upcoming asteroseismological models.

Individual Objects: RS Cha

### Introduction

Asteroseismology represents a modern tool for studying the stellar interiors of the enigmatic group of pre-main sequence (PMS) stars of intermediate mass (2-8  $M_{\odot}$ ), the so-called Herbig Ae/Be stars (Herbig 1960). Since their first systematic classification in 1960, this group of young stars has been studied extensively, but one of the major questions remains unanswered: how can the intense stellar activity and strong stellar winds (e.g., Catala et al. 1986; Böhm & Catala 1995), as well as the many highly variable emission lines observed in the spectra of these stars be explained?

Magnetism is frequently invoked as being responsible for active stellar phenomena. The position of the Herbig stars in the HR diagram indicates that a classical magnetic dynamo mechanism cannot be at work in these stars. Recent spectropolarimetric observations of Herbig stars indicate the presence of significant large-scale magnetic fields only in a small less than 10% fraction of them (Wade et al. 2007). A magnetic origin of the activity seems unlikely as of today. It is therefore of major importance to investigate possible other external or internal origins of this tremendous amount of dissipated energy.

The only way of studying the internal stellar structure in detail is the analysis and the modelling of stellar pulsations, if observed. For several decades, the existence of pulsating intermediate mass PMS stars has been known (Breger 1972; Donati et al. 1997). This observational result motivated Marconi & Palla (1998) to investigate the pulsation characteristics of HR 5999 theoretically, which enabled them to predict the existence of a pre-main-sequence

instability strip, which is crossed by most of the intermediate-mass PMS objects for a significant fraction of their evolution to the main sequence. This strip covers approximately the same area in the HR diagram as the  $\delta$  Scuti variables (see also Zwintz 2008). As of today, more than 30 intermediate-mass PMS stars have revealed to be pulsating at timescales typical of  $\delta$  Scuti stars (e.g., Ripepi & Marconi 2003; Zwintz & Weiss 2003; Catala 2003 and references therein).

RS Chamaeleontis is a bright spectroscopic eclipsing binary star. Both components are Herbig Ae PMS stars of similar mass (close to  $1.9 M_{\odot}$ ). Andersen (1975) already reported small amplitude radial velocity variations on top of the binary radial velocity curve for both components of RS Cha, suggesting the possible presence of stellar pulsations. Photometric observations by McInally & Austin (1977) revealed short-term variations in at least one of the two components, possibly linked to stellar pulsations. Very recently, Alecian et al. (2005) reported radial velocity variations in the residual velocity frame (with respect to the orbital velocity) with amplitudes up to a few  $\text{km s}^{-1}$  and periods of the order of 1h, indicative of  $\delta$  Scuti type pulsations. The pre-main sequence spectroscopic eclipsing binary RS Cha has been studied extensively throughout the last years. Due to its eclipsing nature and the known inclination angle, the system has been fully calibrated (Alejian et al. 2005, 2007a,b).

The aim of our study of the two components of RS Cha is to provide a first set of asteroseismic constraints for forthcoming non-radial pulsation models by determining unambiguously a higher number of periodicities and identifying, in a second step, the corresponding pulsation modes with their respective degree  $\ell$  and azimuthal number  $m$ . To achieve this goal, we decided to perform high resolution spectroscopic observations on a large time basis and with optimized time coverage.

## Observations

The analysis presented in this paper is based on a 14 nights observing run in January 2006 (9<sup>th</sup>-22<sup>nd</sup>) at the 1m Mt John telescope (NZ) equipped with the Hercules echelle spectrograph. We obtained quasi-continuous single-site observations of the target star during these two weeks and obtained a total of 255 individual stellar echelle spectra, each spectrum having an individual exposure time of 10 min. The star was observed in high resolution spectroscopy at  $R \approx 45000$  and covering the wavelength area from 457 to 704 nm, spread over 44 orders. The detector was a 1kx1k Site CCD. The highest S/N ( $\text{pixel}^{-1}$ ) values we obtained reached 210 on Jan 16th, corresponding to almost 300 per resolved element (2 pixels); typical values of S/N ( $\text{pixel}^{-1}$ ) ranged around 80-150 in this run.

Most of the data reduction was carried out following standard reduction procedures using the "ESPRIT" spectroscopic data reduction package (Donati et al. 1997). Details of the subsequent data reduction procedure can be read in Böhm et al. (2008). The intrinsic wavelength calibration accuracy achieved with the "ESPRIT" 2D-polynomial fit procedure is better than 0.22 pm mean rms (i.e.  $2.2 \text{ m}\text{\AA}$ , corresponding to  $120 \text{ ms}^{-1}$  at  $5500 \text{ \AA}$ ) for the Hercules data set. The next step of the data reduction was to calculate for all 255 stellar spectra photospheric LSD-profiles, using a mask corresponding to the spectral type A7 and containing only photospheric lines. The equivalent photospheric profile improves eventually through multiplex information of 1930 individual photospheric lines, most of them being very weak lines. Typically, a spectrum of RS Cha with  $S/N = 150$  ( $\text{pixel}^{-1}$ ) at  $5500 \text{ \AA}$  yields a S/N value of 1400 per velocity step in the resulting LSD profile. The finally achieved precision in radial velocity improves due to the multiplex information and is better than  $50 \text{ ms}^{-1}$  for each individual stellar LSD profile of this data set. The spectroscopic binary LSD profile was then fitted with a double rotational profile with an IDL procedure and yielded for all cases, except the fully merged profiles, precise heliocentric radial velocities of the two components. The parameters of the binary orbit were determined. More details can be read in Böhm et al. (2008).

