Asteroseismology with ground-based photometric observations: abilities, limitations and achievements

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Abstract. Ground-based photometric observations are still the primary source of our knowledge of frequencies of modes excited in different types of pulsating stars. A typical set of photometric observations, accomplished usually by means of a multi-site campaign, allows to detect modes with amplitudes down to \(\sim\)0.1 mmag. The current abilities and limitations of this method of data collection are discussed in view of the requirements of the mode identification methods and asteroseismology. We also present some newest results of the multi-site campaign on stars in open cluster NGC 6910.

1. Asteroseismology: how it works?

The great progress that has been done in helioseismology allowed to test models of internal structure of our daily star with an unprecedented accuracy (see, e.g., [10]). This was possible mainly because solar oscillations can be observed on the solar surface, which together with the development of observational techniques and inversion tools, led to the present understanding of solar structure and its internal rotation. The techniques are now developed to study temporal variations of the solar structure during the solar cycle and investigate in detail smaller structures like sunspots or active regions using seismic techniques [6].

Going from Sun to stars, we lose most of the possibilities. First, stellar surfaces cannot be yet resolved to study non-radial modes. This limits the number of visible modes to those that are not effectively averaged over the stellar disk, i.e., low-degree modes. Next, the number of available photons drops by many orders of magnitude. Thus, even if a star has a large number of modes excited, only a small fraction of them can be detected. As a result, even in the best cases the number of observed modes rarely exceeds a hundred, in comparison to millions available for the Sun.

Moreover, mode identification is easy in the solar case, due to the fact that the frequencies of excited modes obey asymptotic relations. This is very rarely so easy in the stellar case, because even if a large number of modes is observed, many of them cannot be used in seismic analysis as they remain unidentified. Probably the best example of the application of asteroseismology to a real star remains GW Vir, a prototype of pulsating pre-white dwarf (DOV) stars [26]. In this case, most of 125 detected modes could be identified quite easily because they are high-order \(g\) modes obeying asymptotic relation. This led [26] to constrain mass, rotation period, magnetic field and stratification of elements in the stellar interior. On the other hand, we have a star like FG Vir, \(\delta\) Scuti-type pulsator, which has nearly 80 modes detected [8], i.e., a number comparable to GW Vir. However, a relatively fast rotation affecting frequencies of these modes complicates
largely their identification [12, 27]. Consequently, the identification was made for only a small fraction of modes detected in FG Vir: for some of them it is still ambiguous. Therefore, these frequencies cannot be fully exploited in seismic analysis. This comparison shows that some pulsators are better suited for asteroseismology than the others. Nevertheless, it is the number of modes which is the crucial factor defining how many and how accurate stellar parameters could be determined by means of asteroseismology.

The role of observations, in particular the ground-based photometric observations this paper is focused on, is to provide frequencies, amplitudes and phases of as many modes as possible. The yield, in general, depends on two factors: (i) the density of unstable modes for a given pulsator which is intrinsically related to its internal structure and (ii) the detection threshold of observations. We cannot change (i), so that the observational effort is focused on lowering detection threshold in the hope of finding more modes, i.e., modes that have smaller and smaller amplitudes. Fortunately, even if modes have small amplitudes, their frequencies can be derived quite accurately, at least accurate enough to allow comparison with model frequencies.

A typical procedure of seismic modeling is the following:

- We do observations which are used to get frequencies, amplitudes and phases of excited modes. We can do either photometry or spectroscopy or (preferably) both kinds of observations. Usually, it is photometry which provides more modes, but for stars showing solar-like oscillations it is spectroscopy which is doing better [5].
- The modes are identified in terms of the quantum numbers that describe geometry of non-radial pulsations. For this purpose, a variety of mode-identification methods is used. Many of them make use of the spectroscopic data, some require both photometric and spectroscopic data (see, e.g., [11]). Usually, only modes with the largest amplitudes can be identified.
- We use evolutionary models in a certain range of global parameters (mass, radius, log g, effective temperature, age, metallicity, overshooting parameter, rotation frequency, etc.) to calculate theoretical frequencies. Then, we perform frequency match comparing observed and calculated frequencies to constrain the global parameters (with uncertainties). The best model, in the sense of best frequency matching, can be selected in this way.
- Once the best model is selected, the remaining modes can be identified.
- Finally, the stability check should be performed, i.e., all observed modes should be unstable. This is also a good check of the input physics.

2. What we can do with the ground-based photometry?

As already stated above, it is quite obvious that the larger number of modes is available for a given star, the more global parameters (and/or better) can be constrained by means of asteroseismology. Presently, the largest number of modes is observed in some white dwarfs (an example of GW Vir was given above) and subdwarfs (V338 Ser = PG 1605+072 [15] and Balloon 090100001 [3] being the best examples). Nearly 80 modes were detected in the best studied δ Scuti star FG Vir [8], but for the other stars of this type it rarely exceeds a dozen. There is a growing number of detections of solar-like oscillations and for some stars over 30 modes were already detected [4, 7, 9, 16]. For the more massive main-sequence pulsators, β Cephei, SPB and γ Doradus stars, usually not more than several modes are observed. The number is even lower, two or three, for classical pulsating stars like Cepheids or RR Lyrae stars, but the case of two triple-mode Cepheids in the Large Magellanic Cloud [21] shows that even in such case an important information can be obtained using seismic modeling.

