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Introductory Remarks

I am happy to report that the CoAst journal is doing quite well with an increasing number of papers and contributions. Our thanks go to you, the readers, authors and the many hardworking referees.

Starting with the next regular issue we will include a new section (‘Insight’) with reports on asteroseismological papers published elsewhere. (Now, why would you wish to send your papers to other journals?) The reason is quite obvious: it is very easy to miss new, important papers in our field. In our work we are already assisted by the excellent myADS Notification Service and by astro-ph. CoAst will provide an additional platform of up to two pages to enable authors to summarize their paper or to comment on recent developments.

Our cooperation with the Smithsonian/NASA Astrophysics Data System is working well. You might have noticed that the older papers published in CoAst are now also included in the data base; even the contents of the Delta Scuti Star Newsletters (a precursor of CoAst) are now entered for retrieval. As most of you know, the link http://adsabs.harvard.edu/ads_abstracts.html will enable you to get a listing of publications.

Enough unpaid advertisement for this great data service. This year we will be publishing a number of special issues of CoAst. The first publication is the biggest volume to date: the conference proceedings of the ‘Future of Asteroseismology’ meeting (CoAst vol. 150), which should be in the mail at this moment.

Now that you have volume 151 in your hands, it is time to plan the next issue: an announcement can be found on the inside back cover.

Michel Breger
Editor
Searching for $p$-modes in $\eta$ Booëtis & Procyon using MOST satellite data


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Abstract

We present frequency analyses of new photometry obtained in 2005 by the MOST$^1$ (Microvariability & Oscillations of STars) satellite of two solar-type stars, $\eta$ Booëtis and Procyon, and reanalyses of MOST data of these stars obtained in 2004. With improved strategies to identify and correct stray light artifacts in the MOST Fabry Imaging data, we produce amplitude spectra from the reduced data and compare them to $p$-mode oscillation spectra computed from stellar models. We confirm the null result from the 2004 MOST observations of Procyon. We find no evidence for spectral power with regular spaced frequencies characteristic of radial $p$-modes, nor do we find excess power in the expected $p$-mode frequency range. Consequently, we argue the absence of $p$-mode oscillations in Procyon exceeding our detection limit of about 10ppm.

$^1$Based on data from the MOST satellite, a Canadian Space Agency mission, jointly operated by Dynacon Inc., the University of Toronto Institute for Aerospace Studies and the University of British Columbia, with the assistance of the University of Vienna.
For η Boo, the frequencies present in the 2005 data do not match within the resolution those identified in the 2004 data after excluding all frequencies we suspect to be due to stray light contamination. However, there is clear evidence for excess power within the $p$-mode range predicted by models. We discuss the implications of these results for mode lifetimes in these stars and the sensitivity of high-precision photometry to solar-type oscillations in the presence of granulation.

Introduction

Eigenfrequency spectra of acoustic oscillations have been observed in solar-type stars through ground-based spectroscopic measurements of radial velocity, especially with the advent of the few-m/s precision developed for extrasolar planet searches. The study of such $p$-modes photometrically requires a precision of a few parts per million (ppm) or less, which can only be achieved reliably from space. The MOST space mission, lead by J. Matthews and first reviewed by Walker et al. 2003, was designed to obtain such precision for a few bright stars. The long, nearly continuous time coverage possible with MOST would also make it possible to resolve fine structure in the $p$-mode eigenspectrum for asteroseismic modeling.

Two early MOST targets were Procyon (Matthews et al. 2004) and η Boötis (Guenther et al. 2005), both observed in 2004 for about a month each. In the former, no $p$-modes were detected, with strong upper limits on amplitude and mode lifetime. In the latter, radial $p$-modes were identified that are consistent with a stellar structure model appropriate to η Boo, and which extend to low overtones the sequence of modes identified by Kjeldsen et al. (2003) in their spectroscopic data. The astrophysical implications of the results warranted second sets of photometry to confirm, refine or deny the original findings. For this reason, both stars were chosen to be reobserved by MOST in 2005.

The trail of two stars

Procyon and η Boo are more massive than the Sun and are in their post-main-sequence phase of evolution. They have convective envelopes but with different depths. This makes these stars attractive targets to help quantify the driving of $p$-modes by turbulent convection, the mechanism believed to operate in solar-type stars, as in the Sun.

The coupling between the pressure variations associated with $p$-modes and their driving source, the convective motions, is greatest in the very outermost layers of the convective envelope, in a thin region called the superadiabatic layer. Numerical hydrodynamical simulations of stellar convection (Robinson
et al. 2005) show that the convective velocities are greater in stars with thinner convection zones (such as found in the post main-sequence stars Procyon and η Boo) than those with deeper convective envelopes like the Sun. If the amplitudes of the \( p \)-mode pulsations correlate with the maximum turbulent velocities, and hence the depth of the convection zone, then the amplitudes of the \( p \)-modes in stars like Procyon and η Boo should be greater than those observed in the Sun (Christensen-Dalsgaard & Frandsen 1993; Kjeldsen & Bedding 1995; Houdek et al. 1999).

Attempts to observe \( p \)-modes on these stars from the ground have yielded mixed results. For Procyon, the groundbased radial velocity observations show an enhanced region of power in the frequency range 0.5 – 1.5 mHz (e.g., Brown et al 1991; Martic et al. 1999; Eggenberger et al. 2004). The identification of individual peaks and regular spacings is less certain, although both Martic et al. (1999) and Eggenberger et al. (2004) find a frequency spacing of 55 \( \mu \)Hz, which is consistent with model predictions (Chaboyer et al. 1999). In the case of η Boo, several groundbased campaigns have yielded plausible individual \( p \)-mode identifications (Kjeldsen et al. 2003, Carrier et al. 2005). They find a spacing of 40 \( \mu \)Hz, consistent with models. However, there is little coincidence of the actual identified frequencies between the two groups, and even between observing runs by the same group from epoch to epoch.

The results on Procyon and η Boo from MOSTs first year of operation have already been published (Matthews et al. 2004; Guenther et al. 2005). We reported a null detection for Procyon and a possible detection of radial \( p \)-modes on η Boo. The Procyon null detection was a surprise since we expected the amplitudes of the oscillations, as consequence of its very thin convective envelope, to be large enough to be detectable above the noise level of a few ppm in the MOST photometry. The tentative detection of \( p \)-modes on η Boo was also not quite what we expected. We had expected to see a clear and unambiguous signature of \( p \)-modes. What we saw though were many peaks in the spectrum, of which less than a third could be associated with the radial \( p \)-modes of our models. Other peaks in the spectrum of comparable amplitudes could not be unambiguously identified because stellar models appropriate to η Boo show a rich and complex eigenspectrum of nonradial modes which are very sensitive to changes in metallicity, convection parameters and envelope models. This ambiguity makes exact nonradial mode identification in our MOST photometry virtually impossible without additional information on stellar fundamental parameters derived with techniques other than asteroseismology.