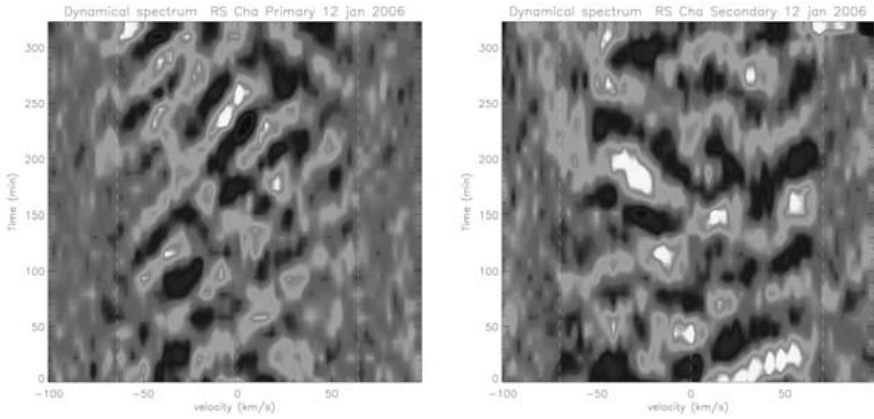


Figure 1: Line profile variations due to the oscillations of RS Cha. As an example, the deviations from the mean intensity are displayed for the night of Jan 12th 2006 (left figure: Primary component; right figure: Secondary component.). The dashed vertical lines represent the borders of the profiles at the respective  $\pm v \sin i$ . Color coding in Figs. 1 represents a dynamical range of about 0.5% of the continuum.

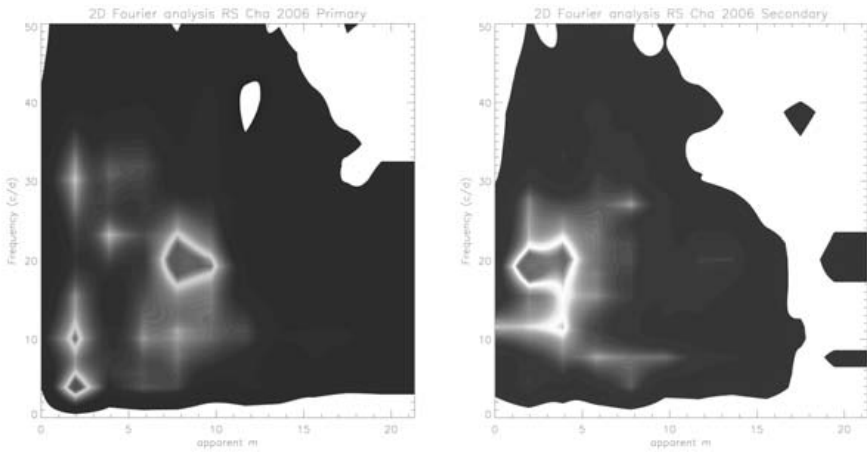


Figure 2: Weighted sum of the individual Fourier 2D amplitude spectra based on all exploitable time series during the 14 nights run; (left figure: Primary component; right figure: Secondary component). Apparent  $|m|$  scales as  $\ell - 2$  for values close to zero, and as  $\ell - 1$  for values lower than 10.

Table 1: Frequency search and mode identification. Summary of the main results for the two dominant frequencies of each component.

| <b>Primary component</b>   |          |                             |                      |
|----------------------------|----------|-----------------------------|----------------------|
|                            | $d^{-1}$ | Identification FPF          | Identification F2D   |
| $f_1$                      | 21.12    | ‘high degree prograde’      | $\ell = 5$ or $6$    |
| $f_2$                      | 30.38    |                             | $\ell = 0$ ?         |
| <b>Secondary component</b> |          |                             |                      |
|                            | $d^{-1}$ | Identification FPF          | Identification F2D   |
| $f_1$                      | 20.11    | $\ell = 0$ or $1$ , $m = 0$ | $\ell = 0, 1$ or $2$ |
| $f_2$                      | 12.81    | $\ell = 2$ , $m = 1$ or $2$ | $\ell = 2$           |

## Detection of non-radial pulsations in both components

Finally, we extracted the two binary components of each LSD profile along its individual orbital radial velocity in order to obtain two files with centered dynamical spectra revealing only the intrinsic stellar profile variations. As an example, Fig. 1 reveals the deviations from the mean (rotational) profile for the night of Jan 12<sup>th</sup>, for the primary and for the secondary component. It can be clearly seen that bumps move through the line profile in a quite complex manner. The time-dependent pattern of the residual profile of the Primary reveals a diagonal trend of the bump movement (bottom left to up-right). These features are due to several high-degree non-radial pulsation modes. The dynamical residual profile of the Secondary shows a chess-board pattern. This represents a first direct detection of non-radial pulsations in Herbig Ae stars by spectroscopic means.