The number of detectable modes depends primarily on the nature of the pulsator and detection threshold, $\sigma_{th}$, of observations. As the former can be only accepted, the main effort is concentrated to lower the latter. Detection threshold can be lowered either by increasing
the number of observations or lowering the accuracy of a single measurement, $\varepsilon$. For a given telescope/detector/target combination, $\varepsilon$ can be lowered only by increasing exposure time (unless target becomes saturated), but this means that during a certain time interval less datapoints will be obtained. This two effects cancel each other so that increasing exposure time does not lead to a considerable change of $\sigma_{th}$. The exposure time should be rather adjusted from the point of view of expected time scale of variability and saturation effects. Thus, the only way to lower $\sigma_{th}$ is to increase the time covered by all observations, either extending the length of the run or increasing duty cycle arranging multisite observations. Alternatively, larger telescopes can be selected to do the job because what primarily defines the final value of $\sigma_{th}$ is the total number of photons acquired.

Much more important reason than given above for organizing multisite campaigns comes from the fact that larger duty cycle allows to avoid problems with aliasing. While for stars with several detectable modes relatively high aliases do not lead to ambiguities, when the number of modes is larger, high duty cycle is a necessity. Hence, a high duty cycle becomes very important when observing compact pulsators and stars with solar-like oscillations.

During the recent years, multisite campaigns became a standard when making ground-based photometric observations used in seismic modeling. For this purpose, a number of formal networks were established. The best known are:

- The Whole Earth Telescope (http://www.physics.udel.edu/darc/wet/),
- The Delta Scuti Network (http://www.univie.ac.at/tops/dsn/intro.html)
- STEPHI (http://www.lesia.obspm.fr/~stephi/).

Over 60 multisite observing campaigns on different classes of pulsating stars were organized by these three networks, but many others were carried out in a less formal way beside these networks. In order to illustrate a typical character of a ground-based photometric campaign, several characteristics for 23 selected campaigns of the last decade are shown in Figs. 1–5.

![Figure 1](image1.png)  
**Figure 1.** A mean telescope size used in selected multisite photometric campaigns of the last decade.

![Figure 2](image2.png)  
**Figure 2.** Number of observing nights for the same campaigns which are shown in Fig. 1.

First, we see in Fig. 1 that a typical size of the telescope used in ground-based photometric campaigns is 60–120 cm. A great advantage of telescopes of this size is that there is no problem in dedicating it to this kind of work for a very long time. On the other hand, the size is large enough to achieve the required accuracy of measurements.

In many campaigns, the number of nights (Fig. 2) exceeds a hundred, but some of these campaigns lasted longer than a single season. More importantly, the number of collected observing hours (Fig. 3) corresponds to more than a week or even a month of continuous
observing. Duty cycles rarely exceed 30% (Fig. 4). As noted above, high duty cycle is not always the most important requirement, but when the number of detected frequencies increase, becomes a crucial parameter. It has to be noted that high duty cycle is not easy to achieve due to the limited possibility of site selection and the weather. If really required, a campaign needs to very well organized, with many ‘backup’ sites. Therefore, the highest duty cycle is usually achieved with already established networks like those listed above.

Detection threshold, the most important parameter from the point of view of our considerations, is shown for the selected campaigns in Fig. 5. We see that for most of them, $\sigma_{th}$ is lower than 1 mmag; for the best ones drops below 0.2 or even 0.1 mmag. The four campaigns with the smallest $\sigma_{th}$, shown in Fig. 5, are the following: M67 campaign [25], WET XCov20 campaign on the rapidly oscillating Ap (roAp) star HR 1217 [20], another roAp star, HD 122970, campaign [14] and the DSN campaign on the $\delta$ Scuti star FG Vir [8].

What is not shown in these figures is the accuracy of a single measurement. Typically, for the best sites it is of the order of 2–3 mmag, for the worst, 7–10 mmag.
3. An example: NGC 6910 campaign

As an example of the latest ground-based photometric campaigns, we show here some very preliminary results of the 2005/2006 campaign on the open cluster NGC 6910. The main motivation for the campaign were the first promising results obtained from seismic modeling of bright β Cephei stars like V836 Cen [1, 13] and ν Eri [22, 2]. It was therefore decided to observe these pulsators in open clusters as the cluster stars share many properties which can be used in modeling. As there were only a few northern open clusters known to contain β Cephei stars, it was decided to choose two: NGC 6910, in which four β Cephei stars were known at that time [17], and χ Persei (NGC 884) with two known β Cephei stars [19, 18]. The first results of the campaign, obtained using part of 2005 data, were already published [23]. The whole set of data is still under reduction, but the first results, shown for χ Per by [24] and NGC 6910 in this paper, are very promising.