In this paper we present the new sets of MOST photometry of Procyon and η Boo obtained in 2005, and a revised strategy to identify \( p \)-mode signals in the data. Much of this strategy involves identifying and removing artifacts in the MOST data introduced by stray light from scattered Earthshine. We apply this
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to the new data and the previously published 2004 photometry, and compare the resulting frequency spectra for each star to stellar models. We also discuss the possibility of short $p$-mode lifetimes and show the consequences of short lifetimes on the observations.

Observations & Data Analysis

The MOST microsatellite houses a 15-cm telescope which feeds a CCD photometer through a custom broadband optical filter. For the brightest stellar targets and the highest photometric precision, starlight is directed through a Fabry microlens to produce a fixed image of the telescope pupil covering about 1500 pixels on the detector. MOST is in a near-polar Sun-synchronous orbit of altitude 820 km, from which it can monitor stars continuously for up to two months within a 54$^\circ$–wide viewing zone. The instrument is capable of achieving noise levels in the Fourier domain for very bright stars of about 1 ppm at frequencies above about 1 – 2 mHz.

It was recognized in the earliest observations (e.g., Matthews et al. 2004; Rucinski et al. 2004) that stray light entering the Fabry field due to scattered Earthshine was modulated with the MOST orbital period. This introduces artifacts in the data at the satellite orbital frequency and its harmonics, and other modulation terms. These effects, other aspects of spacebased CCD photometry, and how they are dealt with in MOST Fabry Imaging photometric reductions, are described in more detail by Reegen et al. (2006) and revisited here in Section Stray light processing.

MOST photometry of Procyon and $\eta$ Boo

The data set for Procyon consists of two runs: 32 days in January 2004 (Matthews et al. 2004), and 17 days in January 2005 (this paper). For $\eta$ Boo, the runs cover: 27 days during April May 2004 (Guenther et al. 2005) and 21 days during March April 2005. In Table 1 we summarize the properties of all four observing runs, listing the start and end dates of each run, its duration, exposure time, number of exposures, duty cycle, and resulting frequency resolution.

Stray light processing

The photometric signal from a MOST Fabry Imaging target star arrives on the CCD in an annulus (see Fig. 1 in Reegen et al. 2006). We define the “Fabry image” to be the image of the telescope entrance pupil produced by a Fabry lens close to the CCD, the “target pixels” to be those pixels located within the
annulus, and the “background pixels” to be the remaining pixels in the square
CCD subraster which represents the Fabry field stored and downloaded from
the satellite. The pixels (58×58 in 2004 and 60×60 in 2005) in the Fabry
field are binned 2×2 before photometric processing. The numbers of binned
target pixels and binned background pixels are about equal: ∼450 each. The
Fabry micro–optics were designed to guide all light from a target star entering
the telescope aperture (even with changing incident angles due to spacecraft
pointing errors) to the same set of pixels on the CCD. The stellar signal in the
target pixels is nearly independent of the small level of satellite pointing jitter.

Photometry obtained from MOST includes a periodic, amplitude–modulated
signal due to stray light entering the instrument from scattered Earthshine. The
stray light variation has a non–sinusoidal shape and its amplitude and shape
depend on the observing season, the location of the star relative to the illu-
minated limb of the Earth, and the orientation (roll) of the spacecraft. The
relative effect of the stray light depends also on the brightness of the star. The
most obvious effect of the stray light variation in frequency analysis of MOST
data is a set of peaks in the Fourier domain at the MOST orbital frequency and
its harmonics. Matthews et al. (2004) aggressively removed the power at those
frequencies by treating the 2004 Procyon data with a running mean filter tuned
to the orbital frequency of about 165 μHz. Guenther et al. (2005) applied a
different reduction scheme, described in detail in Reegen et al. (2006), which
looks for the correlation between the stray light signal in the target pixels and
the stray light signal in the background pixels.

Because stray light does not uniformly illuminate the CCD, it is difficult to
eliminate all of its contributions to the stellar time series, even with pixel decor-
relation, and the remaining signal can be as large as 100 ppm in some cases.
Most of our post-processing of the data is focused on removing this compo-
nent and to estimate the level of contributions of non-stellar signal at a given

<table>
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<tr>
<th>Table 1: Basic parameters of the MOST photometry.</th>
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<tr>
<td>Target</td>
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<td>Date</td>
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<tr>
<td>Duty cycle [%]</td>
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<td>Resolution [μHz]</td>
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Figure 1: The spectral significance spectrum for the background time series (BTS) of Procyon 2004 data. The highest peaks are due to stray light correlated with orbital harmonics. The secondary peaks in the main figure are 1 cycle day$^{-1}$ aliases due to the changing albedo of the earth reflected sunlight. The insert shows a highly magnified portion of the graph surrounding one of the orbital peaks. The peaks shown in the insert, which lie very close to the orbital harmonic peak, are amplitude modulation peaks due to long period changes in the attitude of the MOST satellite.

We begin by removing white noise from both the background time series (BTS) and the target time series (TTS) by applying a Fourier transform algorithm to the data. The SigSpec routine (Reegen 2006, 2007) performs a Fourier transform on the time series data, picks out the peak which is statistically most likely to be real and not an artifact of noise (based on its amplitude and phase), assigns a probability to that peak, and then fits and removes the harmonic signal from the time series. The process is repeated until the peaks found are below a user-specified probability threshold. For well-sampled time series like the MOST photometry presented here, SigSpec and other Discrete Fourier Transforms give identical results. By assigning a probability to a given
frequency (and corresponding amplitude and phase) that it is not caused by white noise, \textit{SigSpec} allows a more rigorous statistical treatment of the resulting amplitude spectrum. Specifically, a peak with a spectral significance equal to sig means that that signal would only occur once in 10\textsuperscript{sig} random Gaussian noise spectra. For example, a spectral significance of 6, means that that peak’s amplitude, frequency and phase would only appear in one in a million Gaussian noise spectra. We have shown mathematically and through simulations that a spectral significance level (“sig”, returned by \textit{SigSpec}) of 5.6 corresponds roughly to a signal-to-noise ratio in amplitude of 4 for a non-modulated periodic wave (Reegen 2005, 2006).

Peaks with high spectral significance are very unlikely to be caused by white noise. Not all noise is white, nor is it necessarily all due to instrumental effects. For example, stars like Procyon and \eta Boo have surface convection zones, which produce granulation noise in the photometry whose amplitude will increase with decreasing frequency.