## Search for frequencies and mode identification

We applied the same methodology in the analysis of both components. A detailed description can be found in Böhm et al. (2008). The search for periodicities was carried out by using Discrete Fourier Transformation (DFT) and least-squares fitting (LSF), a method which fits a sum of sinusoidals to the variations. For the analysis, we used two different software packages: Period04 (Lenz & Breger 2005) for the one-dimensional time-series and FAMIAS (Zima 2007) for the two-dimensional analysis of the variations across the line profile, as well as a complementary IDL-based Fourier 2D analysis tool (for the method see Kennelly 1994). The graphical result of the Fourier 2D method is shown in Fig. 2. Table 1 summarizes the main results for the two dominant pulsation modes of each component.

## Conclusions

For the first time, we detected by direct spectroscopic means non-radial pulsations in both components of a binary Herbig Ae star. A first identification by two complementary methods revealed very different main pulsation modes for the two components: while the dominant mode of the primary component seems to be a high degree prograde mode with  $\ell = 5$  or  $6$ , the dominant mode of the secondary component is identified as a low degree mode with  $\ell = 0, 1$  or  $2$ . Next steps require a precise redetermination of the fundamental parameters and a search for the intrinsic rotation periods of both components. Since first frequencies are known and their associated modes are constraint by the present work we are going to develop a numerical model in order to constrain de internal structure of both components.

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Torsten Böhm during his talk

## A different approach to analyzing the Blazhko effect: the VSAA applied to RR Lyr

K. Kolenberg<sup>1</sup>, and S. Tsantillas<sup>2</sup>

<sup>1</sup> Institut für Astronomie, Türkenschanzstrasse 17, 1180 Vienna, Austria

<sup>2</sup> University of Athens, Greece

### Abstract

The mysterious amplitude and phase modulation observed in many RR Lyrae stars has puzzled astronomers for more than a century. Most commonly quoted hypotheses to explain the phenomenon involve nonradial modes, through either resonances or magnetic fields. However, their reality is still being questioned. Maybe an unknown physical mechanism in the star causes the main radial mode to change its properties over time while no nonradial pulsation modes are involved.

Changing Blazhko periods challenge the existing models for the Blazhko effect. Because of its ability to describe a quasi-periodic time series in a simple way, we used the VSAA (Variable Sine Algorithmic Analysis, Tsantillas & Rovithis-Livaniou 2008) in a first and elementary application to monitor the changing Blazhko period of RR Lyr. Assuming modulation of a single pulsation frequency, we applied the VSAA to an extensive data set of RR Lyr, one of the best studied Blazhko stars. The results show how the amplitude and period of the modulation have changed over the past decades.

Individual Objects: RR Lyr

### The models for the Blazhko effect and their problems

Over the past few years high-quality time series data of modulated RR Lyrae stars have revealed many facts that still need an explanation. Besides a few to-be-elaborated scenarios such as the one proposed by Stothers (2006), the usually quoted hypotheses require the presence of nonradial modes in the star: the resonance models (e.g., Dziembowski & Mizerski 2004) and the magnetic models (e.g., Shibahashi 2000). Each of the models in their present form favors a different type - more specifically: a different degree  $\ell$  - of nonradial mode. However, stating that the resonance model "comes with"  $\ell = 1$  modes and the magnetic model with  $\ell = 2$  modes would be far too simplistic. The currently proposed models for the Blazhko effect need to be revisited, and alternative models such as Stothers' (2006) scenario may also help to make the turn out of an impasse.

### Fourier spectra

For Blazhko stars, classical Fourier techniques result in a frequency spectrum containing a multitude of frequency peaks and side peaks (see Figure 1). The main frequency and its harmonics are easily identifiable. The side peaks, generally equally-spaced triplet structures centered around the main frequency and its harmonics, are also clearly detected. Several authors have attributed the side peaks near the main frequency  $f_0$  to the occurrence of at

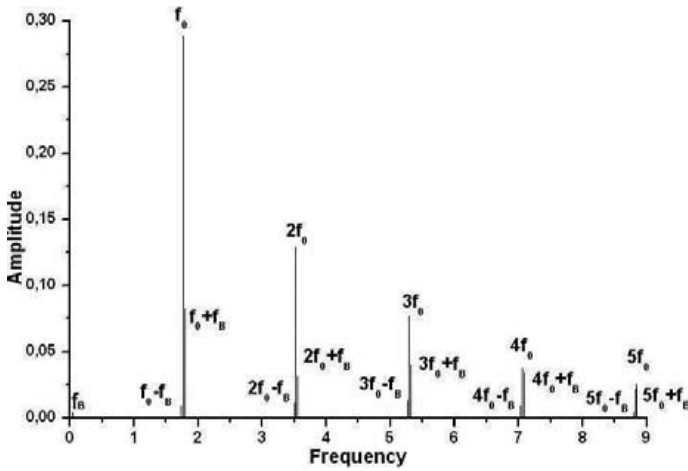


Figure 1: Frequency spectrum resulting from the latest RR Lyr photometric campaign.

least one nonradial mode in the star. No radial mode would have a frequency so close to  $f_0$ . The often observed unequal amplitudes in the triplet structures cannot be described in the extent observed by the models.