As noted above, [17] discovered four β Cephei stars in NGC 6910, NGC 6910 14, 16, 18 and 27\(^1\). The detection threshold for these data was ∼2 mmag. In total, 8 modes were detected in these four β Cephei stars.

The 2005/2006 campaign joined about 50 observers from 13 observatories. Some telescopes were dedicated for the campaign work for several months. The preliminary results we show below were obtained from the analysis of Białków data carried out in 2006. Białków was one of the sites fully dedicated to the campaign work. The 2006 data from Białków were collected during 81 observing nights spread over the time interval of about 230 days (Fig. 6).

![Figure 6](image-url) Differential magnitudes, \(\Delta V\), for NGC 6910 18 plotted against heliocentric Julian Day, showing the distribution of 2006 data obtained in Białków within the multisite campaign on NGC 6910.

As a result, five new β Cephei stars in NGC 6910, NGC 6910 25, 34, 36, 38, and 41 were found. In total, 40 modes were detected in these stars with NGC 6910 18 (12 modes) and NGC 6910 16 (10 modes + 1 combination mode) being the richest. This locates the two stars among those β Cephei stars with the largest number of modes known. The detection threshold for the brightest stars, as calculated from Białków data amounts to 0.3–0.5 mmag, depending on the star. For the complete campaign dataset, we expect detection threshold of the order of 0.1–0.2 mmag. Fourier periodograms for NGC 6910 18, showing several steps in prewhitening procedure, are given in Fig. 7. It can be seen that even after removing of 12 periodic terms,

\(^1\) See the WEBDA database (http://www.univie.ac.at/webda/) for the numbering system used for stars in the cluster field.
some extra power in the frequency range between 5 and 10 d$^{-1}$ remains. We may expect that analysis of the full dataset may lead to the detection of more modes in this star.

![Frequency spectra for 2006 Białkòw data of NGC 6910 18. Several steps of prewhitening are shown: original data, after removing of 3, 7 and 12 periodic terms. Note that ordinate has different scale in different panels.](image)

**Figure 7.** Fourier frequency spectra for 2006 Białkòw data of NGC 6910 18. Several steps of prewhitening are shown: original data, after removing of 3, 7 and 12 periodic terms. Note that ordinate has different scale in different panels.

Figure 8 shows frequency spectra for all nine β Cephei stars in NGC 6910. Going from top to bottom, we follow the sequence from the brightest to the faintest stars in the cluster. As can be seen, the detected frequencies become higher and higher when we go to fainter stars. In fact, this is what we may expect because for cluster members, which are believed to lie at the same isochrone, going from brighter to fainter stars, we go towards stars with smaller masses and smaller radii. Stars with smaller radii are expected to pulsate with higher frequencies. We do not have the modes identified yet, but some kind of this period-luminosity relation can be expected. In this picture, NGC 6910 34 and 38 seem to be exceptional as the range of detected frequencies is very large for them. This may mean that not only the two low-frequency modes (1.23 and 1.36 d$^{-1}$) in NGC 6910 38 are g modes, but also those with higher frequencies: 3.83 d$^{-1}$ for NGC 6910 34, 4.79 d$^{-1}$ for NGC 6910 38 and even 4.73 and 5.19 d$^{-1}$ for NGC 6910 36. Clearly, a thorough analysis of the campaign data should allow to solve the problem. Nevertheless, NGC 6910 38 remains a very good candidate for a hybrid β Cephei/SPB pulsator in the cluster.

The β Cephei stars are not the only pulsators discovered in NGC 6910. The ability of detection of low-amplitude modes with data obtained within this kind of a ground-based campaign is maybe even better illustrated by the fact that four δ Scuti stars were discovered in the cluster field. None if them is member of the cluster. Figure 9 shows frequency spectra for the four δ Scuti stars. It is enough to say that as many as 17 modes were detected in NGC 6910 12. The strongest has an amplitude barely exceeding 2 mmag.
4. Conclusions
Although asteroseismology is still in its infancy, we are getting data which will allow seismic analysis providing reliable information on the internal structure of stars. The ground-based photometric campaigns regularly provide data which allow detection of modes with sub-mmag amplitudes. Whereas satellite time-series data are (and will be) better than the ground-based ones in the sense of better accuracy and higher duty cycle, the ground based observations are more flexible in the target selection, time and duration of observations. There is no doubt that the two sources of data might be regarded as complementary in our quest for understanding pulsating stars.

A large effort undertaken to lower detection threshold allows for detection of more modes, also those which were usually regarded as undetectable, i.e., modes with $\ell > 2$. While for some stars this might be regarded as a complication, in general, it opens a new possibilities to study pulsating stars.

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Figure 9. Fourier frequency spectra for 2006 Białków data of four δ Scuti stars. 17 modes were detected in NGC6910 12, five in NGC6910 15 and 90, and a single mode in NGC6910 132.

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