After applying \textit{SigSpec} to the BTS in a threshold limited spectral significance spectrum we obtain, as presented in Section 3, only instrumental signal, as expected for the background. The same analysis applied to the TTS yields stellar plus instrumental signal, provided that the threshold limit is set high enough to reject random white noise. With the instrumental signal clearly identified in the BTS, our next step is to remove this signal from the TTS, leaving behind, presumably, the intrinsic stellar signal. In an early version of our reduction routine, we accomplished this by removing the corresponding significant peaks found in the BTS from the TTS. Of course, if there is any intrinsic stellar power coincidentally at those frequencies, it is also removed. A shortcoming of this approach is that – formally – a tiny signal in the BTS can eliminate a large signal in the TTS, which may actually be dominated by the stellar variations. To address this possibility, we transformed a given measured BTS signal amplitude to the (usually higher) intensity level of the TTS and assumed that stray light components are additive in the TTS.

Recognizing Artifacts in the data

Background signal

The background intensity consists mainly of three components: the bias level of the CCD, the stray light signal, and (as a minor component) the sky background. The stray light signal increases linearly with the exposure time while the bias level remains approximately constant.

After applying our analysis to the BTS of the 2004 Procyon observations, we obtain the spectral significance spectrum shown in Figure 1 (for spectral
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The largest significant peaks correspond to the expected orbital harmonics. The smaller peaks surrounding the largest peaks are side lobes separated by multiples of 1 cycle day$^{-1}$. The amplitude of the stray light is modulated by both the orbital period of the satellite and its Sun-synchronous nature, which brings MOST over a similar part of the Earth after one day, so similar albedo features affect the stray light as they rotate into view. There is additional structure (see inset in Figure 1) associated with the slower modulation of the stray light signal during the long observing run, as the orientation of the satellite orbit and the position of the star with respect to the illuminated Earth change. All of the peaks in the background spectrum, except those at very low frequencies near 0 $\mu$Hz, are associated with stray light. The largest peaks at the orbital frequency and its first harmonic have amplitudes of 13.9 mmag and 6.4 mmag, respectively.

Figure 2: An echelle diagram with folding frequency $1/d^{-1}$ for the BTS of Procyon 2004 data, filled circles, and Procyon 2005 data, open circles. The distribution of peaks into "plus shaped crosses is due to both 1 cycle day$^{-1}$ aliases and modulation effects on the orbital harmonics of stray light. The slope comes from the incommensurability of orbit and 1-day period.
The easiest way to distinguish the 1 d$^{-1}$ side lobes from the amplitude modulation peaks is to fold the spectrum into an echelle diagram with a folding frequency of 1 cycle day$^{-1}$. In Figure 2, the frequencies of the peaks in the background spectral significance spectrum for the Procyon 2004 and 2005 data are plotted in this way (as dots and open circles, respectively). We are not concerned with the very low frequency peaks running along the bottom of Fig. 2, since the window function of the high–duty–cycle MOST data has little spectral leakage and this power does not contaminate the higher frequencies of interest for stellar $p$-modes. The remaining peaks fall nicely into groups, with the groups themselves falling along a diagonal line. The peaks within each group fall on a “+”–shaped orthogonal grid. Each group of peaks corresponds to an orbital harmonic. The vertically aligned peaks of each cross correspond to peaks that are 1 d$^{-1}$ side lobes of the orbital harmonic. That is they correspond to $j \cdot f_o \pm k$ (1 cycle day$^{-1}$), where $j$ is an integer corresponding to the order of the orbital harmonic, $k$ is an integer corresponding to the order of the 1 day side lobe, and $f_o$ is the orbital harmonic frequency (in units of cycles day$^{-1}$). The slow variation of the stray light signal over the duration of the run introduces beat frequencies in the Fourier Transform, which can be seen as the horizontally aligned peaks in each cross in Fig. 2. All the orbital and 1 d$^{-1}$ side lobe peaks are amplitude-modulated but, in the case of the 2004 Procyon photometry, only the orbital harmonics themselves have large enough amplitudes to reveal modulation effects. In the case of $\eta$ Boo, the amplitude modulation peaks are visible even for the higher-order 1 d$^{-1}$ side lobes, i.e., $k \neq 1$.

Note that there are no other peaks in the spectral significance spectrum of the background. Our analysis has not only identified the periodic components in the background (in this case due to stray light), but suppressed any other peaks due to random white noise. In Figure 2, the orbital harmonics and 1 d$^{-1}$ side lobes for the 2004 and 2005 Procyon data coincide. The peaks due to slower amplitude modulation do not match up, as expected, since the orientation of the MOST telescope was not exactly the same in both runs and the 2005 observations extended later into the season than those in 2004 (see Table 1). We can measure the variation in amplitude of an orbital harmonic as a function of time by splitting the BTS into subsets, as shown in Figure 3 for the three lowest orbital harmonics in both Procyon data sets, with running bins 4 days long spaced by 1–day intervals. The long-term amplitude modulation is comparable for all the 1-d$^{-1}$ side lobe peaks around the orbital harmonic peaks.

The background spectra for the $\eta$ Boo observing runs are more densely filled with stray–light–related signals. Both the orbital harmonics and the 1-d$^{-1}$ side lobes of the orbital harmonics are modulated in amplitude. The increased number of peaks compared to those for Procyon is mainly due to the increased relative contribution of the stray light background since $\eta$ Boo is more than 2
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Figure 3: Modulation of the stray light amplitudes over the duration of the observations for Procyon 2004 and 2005 BTS data. The amplitude of the orbit and 1/d side lobe peaks in stray light change during the observing run due to changes in the attitude of the MOST satellite as it, and the earth, orbit the Sun.

magnitudes fainter than Procyon.

Target signal

Having identified the periodic stray light signals in the background pixels of the Fabry image, we then proceed to filter those signals from the target pixels.

As before, we first produce a spectral significance spectrum, now for the target time series (TTS). Because the stray light signal is periodic (albeit modulated), it is not identified as statistical noise and is not filtered by this process. The target spectral significance spectrum, therefore, contains both stray light signal and any other periodic variations intrinsic to the star. We have seen in Figure 2 that the orbital harmonics are accompanied by side lobes separated by 1 d$^{-1}$. The long-term amplitude modulation is comparable for all the 1-d$^{-1}$ side...
lobes around each orbital harmonic. Therefore, most of the beat frequencies produced by that modulation have at least one companion $1 \text{d}^{-1}$ away, within a conservative frequency resolution given by $\pm 1/(\text{time span of the data})$. We assume that each peak in the target spectral significance spectrum which is part of a $1 \text{d}^{-1}$ pair is due to remaining stray light signal and we reject both. We stress that these pairs are not due to daily aliases produced by the spectral window function, as is a problem for ground-based observations, since MOST observations do not have daily gaps.