It was recently shown by Hurta et al. (2008) that the variations of the star RV UMa can be described by a quintuplet solution rather than a triplet. Also Kolenberg et al. (2008a) find evidence for quintuplet frequencies in data of the southern Blazhko star SS For. With the increasing quality of data sets on Blazhko stars and the advent of high-quality quasi-uninterrupted satellite data, we may expect to detect many more quintuplet (generally: multiplet) structures in data of Blazhko stars in the near future.

#### Changing Blazhko periods

Changing Blazhko periods represent an additional challenge to the currently proposed hypotheses for the Blazhko effect. Several Blazhko stars are known to have shown changes in their Blazhko period (e.g. XZ Cyg - see LaCluyzé et al. 2004; RR Lyr - see Kolenberg et al. 2006). RR Lyr is one of the best studied Blazhko stars and over the past decades gradually decreasing values of its modulation period have been reported: from 40.8 days (Fringant 1961; Szeidl 1988), over 39-40 days (Belserene 1999; Smith et al. 2003) to values below 39 days (Kolenberg et al. 2006; Kolenberg et al. 2008b).

#### A way to analyze the changing periods in Blazhko stars

The Blazhko frequency itself can be observed in time series data when the quality and time coverage of the set is sufficient. Jurcsik et al. (2006) pointed out its discrepant behaviour. If observed (with small amplitude) in the frequency spectrum of a Blazhko star, the colour behaviour of the Blazhko frequency differs from that of the main frequency, its harmonics and the adjacent sidepeaks. The side lobe frequencies in the triplets seem to share the same colour behaviour as the main frequency and its harmonic.

This observation supports the hypothesis of a single mechanism, acting on the time scale of the Blazhko frequency, causing the Blazhko effect. From our observations it seems that this time scale may also vary.

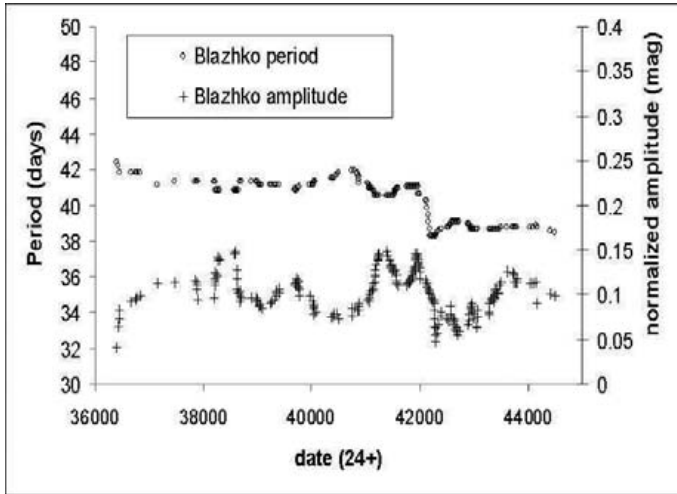


Figure 2: Blazhko period changes in RR Lyr between 1958 and 1980 determined with the VSAA.

The Variable Sine Algorithmic Analysis (Tsantillas & Rovithis-Livaniou 2008) provides a tool that can easily be applied to times and amplitudes of maximum light of the Blazhko effect.

Szeidl et al. (1997) compiled half a century of photometric data gathered at Konkoly observatory between 1943 and 1993. For a uniform subset of the data, gathered between 1958 and 1980, we selected the maxima in order to investigate the changes in the strength (amplitude) and duration (period) of the Blazhko cycle. The results of the VSAA (Figure 2) show a long-term decrease of the Blazhko period with possibly small periods of increase. Started from a value close to 41 days, the Blazhko period has decreased to below 39 days over the past few decades. From our analysis the Blazhko amplitude seems to oscillate around a constant value.

We also applied the VSAA to two recent data sets of RR Lyr, gathered in 2003-2004 and in 2006-2007. The frequency spectrum obtained through Fourier analysis for the latter one is shown in Figure 1. Note that in our Fourier analysis the Blazhko frequency  $f_B$  obtained a fixed value. When applying the VSAA to the set of obtained maxima of our data set, we find evidence of a changing Blazhko period, even during our observing run (see Figure 4, Tsantillas & Rovithis-Livaniou 2008).

The results obtained with the VSAA also confirm our observations of a shortening Blazhko period for RR Lyrae obtained using Fourier techniques (see also poster by Kolenberg et al. 2008b).

## Discussion

As a first application, we applied the VSAA in an elementary way to trace the *changes of the Blazhko period*.

