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On the benefits of photometry for roAp theory: MOST observations of γ Equulei (HD 201601)

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Abstract. We discuss the potential of space photometry for rapidly oscillating Ap (roAp) stars. In reference to the MOST[1] observations of γ Equ (Gruberbauer *et al.*, 2008), we show that several aspects of the roAp phenomenon demand longer observational time bases and better time sampling than those currently feasible using spectroscopy. We conclude that, in order to improve our understanding of roAp stars, photometry is still an important tool which should not be neglected.

Key words: stars: chemically peculiar – stars: oscillation – methods: observational – techniques: space photometry

1. Introduction

Throughout this workshop, many exciting talks were delivered, mostly revolving around spectroscopic observations. Some of these enable us to resolve the horizontal and vertical structure of the atmospheres of CP stars. Of course, this is also applicable to roAp stars, whence it follows that the vertical profile of their pulsation can be studied (e.g., Ryabchikova *et al.*, 2007), which is another hint at the potential of roAp stars for asteroseismological studies. This exciting prospect, however, is a means to probe the atmosphere and the depth-dependent characteristics of the pulsation, in contrast to asteroseismic investigations in general. Their ultimate goal is to derive the stars' fundamental parameters and their interior structure from the mode spectra alone.

In the last few years, there has been tremendous progress in the modelling of theoretical roAp mode spectra by incorporating the effects of the magnetic field (Saio, 2005; Cunha, 2006). In order to test and improve these efforts, it is evidently necessary to derive reliable sets of p-mode frequencies from observations (and, of course, to test if there even is such a thing as a "reliable set"). We think that this can currently only be achieved using high-precision photometric observations. As an example, we will briefly describe our investigation on the MOST observations of γ Equ.

[1]The MOST satellite is a Canadian Space Agency mission, jointly operated by Dynacon Inc., the University of Toronto Institute of Aerospace Studies and the University of British Columbia with the assistance of the University of Vienna.

2. MOST and γ Equ

2.1. Premise

MOST, launched in 2003, is a Canadian satellite project, aiming at the detection of solar-like oscillations in stars other than the Sun. The goal of the instrument design was therefore to reliably monitor stellar variability down to semi-amplitudes of a few parts per million (ppm), and to observe the same target continuously up to several weeks. The latter provides a reasonable time base and excellent sampling both of which are needed to unambiguously identify pulsation frequencies. A more elaborate description of the instrument can be found in Walker *et al.* (2003). Amongst its list of targets was the well-studied roAp star γ Equ, which was eventually observed with the space telescope in 2004 for over 19 days.

For a timeline of investigations concerning γ Equ, we refer to Gruberbauer *et al.* (2008) and references therein. A few studies have to be pointed out, however, for the sake of discussion. Prior to the MOST observations, γ Equ was already known to be a multi-mode pulsator. Although initially found to show only a single reliable frequency (Kurtz, 1983), Martinez *et al.* (1996) were able to cross-identify frequencies from data of various observers, albeit with some inconsistencies, leading to the estimate of at least 4 separate pulsation frequencies. Still, γ Equ's mode spectrum remained poorly understood. In recent years, spectroscopic investigations have provided us with a clearer picture of the star's atmosphere and its interplay with pulsation (among others, Kochukhov, Ryabchikova 2001; Ryabchikova *et al.*, 2002; Shibahashi *et al.*, 2004) but, due to short time bases, could not help to refine our knowledge of the individual frequencies of γ Equ. Thanks to MOST this has now been achieved.