Not all stray light components are parts of $1 \text{d}^{-1}$ pairs. To filter out the remaining stray light signal, we search through the residual target spectral significance spectrum, identify and remove all peaks from the spectrum that match peaks in the background spectral significance spectrum. We consider peaks to match if their frequencies agree within the frequency resolution (see Table 1). This approach, unfortunately, may also remove any intrinsic stellar signal near those frequencies. To avoid removing a high amplitude target peak just because it is located close to the frequency of a very low amplitude background peak, we compare the amplitudes and re-introduce the removed frequency if the removed frequency’s amplitude is much greater than the background peak’s amplitude.

The approximate percentages of significant peaks we identify as instrumental and remove are: Procyon 2004, 70.3%; Procyon 2005, 74.4%; $\eta$ Boo 2004 85%, and $\eta$ Boo 2005, 84.6%. The approximate percentages of the frequency ranges covered by these instrumental signals (taking into account the inherent frequency resolutions of the data sets) are: Procyon 2004, 5.3%; Procyon 2005, 9.3%; $\eta$ Boo 2004, 49.8% and $\eta$ Boo 2005, 42.1%. If $p$-modes are present in our target spectral significance spectra, then these latter percentages represent approximately the percentage of $p$-mode peaks which have likely been filtered out along with the stray light signal.

**Searching for $p$-modes**

No $p$-modes in Procyon

In Figure 4, we plot an echelle diagram for the peaks in the filtered 2004 and 2005 Procyon data together. The echelle folding frequency is 53 $\mu$Hz (close to the average spacing predicted by stellar models) and the figure contains only frequencies which we are convinced are not contaminated by instrumental effects. No frequencies of the 2004 and 2005 data set overlap nor are there any obvious $p$-mode alignments in either data set. Note that because the 2005 run is shorter than the 2004 run, the noise level in the 2005 data is higher; hence, there are fewer peaks with $\text{sig} \geq 5.6$. The model frequencies also shown in this figure will be discussed later in this Section.
Searching for $p$-modes in $\eta$ Boötes and Procyon using MOST satellite data

Figure 4: An echelle diagram comparing the Procyon 2004, filled circles, and Procyon 2005, filled triangles, spectral significance spectra to $p$-modes of models of Procyon (open symbols). The model mode frequencies are the average of all models that lie within $1\sigma$ of Procyons mass, luminosity, and effective temperature (see Table 2). The error bars show the range of frequencies for each mode for models that lie within $1\sigma$ of Procyons mass, luminosity, and effective temperature.

Ignoring the stray light and considering only true statistical noise for the 2004 Procyon data, the lowest peaks we can identify above the noise threshold (set at sig = 4) have amplitudes of about 10 ppm. The peaks from the 2004 spectrum with sig $\geq$ 5.6 have amplitudes $\geq$ 12 ppm. For the 2005 Procyon data (shown in Fig. 5), the corresponding amplitudes are about 11 ppm and 14 ppm. The echelle structure of $p$-modes in Procyon may not exhibit as simple an asymptotic pattern as expected. To explore this, we have examined stellar models taken from one of the author's (DBGs) dense and extensive grids (Guenther et al. 2005). Using typical values for the temperature, luminosity and composition of Procyon, along with a mass constraint based on its binary orbit (Girard et al. 2000), we selected models in the grid that fall within $1\sigma$
Figure 5: Amplitude spectrum of Procyon from stray light reduced MOST 2005 data. The vertical dashed lines correspond to the satellites orbit frequency (164.34 $\mu$Hz) and its overtones. The corresponding spectral significance spectrum peaks for spectral significances greater than 4.0 are shown in the insert.

of these constraints. Because the models are based on standard physics, discrepancies between the observed oscillation spectrum and the model predicted spectra will highlight inadequacies in the models. For example, increasingly poorer fits at higher frequencies could indicate problems with modeling the sur-
Searching for $p$-modes in η Boötis and Procyon using MOST satellite data

face layers, such as those implied by the 0.25% discrepancy that exists between
the Sun’s observed frequencies and those of the standard solar model (Guenther & Brown, 2004). The adopted stellar parameters are listed in Table 2, and the average values (and standard deviations) of key properties of the best models are given in Table 3. Those properties are: mass, age, log effective temperature ($\log$ Teff), log luminosity ($\log$ $L/L_\odot$), mass of the convective envelope ($M_{\text{CE}}$), mass of the convective core ($M_{\text{CC}}$), acoustic cut-off frequency ($\nu_{\text{cutoff}}$), characteristic $p$-mode frequency spacing ($\Delta \nu$), characteristic g-mode period spacing ($\Delta \Pi$), average large $l = 0$ frequency separation ($< \Delta \nu_0 >$), average large $l = 1$ frequency separation ($< \Delta \nu_1 >$), and average small $l = 0$ frequency separation ($< \delta \nu_0 >$). The spacings are averaged over radial orders $n = 10–30$. For each set of constraints, properties are listed for the closest model and the average of all the models that lie within 1$\sigma$ of the constraints. The uncertainties are standard deviations of the averages. The LT and LTM labels identify the constraints used on the models, with LT corresponding to luminosity and effective temperature and LTM corresponding to luminosity, effective temperature, and mass. The constraints are the uncertainties in Table 2.

Models constrained by the luminosity, surface temperature, and mass of Procyon have a characteristic spacing $\Delta \nu$ that varies as a function of $\log L/L_\odot$ and $\log$ Teff near Procyon’s position in the H–R Diagram, as shown in the contour plot in Figure 6. Within the 1$\sigma$ uncertainties for $\log L/L_\odot$ and $\log$ Teff (the boundaries of Fig. 6), $\Delta \nu$ varies from 53 $\mu$Hz to 56 $\mu$Hz. Figure 4 is an echelle diagram with folding frequency 53 $\mu$Hz for the averaged values of the model $l = 0$, 1, 2, and 3 $p$-mode frequencies for Procyon, compared to the identified 2004 and 2005 Procyon peaks with spectral significance $\geq 5.6$. The model frequencies shown are not taken from a single best-fitting model but are, for each mode, the numerical average of all the models with $Z=0.02$ that lie within 1$\sigma$ of Procyon’s mass, luminosity, and effective temperature constraints. The range of frequencies for the radial ($l = 0$) $p$-modes in all these accepted models is indicated by error bars in Figure 4. The $p$-mode frequency uncertainty due to mass, luminosity, and effective temperature constraints on the model increases with increasing frequency. Note that the $p$-mode frequencies for a given value of $l$ are not scattered randomly between the error bars but align themselves along a vertical sequence which itself lies between the left and right edges defined by the uncertainty bars.