In a future application, we will extend the technique to be applied to non-sinusoidal light variations such as observed in RR Lyrae stars. This will allow us to trace the *frequency and amplitude variations of the main pulsation mode*. In such an application, both the main



frequency and the amplitudes of both this frequency and its harmonics are traced in their variations over the Blazhko cycle. The difference with the analysis of Fourier parameters as presented by Jurcsik et al. (2005) and Kolenberg et al. (2006) is that in the VSAA we allow the period itself to change over the Blazhko cycle. This is equivalent to changes in the phase when keeping the period constant.

If structural changes happen in the star over the Blazhko cycle, it is possible that the mean temperature, luminosity and radius of the star show a variation over the Blazhko cycle. Hence, allowing a variable pulsation period over the Blazhko cycle in the analysis may offer an interesting alternative to the classical Fourier technique when analyzing Blazhko time series data.

What physical mechanism causes the change in Blazhko period and amplitude, and the variation in pulsation period and amplitude, i.e., what causes the Blazhko effect altogether, is a question that will hopefully be answered in the near future.

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## DISCUSSION

**Kovács:** I agree with you that the major problem in the current models of the Blazhko effect is of finding an explanation for the widely observed asymmetric modulation side lobe components. In comparison, the model preference based on triplet vs. quintuplet interpretation is of secondary importance.

**Kolenberg:** Indeed, none of the presently proposed models manages to explain the side peak asymmetry in the degree it is observed. Both in the resonance model and in the magnetic model there are attempts to reproduce the asymmetry of the side peaks. But in reality we often see even more pronounced asymmetry.

**Kovács:** I feel a major problem (or misunderstanding) with Stothers' idea for explaining the Blazhko effect. The major ingredient of his idea is based on the asymptotic period change (linear vs. nonlinear) in nonlinear hydrodynamic simulations. Currently available results (see the works of Buchler, Szabo & Kollath) show that this change is always positive, leading to (slight) period increase. In addition, these changes occur on very large time scales (thousand pulsational cycles, depending on model initialization), whereas there are Blazhko stars with modulation periods under 10 days.

**Kolenberg:** Thanks for this valuable comment. As you say, the Stothers' scenario also does not fully explain the observations. In general, I encourage the exploration of alternative paths (including those that do not require the existence of nonradial modes) in trying to solve the Blazhko puzzle.

## Regularities in the frequency spacings of Delta Scuti stars and the s-f Diagram

M. Breger<sup>1</sup>, P. Lenz<sup>1</sup>, and A. A. Pamyatnykh<sup>1,2</sup>

<sup>1</sup> Astronomisches Institut der Universität Wien, Türkenschanzstr. 17, A-1180 Wien, Austria

<sup>2</sup> Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland

### Abstract

Statistical analyses of several  $\delta$  Scuti stars (FG Vir, 44 Tau, BL Cam and others) show that the photometrically observed frequencies cluster around the frequencies of the radial modes over many radial orders. The observed regularities can be partly explained by modes trapped in the stellar envelope. This mode selection mechanism was already proposed by Dziembowski & Królikowska (1990) and was shown to be efficient for  $\ell = 1$  modes. New pulsation model calculations confirm the observed regularities.

We present the s-f diagram, which compares the average separation of the radial frequencies ( $s$ ) with the frequency of the lowest unstable radial mode ( $f$ ). The diagram provides an estimate for the  $\log g$  value of the observed star, if we assume that the centers of the observed frequency clusters correspond to the radial mode frequencies. This assumption is confirmed by examples of well-studied  $\delta$  Scuti variables in which radial modes were definitely identified.

Individual Objects: FG Vir, 44 Tau, BL Cam

### Introduction

Recent observational campaigns carried out with earth-based telescopes or space missions concentrating on selected stars have revealed a rich spectrum of radial and nonradial modes covering a wide range in frequencies. This range in frequencies varies from star to star and depends on a variety of factors, not all of which are understood. The question of which modes are selected by the star is not solved at the present time.

The question arises of whether the mixture of the excited radial and nonradial modes shows frequencies which are essentially randomly distributed over the range of unstable frequencies or whether they tend to form groups. An example of the latter is the regular spacing found in high-order nonradial pulsation (the asymptotic case), as detected in the Sun and white dwarfs. The  $\delta$  Scuti stars, on the other hand, pulsate with low-order p (and g) modes. Here we examine the frequency distribution of mostly nonradial modes in a number of well-observed  $\delta$  Scuti stars in order to search for regularities.

### Regularities in the frequency distribution

The detection of the complex mixture of excited nonradial and (a few) radial modes observed in  $\delta$  Scuti stars requires extensive photometric studies. Sufficient information for meaningful statistical analyses concerning regularities in the frequency spacings is only available for a few stars. We find that three well-studied stars show pronounced regularities:

(i) FG Vir is probably the best  $\delta$  Scuti star to examine systematics in the pulsation frequencies. More than 75 frequencies of pulsation are known (Breger et al. 2005). The frequency resolution is excellent so that combination frequencies and harmonics can be eliminated; this leaves 68 independent frequencies covering a wide range from 5.7 to 44  $\text{cd}^{-1}$ . The regions with most frequencies are around 12, 23 and 34  $\text{cd}^{-1}$ , but the data contain considerably more information than a spacing of 11  $\text{cd}^{-1}$ , which corresponds to three radial orders. A statistical analysis shows a pronounced regularity with a spacing of 3.7  $\text{cd}^{-1}$ , which corresponds to the average spacing of consecutive radial orders for these mainly nonradial modes.