2.2. Results

The 19 days of MOST observations of γ Equ, culminating in almost 49 000 exposures, delivered highly precise measurements with unprecedented time sampling for this star. The data have been thoroughly analysed and the results are presented in Gruberbauer *et al.* (2008). Among these results are the following, which show why precise photometry could help in the understanding of roAp stars :

1. The authors have identified 7 frequencies intrinsic to γ Equ with semi-amplitudes as low as 18 ppm.

2. Due to the relatively long time base, in comparison to single-site spectroscopic observations, the 1σ-frequency uncertainties are estimated to lie below $0.1\,\mu$Hz

3. The authors state that 2 of the 7 frequencies correspond to the first and second harmonic to the dominant frequency.

4. All 4 frequencies from Martinez *et al.* (1996) have been found consistently in this single data set.

5. Most important though is the detection of an additional $5^{\rm th}$ frequency, closely spaced to the primary frequency.

6. After excluding the 2 harmonics, all 5 remaining frequencies were fitted to magnetic pulsation models. The model corresponding to the best fit reproduces the observed frequencies to within the observational uncertainties. Its parameters match γ Equ's assumed position in the HR diagram quite well.

3. Implications of the MOST results for γ Equ

As stated in point **1** of Section 2.2, MOST observed very small amplitudes in γ Equ. One can expect that these small light variations will be accompanied by small changes in radial velocity. Today, radial velocity measurements are becoming more precise than ever, and high quality time series can be constructed. A large number of data points is needed, though, in order to reduce the noise in Fourier space to a level that enables the detection of such weak signal. Alas, it is still almost impossible to obtain enough observing time at the best spectroscopic instruments in order to compete with space instruments. Also, daily aliasing would make it difficult to identify all 7 frequencies of γ Equ unambiguously. This eventually results in an incomplete picture of the star's pulsation, reducing the observations' potential to be a test for roAp theory, and could lead to false conclusions.

Point **2** mentions very small observational uncertainties on the frequency values. Small frequency uncertainties are necessary for resolving closely spaced frequencies, but also for testing theoretical models. A least-squares algorithm, like the χ^2-test employed in Gruberbauer *et al.* (2008), only makes sense, if the observations put enough constraints on the model frequencies. Therefore, in order to test roAp theory, long time bases are inevitable, since the frequency uncertainty is inversely proportional to the time base of the data set.

Point **3** has a special relevance for recent studies of γ Equ and other roAp stars. Kochukhov an Ryabchikova (2001) found strange blue-to-red-moving features in the line profile variations (LPV) of γ Equ. According to them, these features might be explained through modes with $m \neq 0$. This led to a discussion about other possible explanations, e.g. whether these features might be caused by shock waves or turbulence (Shibahashi *et al.*, 2004; Kochukhov *et al.*, 2007; Shibahashi *et al.*, 2007). Since similar characteristics have been found in many other roAp stars, they need to be understood in context of the roAp phenomenon. The detection of the first and second harmonic to the dominant frequency by MOST shows that photometry is also sensitive to these effects. This might help to rule out explanations, which are only applicable to spectroscopic observations. However, the first harmonic, as found in the MOST data, only has a semi-amplitude of about 40 ppm, and the second harmonic is an even weaker signal. As such, very precise photometry is needed for its detection.

Point **4** confines the answers to a question that has often been posed: Are roAp pulsations consistent over a longer time base, or is the signal damped and re-excited, similar to solar-like oscillations? The MOST observations of γ Equ show no convincing evidence that indicates a mode lifetime shorter than the observation run (19 days). Spectroscopic observations are currently obtained for a few hours at a time, often with daily or even longer gaps in between. To gather more evidence for the determination of mode lifetimes, extended observations with sufficient precision and a low detection threshold are necessary. Only space missions like MOST or COROT, and, to some extent ground-based observation networks like the Whole Earth Telescope (WET), currently meet these requirements.