There is still no evidence in the MOST photometry to indicate $p$-modes in Procyon, not even an excess of power centred near 800 $\mu$Hz. Either the $p$-mode luminosity amplitudes fall near or below the sensitivity of MOST after stray light filtering or the mode lifetimes are short enough to prevent clear identification in the complete data sets.
Figure 6: A contour plot showing the characteristic spacing $\Delta \nu$ for models of Procyon in the vicinity of its position in the HR-diagram. The log Teff and log $L/L_\odot$ axis ranges correspond to the 1$\sigma$ box around Procyon's HR-diagram location. The contour labels are in units of $\mu$Hz.

Possible $p$-modes in $\eta$ Boo

We carried out identical filtering of the data for this star to remove first the d$^{-1}$ multiplets, then the remaining background peaks. The more aggressive stray light filtering performed for the present study has eliminated all the peaks identified in 2004 as radial modes. Although these frequencies may still contain a significant amount of stellar signal, we are unable to confirm this. The echelle diagram of the identified intrinsic peaks in the MOST $\eta$ Boo photometry is plotted in Figure 7.

For the 2004 $\eta$ Boo data, the lowest peaks we can identify above the noise threshold set at sig = 4 have amplitudes of about 7 ppm. The 2004 peaks used for Fig. 7 with sig $\geq$ 5.6 have amplitudes $\geq$ 9 ppm. For the 2005 data (see Fig. 8), the lowest peaks above the noise threshold (sig = 4) have amplitudes
Table 2: Properties of the MOST targets.

<table>
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<tr>
<th>Name</th>
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<th>$T_{\text{eff}}$</th>
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<td>6530 ±50K</td>
<td>7.23 ±0.35</td>
<td>1.497 ±0.037</td>
</tr>
<tr>
<td>η Boo</td>
<td>0.04</td>
<td>6028 ±45K</td>
<td>9.02 ±0.22</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 7: An echelle diagram comparing the η Boo 2004, filled circles, and η Boo 2005, filled triangles, spectral significance spectra to $p$-modes of models of η Boo (open symbols). The model mode frequencies are the average of all models that lie within 1σ of η Boos luminosity and effective temperature (Table 2). The error bars show the range of frequencies for each mode for models that lie within 1σ of η Boos luminosity, and effective temperature.
of about 9 ppm, and those in Fig. 7 (sig $\geq$ 5.6) have amplitudes $\geq$ 11 ppm. The frequencies plotted in Fig. 7 are different from those discussed in Guenther et al. (2005), because of the more rigorous and conservative approach adopted in this paper.

We also compared the observed echelle diagram with models from Guenther et al. (2005), as we did for Procyon above. The $\eta$ Boo models are constrained by its luminosity and effective temperature (see Table 2), and the derived key
model parameters are shown in Table 3. Figure 7 also compares the averaged $p$-mode frequencies of the best-fitted models and the frequencies of the peaks in the 2004 and 2005 $\eta$ Boo data sets with spectral significance $\geq 5.6$. $\eta$ Boo has a more evolved core; hence, the nonradial $p$-modes are subject to mode bumping. As a consequence, the $l = 1, 2$ and $3$ $p$-mode sequences do not fall along easily identifiable vertical sequences. Additionally, as noted in Guenther et al. (2005), the nonradial $p$-mode frequencies that are bumped are very sensitive to the age, mass, and composition of the model. Both effects in combination make model comparisons difficult. The radial $p$-modes identified in Guenther et al. (2005) lie outside of the indicated error bars, consistent with the fact that the best model fit to these modes was also just outside the $1\sigma$ observational uncertainty error box.

Constraints on mode lifetimes?

Since we do not see a clear radial ($l = 0$) sequence in any of our echelle diagrams for Procyon or $\eta$ Boo, what is the origin of the peaks that remain in the target signal spectral significance spectrum after the background peaks have been removed? It seems unlikely that the remaining peaks are due to stray light since our identification of stray light in the background time series (BTS) is very effective. If they are intrinsic to the star, why do the observations from two epochs a year apart for the same star show so few frequencies in common (while the background spectral significance spectra for the same star in the two epochs are nearly identical)? Could this be a consequence of $p$-modes in these stars having short lifetimes?

Because the convective envelopes are shallow in these stars, the superadiabatic limit is closer to the optically thin surface than in the Sun, and the $p$-modes are subject to stronger radiative damping. This shortens their lifetimes compared to solar $p$-modes. The short lifetimes cause the amplitudes of the modes to vary on similar time scales, which in turn leads to modulation effects in the Fourier transform spectrum. The modulation effects include both splitting and smearing of the peaks. We must add that short 2 day variations could also be a consequence of variations in the forcing function itself. Robinson et al. (2005) found in their 3D numerical simulations of convection that the superadiabatic layer, the layer that provides most of the force driving turbulent convective motions, itself oscillates into and out of the very thin surface convective envelope in Procyon.

In an attempt to see if the identified peaks are the consequence of modulated amplitudes, we applied a running window 6 days wide to the TTS (target time series) of each star, and then applied our analysis routine to each windowed data set. We show a portion of the resulting time-evolving spectral significance
Figure 9: An intensity plot showing the changing amplitudes (and frequencies), over time, of peaks in the spectral significance spectrum of η Boo 2004 data. As individual peaks rise and fall in amplitude, they can shift in frequency and split into multiple peaks in the Fourier domain. Only a small portion of the spectral significance spectrum is shown.

Figure 10: Same as Fig. 9 but for Procyon data.

spectrum for the 2004 η Boo data in Figure 9. As shown in Figure 10, similar results are seen for Procyon. These figures indicate that the peaks in the spectrum vary in amplitude over a timescale of about 2 days. The amplitude variation alone leads to perturbations in the frequency positions by approximately 0.5 cycle day$^{-1}$ (~5 µHz).
If the peaks are $p$-modes and the modulation is intrinsic, then one has to dramatically expand the duration of the observation to give the damped and re-excited modes a chance to form well-defined Lorentzian profiles in the Fourier domain. If the length of observations is comparable to a modes lifetime (or only a few times longer) then the modes peak can fall over a relatively wide range of frequencies around the modes true frequency.