(ii) Extensive campaigns of 44 Tau covering five observing seasons have led to the detection of 49 frequencies (Breger & Lenz 2008). As already found in FG Vir, the frequencies of 44 Tau also show a regularity with a preferred spacing of one radial order.

(iii) The star BL Cam (Rodríguez et al. 2007). While the two stars listed above are small-amplitude  $\delta$  Scuti variables, BL Cam is a high-amplitude, extremely metal-deficient variable (also known as HADS, SX Phe-type). Rodríguez et al. (2007) identified 25 frequencies, of which 22 represent independent modes. The study is remarkable because of the difficulty of detecting such a large number of small-amplitude nonradial modes in the presence of a dominant radial fundamental mode of high amplitude. The authors note that the frequencies of the nonradial modes cluster in groups near 25, 32, 46, 51–53, and 72–80  $\text{cd}^{-1}$ . This implies separations similar to the separation of adjacent radial orders.

## Frequencies of nonradial modes near those of radial modes

In the previous section, we have shown that in a number of well-studied  $\delta$  Scuti stars, the frequencies of the nonradial modes are not distributed at random but show a preferred spacing corresponding to that of the radial modes. We wish to emphasize that this is only a preferred spacing and that other spacings do (and should) occur. The question arises of where in the frequency spectrum these concentrations of nonradial modes occur, e.g., possibly halfway between radial modes of successive radial orders, as would be expected in the asymptotic case for the  $\ell = 1$  modes. For the three stars, at least one radial mode has been identified in each star. We have computed the frequencies of the other radial modes from the known properties of the stars. The same codes as described in Lenz et al. (2008) were used. Knowing the radial frequencies, it was possible to compute the frequency difference of each observed mode to the nearby radial modes.

The histograms of the frequency differences are shown for the three stars in Fig. 1. The results are striking: The frequencies of the photometrically detected nonradial modes are not distributed at random but tend to cluster around those of the radial modes. These nonradial modes are mostly  $\ell = 1$  and 2 modes, but in the case of FG Vir they may also be the small-amplitude  $\ell = 3$  and 4 modes.

Three additional  $\delta$  Scuti stars (XX Pyx, BI CMi and  $\epsilon$  Cep) with 20+ known frequencies (i.e., borderline statistics) were also examined. They are less ideal for the study because of close-binary nature or uncertain physical parameters. The stars show the radial-spacing regularities, but less pronounced than the three stars examined in the previous section.

We conclude that in  $\delta$  Scuti stars, the detected nonradial modes tend to cluster around the radial modes. This effect has previously been predicted: Dziembowski & Królikowska (1990) examined *mode trapping* in the stellar envelope as a mechanism for mode selection in  $\delta$  Scuti stars. They show that some modes of  $\ell = 1$  are trapped in the envelope and, therefore, are less coupled to  $g$  modes in the deep interior. They have a higher probability to be excited to observable amplitudes than other modes. Trapped modes are nonradial counterparts of the acoustic radial modes and at low spherical harmonic degrees their frequencies are close to those of the radial modes. Mode trapping is not effective for  $\ell = 2$  modes. However, the observations show that even modes identified with  $\ell = 2$  are located close to the radial modes. This means that an additional mode selection might exist.

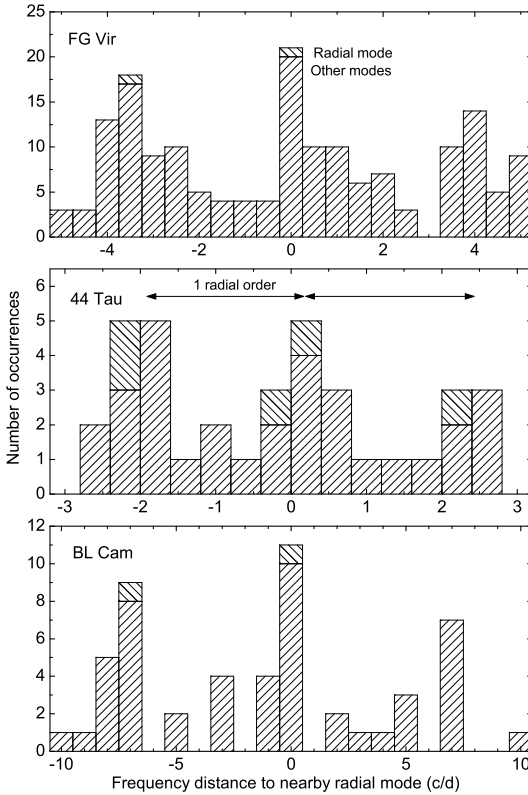


Figure 1: Histogram of the frequency distances of individual modes to the frequency of the nearest radial mode. The frequencies of the radial modes were either observed or computed from models. This diagram shows that the observed nonradial modes are not distributed at random but tend to cluster around the radial modes.