The most unexpected result from Gruberbauer *et al.* (2008) probably concerns point **5**. Amplitude modulation or amplitude change, unrelated to stellar rotation, in roAp stars has been reported or suggested multiple times. One of the possible explanations is that we simply see the beating of two closely spaced frequencies. Beating can be misinterpreted as amplitude modulation, if the time base of the observations is not long enough to resolve the involved frequencies, or if the data quality is not good enough to reliably derive time-resolved amplitudes and phases. Gruberbauer *et al.* (2008) report the detection of a previously unresolved frequency, very close to the primary frequency. This frequency doublet would result in a beating period of about 14.3 days. Observations with short time bases would not be able to distinguish between amplitude modulation and beating. An investigation of the pulsation models fitted to the MOST data also reveals, why such a beating phenomenon might be more common in roAp stars. As shown in Fig. 1, the influence of the magnetic field can lead to closely spaced modes of different spherical degree ℓ (for a discussion on the meaning of ℓ-values in magnetic models we refer to Section 4), because the sequences of different ℓ sometimes intersect.

4. Discussion on mode identification and photometry

Mode identification is perhaps the most important prerequisite for asteroseismology. Only when the assignment of mode parameters (ℓ, m, n) to a specific observed frequency is established, can it be used to obtain information about the interior of the star. Usually, spectroscopy is the preferred tool. The mode parameters can be deduced from the line profile variations, and (in contrast to mode identification through photometry) $m \neq 0$ modes can also be analysed.

In the case of roAp stars, line profile variations are a much more difficult problem. As shown in Saio (2005), and for the more specific case of γ Equ in Gruberbauer *et al.* (2008), theory predicts that a single mode cannot be assigned to a single spherical harmonic because of magnetic effects. To describe

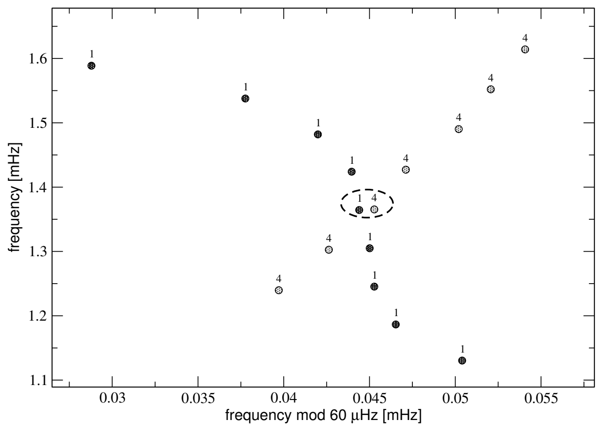

Figure 1. $\ell = 1$ (black) and $\ell = 4$ (grey) mode sequences for the model that fits best to the observed frequencies of γ Equ. The ellipse shows two closely spaced modes around 1.365 mHz, which lead to apparent beating, if the observational time base is too short.

the latitudinal distribution of amplitude of a pulsation mode over the stellar disc of magnetic stars, a single Legendre function is not sufficient. One needs to "construct" a mode which distributes its kinetic energy amongst a series of spherical harmonics (e.g., the ℓ-values in Fig. 1 are merely those of the spherical harmonic that contributes most of the kinetic energy to the pulsation mode).

A latitudinal amplitude dependence, as predicted by the magnetic pulsation models, can be tested by means of studying the line profile variations. An excellent example for this proposal are the excellent results in Kochukhov (2004). However, mode identification for roAp stars, as an unbiased observational effort, cannot work the way it is currently established. The only approach to mode identification in an unbiased fashion, therefore, has to rely on the frequency values alone, and on fitting them to magnetic model frequencies. As stated in Section 3, we think that presently only space photometry and ground-based networks like the WET can currently achieve uncertainties and detection thresholds that are low enough to make this a feasible task.

5. Conclusion

We have established that continuous and extended high-precision photometry is a necessary requirement to investigate some of the phenomena that roAp stars exhibit. It is also the only current mean to obtain an accurate overall picture of their mode spectra, needed to test models in terms of the frequencies they predict. As expressed by point **5** in Section 2.2, such a model test for γ Equ yields very positive results. To summarize, we would like to encourage the community to pursue the study of roAp stars with modern spectroscopic instruments. Still, we feel obliged to stress that for progress in this field, the combined efforts of spectroscopic and photometric investigations are mandatory.

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