Conclusions

Analysis of the 2005 MOST photometry of Procyon and reanalysis of the 2004 data for that star reinforce the null $p$-mode detection reported by Matthews et al. (2004). The same type of analysis for the 2004 and 2005 MOST photometry of $\eta$ Boo confirms the excess of power in the frequency range expected for $p$-modes but there is little agreement between identified frequencies in the two epochs. Our analysis suggests that the $p$-mode lifetimes in $\eta$ Boo may be as short as about 2 days, which could account for the epoch-to-epoch differences. The groundbased spectroscopic campaigns on $\eta$ Boo carried out by Kjeldsen et al. (2003) and Carrier et al. (2005) also do not identify the same frequencies in that star from epoch to epoch, which is also consistent with short mode lifetimes.

We have applied a more rigorous and conservative approach to stray light reduction than those used originally for the Procyon 2004 data (Matthews et al. 2004) and for the $\eta$ Boo 2004 data (Guenther et al. 2005). In the former case, the high brightness of Procyon reduces the relative stray light effects, and our analysis affects only about 5-10% of the frequency range relevant for $p$-mode detection. In the case of the fainter $\eta$ Boo, the new more aggressive treatment of stray light modulation gives a more robust identification of the intrinsic stellar frequencies. However, for this star, up to about 50% of the relevant frequency range may be affected.

We have produced $p$-mode model eigenspectra for Procyon and $\eta$ Boo based on observed parameters of the two stars. However, the models cannot validate the frequency identifications in $\eta$ Boo because the uncertainties in model parameters are too large. Even if we had evidence of $p$-modes in the photometry of Procyon, whose mass is well determined by its binary orbit, the uncertainties in the model eigenfrequencies would present a challenge to asteroseismic fitting. The possibility of short mode lifetimes makes the challenge even more severe.

The data presented here for Procyon and $\eta$ Boo are available for download from the MOST Public Data Archive through the Science link at http://www.astro.ubc.ca/MOST.
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On the nature of the $\delta$ Scuti star star HD 115520

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Abstract

As a continuation of the study of the newly found $\delta$ Scuti star HD 115520, we present a period analysis of recently acquired photometric data covering four nights, as well as some conclusions on the nature of this star.

Introduction

In 2007 Peña et al. (2007, Paper I) confirmed the belonging of HD 115520 to the $\delta$ Scuti class which was considered as a standard star in a 2005 observing run. From the relatively large scatter shown, Peña et al.(2006) consider it as a variable candidate. With this in mind, new data were acquired in two new nights in 2006 which established it as a $\delta$ Scuti star. In the present paper we present new observations which were performed in 2007 with the same instrumentation over a period of four nights and which have served to determine its periodic content. The found frequencies explain the behavior of both seasons separated by more than one year.

Observations

These were taken at the Observatorio Astronómico Nacional, México using the 1.5 m telescope to which a spectrophotometer was attached. The observing season was carried out on four consecutive nights in March and April, 2007. The following observing routine was employed: a multiple series of integrations
Table 1: Characteristics of the observed stars. The spectral types were taken from the SIMBAD database.

<table>
<thead>
<tr>
<th>ID</th>
<th>V</th>
<th>(b − y)</th>
<th>m₁</th>
<th>c₁</th>
<th>N</th>
<th>SpTyp</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 115520</td>
<td>8.435</td>
<td>0.132</td>
<td>0.171</td>
<td>0.806</td>
<td>459</td>
<td>F0</td>
</tr>
<tr>
<td>HD 116879</td>
<td>7.953</td>
<td>0.272</td>
<td>0.144</td>
<td>0.634</td>
<td>120</td>
<td>F5</td>
</tr>
<tr>
<td>HD 114311</td>
<td>9.037</td>
<td>0.334</td>
<td>0.157</td>
<td>0.474</td>
<td>122</td>
<td>F6V</td>
</tr>
</tbody>
</table>

was carried out, consisting of five 10 s integrations of the star to which one 10 s integration of the sky was subtracted. Two reference stars were also observed C1: HD116879 and C2: HD114311. These were observed in the following sequence to optimize the time coverage of the variable: V, sky, C1, V, V, C2, V. A series of standard stars was also observed at the beginning and at the end of each night to transform the data into the standard system. The absolute photometric values of the 2007 campaign are provided in an archive. The accuracy of the season is deduced from the differences between the reduced and the previously reported values of the standard stars. Due to the fact that the last night was of lower quality, and hence less accurate, the mean values of the differences are calculated only from the standards of the first three nights. They are: 0.015, 0.008, 0.007, 0.011 mag for V, (b − y), m₁, and c₁, respectively.

However, since the amplitude of the star is typical of a δ Scuti star (∼20 mmag, see Figure 4), we preferred to analyze the data for the periodic content through differential photometry in the y filter for which use was made of the reference stars C1 and C2 to increase the accuracy of the photometry to thousands of magnitude. Table 1 lists the characteristics of the observed stars. A magnitude value of the reference stars was interpolated at the time of the variable and the final values, to which the average value of each night was subtracted, are presented in Table 1. The whole reduction procedure is shown in Figure 1 for the night of March 30/31. The 2006 season was reduced in the same fashion to match the newly acquired data.

Frequency determination

With the relatively few data points acquired in the 2006 season (only two short nights) we were able to demonstrate the star’s variability and found evidence of at least two close frequencies which might explain the resulting beating behavior of the light curve. Since the new photometric data is constituted of four long consecutive nights, we are now able to determine the pulsational frequencies with greater precision. Two numerical packages were utilized: Period04 (Lenz and Breger, 2004) and ISWF (Alvarez et al., 1998). With Period04 the first run examined gave a frequency of 17.8643 c/d with an amplitude of 0.0140
Figure 1: Y variation of the observed stars HD 115520, C1 and C2 on the night of March 30/31, 2007. Y axis is V in magnitudes, X axis is time (time shown = HJD - 2454100.0)

mag in the frequency interval between 0 and 30 c/d with a step rate of 0.0150. Prewhitening of this frequency consecutively yielded the results shown in Figure 2. On the other hand, the ISWF package yielded the following frequencies (in c/d) listed in diminishing amplitudes (in parentheses, in mmag) 17.850 (13.877); 14.7786 (10.334); 17.4527 (6.415); 13.5217 (4.236) and 18.1831 (3.973).

As can be seen, the two previously determined main frequencies, although slightly numerically different are confirmed. In the 2006 season we obtained 18.82 and 14.63 c/d. Given the complex window function of observations on only two nights from only one observatory, we might consider them the same. On the other hand, when the whole dataset was utilized with a step rate of 0.00015, Period04 yielded peaks at 17.8373 and 14.7537 c/d, (see Figure 3 and Table 2). The rest of the frequencies might be disregarded because they do not significantly improve the residuals. Their peaks are indistinguishable from
Figure 2: Periodograms of the four consecutively observed nights in 2007. From top to bottom, window, first frequency obtained at 17.86c/d, periodogram after prewhitening this with a resulting peak at 14.79c/d, and finally the prewhitened histogram of the two previously determined frequencies with a peak at 17.400c/d.