If the star rotates, its oscillation frequencies split into multiplets which disturb the grouping of the modes around radial frequencies. We tested this effect and found that at rotational velocities less than 100 km/s the regularities in the frequency spectra still remain easily detectable. Moreover, mostly axisymmetric modes are observed, which are only slightly influenced by rotation.

### Application of Regularities: The s-f diagram

We shall now assume that the centers of the observed frequency clusters correspond to the frequencies of the radial modes. Our observations of the stars examined above show that this assumption is almost satisfied. With this assumption the presence of regularities in observed frequency spectra may be used to infer fundamental parameters of stars in the  $\delta$  Scuti domain in the HRD if these parameters are uncertain or unknown.

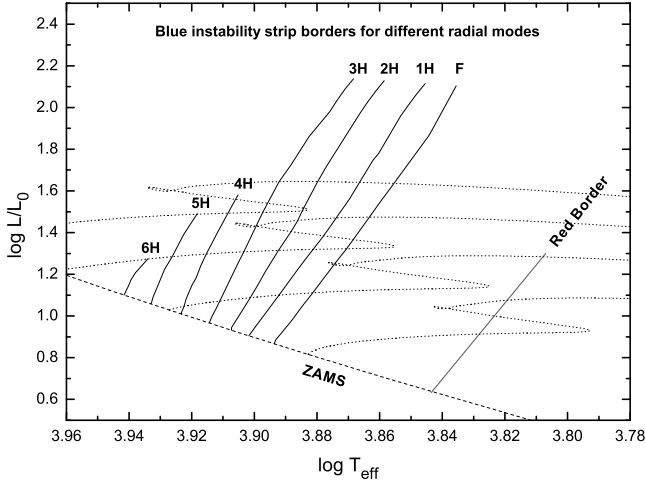


Figure 2: Predicted blue instability strip borders of the radial modes. Evolutionary tracks for models with 1.6, 1.8, 2.0 and 2.2  $M_{\odot}$  are given by dotted lines. The red border was taken from Dupret et al. (2004).

We followed the evolution of a star and computed radial frequencies of the modes. The same codes as described in Lenz et al. (2008) were used. A detailed inspection of the results reveals an excellent possibility to determine the  $\log g$  value of a star by means of two parameters: the average frequency separation between the radial modes,  $s$ , and the frequency of the lowest unstable radial mode,  $f$ .

Mode instability calculations show that the lowest-frequency cluster corresponds to the position of the radial fundamental mode only for the cool  $\delta$  Scuti stars. For the hotter stars, instability shifts to higher radial orders. The position of blue instability borders for modes up to the sixth radial overtone in a HR diagram is given in Fig. 2. While the values of both the  $s$  and  $f$  parameters depend on the mean density and, therefore, the evolutionary stage of a star, the  $f$  value also includes a temperature dependence.

Fig. 3 shows the grid for the  $\log g$  determination for stars in the  $\delta$  Scuti domain. The grid points were derived from the position of unstable radial modes. The  $s$  value was derived from the average spacing of all unstable radial modes, while  $f$  is the frequency of the lowest unstable radial mode. The  $s$  and  $f$  values from different models with the same  $\log g$  value were averaged to obtain the grid points. As can be seen in Fig. 3, the transition between main-sequence models and post-main sequence models takes place at  $\log g$  values between 3.90 and 3.75.

We note that the  $s$ - $f$  diagram is in some respect similar to Petersen diagrams (period ratios of consecutive overtones versus the longer period of each pair). Petersen diagrams also allow to determine the order of observed radial modes, as shown in Fig. 6 of Olech et al. (2005).

The grid presented in this paper was obtained with the standard values for chemical composition ( $X=0.70$ ,  $Z=0.02$ , OPAL GN93) for nonrotating models. Since the frequencies and the instability of radial modes are affected by changes of metallicity, rotation, helium abundance and convection, we also computed corresponding models to test for all these effects. The detailed results of these tests will be presented in a forthcoming paper. We conclude that the accuracy of  $\log g$  determination with the  $s$ - $f$  diagram is comparable or even better than photometrical estimates.