Figure 3: Periodograms of all the observed nights. From top to bottom, window, first frequency obtained at 17.8375c/d, periodogram after prewhitening this with a resulting peak at 14.7537c/d, and finally the prewhitened histogram of the two previously determined frequencies with a peak at 16.5121c/d.
On the nature of the δ Scuti star star HD 115520

Table 2: Frequencies, amplitudes and phases derived

<table>
<thead>
<tr>
<th>Frequency (c/d)</th>
<th>Amplitude (mag)</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1 17.8375</td>
<td>0.0131</td>
<td>0.1028</td>
</tr>
<tr>
<td>F2 14.7537</td>
<td>0.0108</td>
<td>0.2612</td>
</tr>
<tr>
<td>F3 16.5121</td>
<td>0.0070</td>
<td>0.5646</td>
</tr>
</tbody>
</table>

Figure 4: \( y \) variation of HD 115520 (dots). \( y \) axis is \( y \) in magnitudes, \( X \) axis is time.

... each other due to the aliasing caused by the window function. Therefore, we will consider as definitive only the first two frequencies listed in Table 2. Figure 4 shows the light curves of the six observed nights.

Physical parameters

As it has been already described in paper I, we carried out a well-known procedure to determine reddening as well as unreddened colors using the photometric mean \( uvby - \beta \) values reported in Table 3. Table 4 lists the reddening, the unreddened indexes, the absolute magnitude, and the distance. Its position on the \([m_1] - [c_1]\) diagram established it to be an A8V star. Its temperature and
log of surface gravity can be determined by locating HD 115520 in the \((b-y)_0\) vs. \(c_0\) grids of Lester et al. (1986, hereafter LGK86) (Figure 5); the values we determine are 7700 K and 4, respectively. As was stated in Paper I, we compared our results with those in a paper by Behr (2003) who found an effective temperature \(T_{\text{eff}}\) of 8199 (+449,–317), a log \(g\) 4.63 (+0.34,–0.23), an \([\text{Fe/H}]\) 0.62 (+0.13) and a stellar type belonging to the main-sequence for this star. Although Behr (2003) has evaluated physical parameters for this star, and his numerical values coincide with ours, we feel that we have more data to determine the physical characteristics. Nevertheless, we have employed his reported metallicity of HD 115520 to discriminate between the models that explain the star’s behavior.

The evolutionary status of HD 115520

The determination of the evolutionary stage of a field star requires precise estimates of its global parameters. In the case of HD 115520 the distance as determined from Strömgren photometry is 140 pc which leads an \(M_V\) of 2.86 mag by using the calibrations of Shobbrook (1984). On the other hand, the distance value of 300 pc estimated from a parallax of 3.29 ± 0.97 mas provided by the Hipparcos catalogue (Perryman et al. 1997) yields an \(M_V\) of 1.02 mag which is quite different from the photometric value. This ambiguity can be explained by the uncertainties in the determination of each measured distance. The large relative error \((\sigma(\pi))/\pi \sim 0.30\) of the Hipparcos parallax for HD 115520 implies an \(\sigma(M_V) > 0.5\) mag, whereas in the present paper the uncertainty in the apparent magnitude derived as explained in Peña & Sareyan (2006) from the standard deviation of 579 data points of the two seasons gives an \(m_V = 8.4305 ± 0.0178\) (see Table 3) and an \(\sigma(M_V) < 0.1\) mag. Although this latter value does not include the uncertainty in \(M_V\) due to the photometric calibrations which can be as large as 0.3 mag for early type stars (e.g. Balona & Shobbrook 1984), we think that the photometric distance is more reliable than the trigonometric one because different photometric calibrations (Balona

### Table 3: Mean values of the uvby photometry (in mag) of HD 115520 from the two seasons

<table>
<thead>
<tr>
<th></th>
<th>average</th>
<th>sigma</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V)</td>
<td>8.4305</td>
<td>0.0178</td>
<td>579</td>
</tr>
<tr>
<td>((b-y))</td>
<td>0.1334</td>
<td>0.0070</td>
<td>584</td>
</tr>
<tr>
<td>(m_1)</td>
<td>0.1701</td>
<td>0.0051</td>
<td>580</td>
</tr>
<tr>
<td>(c_1)</td>
<td>0.8068</td>
<td>0.0139</td>
<td>584</td>
</tr>
<tr>
<td>(\beta)</td>
<td>2.8108</td>
<td>0.0133</td>
<td>67</td>
</tr>
</tbody>
</table>
Table 4: Reddening and unreddened parameters of HD 115520

<table>
<thead>
<tr>
<th>E(b − y)</th>
<th>(b − y)_0</th>
<th>m_0</th>
<th>c_0</th>
<th>V_0</th>
<th>M_V</th>
<th>D_M</th>
<th>dst (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0.135</td>
<td>0.170</td>
<td>0.807</td>
<td>8.43</td>
<td>2.68</td>
<td>5.75</td>
<td>141</td>
</tr>
</tbody>
</table>

& Shobbrook (1984) and Nissen (1988)) lead to similar distance values for HD 115520. Furthermore, similar values of m_V for HD 115520 have already been reported in previous papers (Olsen 1983, Crawford & Perry 1989, Paper I). Therefore, we will use the photometrically determined distance to try to establish the evolutionary status of HD 115520.

Figure 6 shows the observed position of HD 115520 (asterisk) in the HR diagram and its associated uncertainty (cross upon the asterisk). PMS and post-MS evolutionary tracks giving a range of masses between 1.45-1.60 M_☉ for HD 115520 are shown with dotted and continuous lines respectively. These evolutionary sequences were computed by using the CESAM evolution code (Morel 1997) with an input physics appropriate to δ Scuti stars and a chemical initial composition of Z = 0.013 and Y = 0.28. Also shown are the theoretical pre-MS instability strip boundaries of the first three radial modes obtained by Marconi & Palla (1998).

According to the models depicted in Fig. 6 HD 115520 could either be in pre-MS stage with an age between 15-20 Myr or post-MS stage with an age between 500-700 Myr. In the former case, the age was estimated as the time spent by the star travelling from the birthline to the ZAMS in the HR diagram according to the isochrones given by Tout et al. (1999).

As shown by Suran et al. (2001) non-radial oscillation spectra in the low frequency domain can be used to discriminate between the pre- and post-MS stage. In the present case, however, this is seldom possible since the two detected peaks in HD 115520 are most likely due to radial oscillations. In fact, we have tried to reproduce the observed periods computing linear adiabatic pulsation models of HD 115520 for some selected pre- and post-MS models located within the error box in Figure 6, but no satisfactory fit between observed and theoretical frequencies was found. Therefore, more observational efforts are required to establish the true nature of this interesting object.