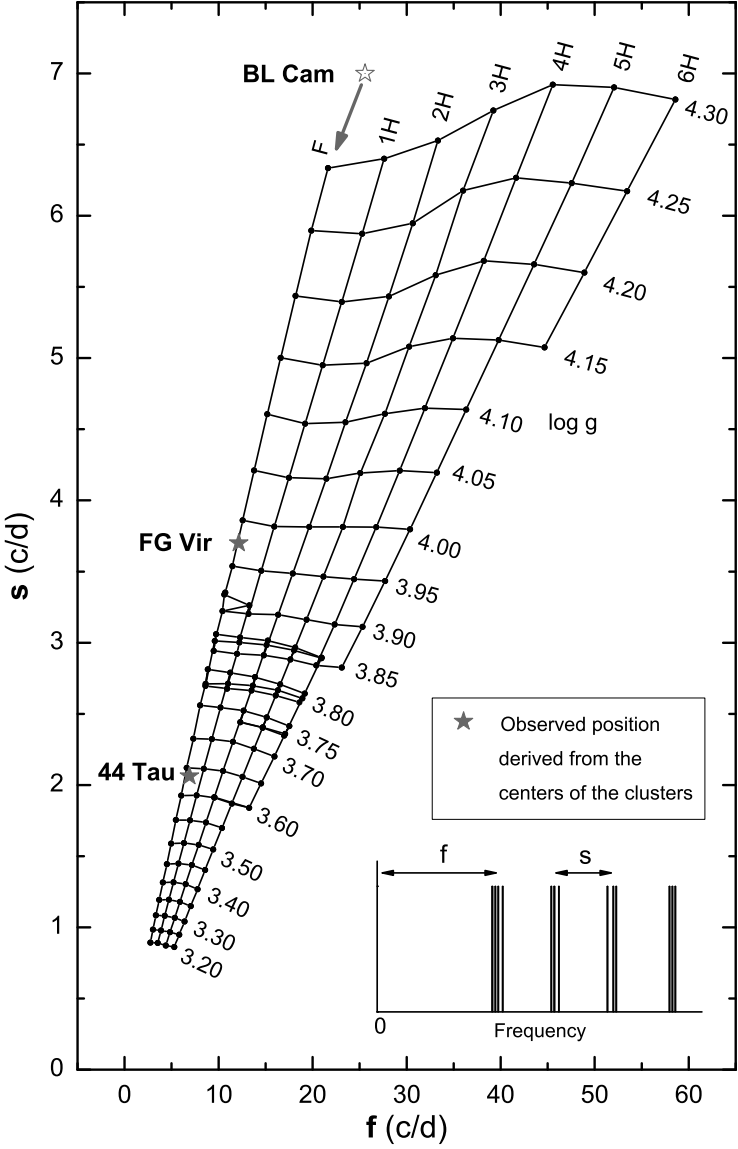


Figure 3: Average separation of the radial modes,  $s$ , against the frequency of the lowest-frequency radial mode,  $f$ . We assume that each unstable radial mode represents the center of a cluster as illustrated on the bottom right. The grid makes it possible to determine  $\log g$  and the order of the radial mode corresponding to the lowest frequency cluster. The asterisks correspond to observed values for the cluster centers of 44Tau, FG Vir and BL Cam.

In Fig. 3 the observed positions (derived from the centers of the clusters) of FG Vir, 44 Tau and BL Cam are shown. FG Vir and 44 Tau have normal chemical composition, whereas BL Cam is extremely metal-deficient ( $Z=0.0001$ ). We computed pulsation models for BL Cam to determine the shift of the corresponding grid in  $\log g$  accurately. The amount of the shift is shown in Fig. 3 by an arrow.

If we are close to the asymptotic regime (oscillations in higher overtones), the spacings between frequency clusters can be two times smaller than the separation between consecutive radial modes, because asymptotic  $\ell = 1$  modes lie halfway between radial modes. Consider a star with an observed frequency separation of  $2 \text{ cd}^{-1}$  and a first frequency cluster at  $10 \text{ cd}^{-1}$ . If we misinterpret this frequency difference to correspond to the separation between  $\ell=0$  and  $\ell=1$  modes (as in the asymptotic case), the predicted radial separation would be  $4 \text{ cd}^{-1}$ . This value is located outside the grids shown in the  $s$ - $f$  diagram, and no unstable modes are expected. Consequently, the incorrect value of  $4 \text{ cd}^{-1}$  is ruled out so that  $2 \text{ cd}^{-1}$  has to be the separation of radial frequencies. Any ambiguities may be ruled out this way and an incorrect  $\log g$  determination is avoided.

## Conclusion

In the observed pulsation spectra of well-studied  $\delta$  Scuti stars a regular distribution of frequencies can be found. The detected nonradial frequencies tend to cluster in groups around radial modes. The comparison of the observations with theoretical pulsation models reveals that the cluster pattern may be due to trapping of modes in the stellar envelope. We present the  $s$ - $f$  diagram. It relates the two parameters, viz.,  $f$ , the frequency of the lowest radial mode, and  $s$ , the mean spacing between the radial modes. Only linearly unstable modes are considered. For stars in the  $\delta$  Scuti domain in the HRD the  $s$ - $f$  diagram allows to infer the stellar  $\log g$  value and to determine the order of the radial mode associated with the lowest-frequency cluster.

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## DISCUSSION

**Noels:** In your solution diagram, what would the effect of the "factor 2 error"?

**Breger:** It is very fortunate that an of factor two in  $s$  would usually put you outside the grid of realistic models for stars. So it would be easy to spot in most cases.



Souza Oliveira Kepler



Wolfgang Zima and Michel Breger