Conclusions

We have presented the analysis of new uvby photometric observations of δ Scuti star HD 115520 carried out during four nights in March and April, 2007 at the Observatorio Astronómico Nacional, México. These data were added to the previously observed two nights in 2006 resulting a total of 580 data
Figure 5: Location of the photometric data of HD 115520 in the grids of LGK86.

Figure 6: Position of HD 115520 in the HR diagram.
points of $uvby$ photometry which allowed us to search for the true nature of this $\delta$ Scuti variable. The two oscillations frequencies detected in 2006 have been confirmed in this season. We have found that both stages pre-MS and post-MS are possible to account for the observed luminosity and temperature of the star. We thus conclude that HD 115520 represents a good candidate for asteroseismological studies of young $\delta$ Scuti stars.

Acknowledgments. We would like to thank the assistance of the staff of the OAN during the observations. This paper was partially supported by Papiit IN108106. GM and BV thank the OAN for allowing the use of the telescope time and to Dr. Jorge Sosa of IPN for the support. J. Miller and J. Orta did the proofreading and typing, respectively. This article has made use of the SIMBAD database operated at CDS, Strasbourg, France and ADS, NASA Astrophysics Data Systems hosted by Harvard-Smithsonian Center for Astrophysics.

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Photometric observations and frequency analysis of the $\delta$ Scuti NT Hya

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I. Metaxa and Bas. Pavlou, GR-15236 Athens, Greece

Abstract

NT Hya is a $\delta$ Scuti star discovered by Hipparcos. About 2200 observations were acquired with the 30 inch SAAO telescope in the nights of February 2, 3 and 4, 2006 in V filter. These data show four pulsation frequencies of the star. Two of them may form a doublet separated by 0.64 c/d ($\Delta f/f = 9\%$) with similar amplitudes. The period listed in the Hipparcos Catalogue is between the doublet frequencies.

Introduction and Observations

NT Hya (HD 78422) is listed in the revised catalogue of $\delta$ Sct stars by Rodriguez et al. (2000) as a F0 variable star with mean $V=7.37$, amplitude 0.06 magnitudes and frequency 6.940 c/d. Its entry was based on information taken from the catalogue presented by Kazarovets et al. (1999). Their name-list introduces GCVS names for 3153 variable stars discovered by the Hipparcos mission (HIP 44813). The mentioned information of the Rodriguez et al. catalogue was adopted from the corresponding Hipparcos catalogue entry (ESA 1997). We tried to determine its high frequency pulsations by means of photometric observations. These were scheduled in the week 31/1/2006 - 6/2/2006 with the 30 inch telescope of the South African Astronomical Observatory, using the UCT photometer and V filter.

Due to weather conditions observations were made only during a large part of the third and the fifth nights and the photometric fourth night of this period. During these nights 2214 measurements of NT Hya were collected. The exposure time was always 10 seconds. Table 1 gives a journal of observations providing an overview of date, number of data points and photometric hours per
Photometric observations and frequency analysis of the δ Scuti NT Hya

Figure 1: 2006 observations of NT Hya, together with the fit of the frequencies found

Figure 2: The observations of the 3rd night and the fit of the four frequencies

<table>
<thead>
<tr>
<th>HJD</th>
<th>Photometric Hours</th>
<th>NT Hya</th>
<th>Comp.</th>
<th>Sky</th>
</tr>
</thead>
<tbody>
<tr>
<td>2450000+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3769</td>
<td>4.77</td>
<td>724</td>
<td>290</td>
<td>54</td>
</tr>
<tr>
<td>3770</td>
<td>7.42</td>
<td>1209</td>
<td>581</td>
<td>81</td>
</tr>
<tr>
<td>3771</td>
<td>3.25</td>
<td>281</td>
<td>155</td>
<td>46</td>
</tr>
</tbody>
</table>
night. The comparison star was the HIP 44940 V=7.8 and (B-V) =-0.08 and an anonymous V=8.5 star was used as a check star. The standard observing sequence proposed by Henden & Kaitchuck (1982) for monitoring stars varying rapidly was followed. The comparison star was observed every 15 minutes and 7-10 exposures have been obtained each time. The sky was observed at the beginning and the end of the observations, as well as after each observation of the comparison. The check star was mainly observed during the third clear night and its limited number of observations show random deviations around 0.005 mag relative to the comparison star.

Frequency analysis

At a first glance the light curve shows intense variations from night to night. The largest peak-to-peak amplitude is 0.12 mag. Figure 1 shows the complete data set of our 2006 observations of NT Hya.

The Fourier analysis was performed using Period04 (Lenz & Breger 2005). Four frequencies were detected and listed in Table 2 together with their semi-amplitudes, in order of decreasing amplitude.

Discussion and Conclusion

We note that the difference of 0.64 c/d between the two frequencies, $f_1$ and $f_2$, is below the proposed frequency resolution of 1.5/dT limit by Loumos & Deeming (1978) and therefore need to be confirmed. $f_3$ could be a combination frequency of $f_1$ and $f_2$. Adding $f_4$ to the other three fitted frequencies reduces the residuals between the fit and the observations to 0.0058 mag, although minor deviations between the fit and the data remain for the third night, as shown in Fig. 2.

<table>
<thead>
<tr>
<th>Id.</th>
<th>Frequency [c/d]</th>
<th>Semi-ampl. [mag]</th>
<th>Phase [cycles]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1$</td>
<td>6.50</td>
<td>0.024</td>
<td>0.893</td>
</tr>
<tr>
<td>$f_2$</td>
<td>7.14</td>
<td>0.023</td>
<td>0.666</td>
</tr>
<tr>
<td>$f_3$</td>
<td>13.59</td>
<td>0.009</td>
<td>0.067</td>
</tr>
<tr>
<td>$f_4$</td>
<td>10.43</td>
<td>0.006</td>
<td>0.129</td>
</tr>
</tbody>
</table>
Photometric observations and frequency analysis of the δ Scuti NT Hya

The main period of NT Hya given by the Hipparcos catalogue is between the two frequencies $f_1$ and $f_2$. The ratio of these frequencies indicates non-radial pulsation for at least one of the modes ($f_1/f_2 = 0.91$).

Follow-up observations are needed for giving an clear answer to the nature and the relations of $f_1$, $f_2$ and $f_3$.

Acknowledgments. Authors are extremely thankful for anonymous referees remarks in general and for those on the section of frequency analysis in particular.

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Asteroseismology of $\delta$ Scuti stars in open clusters: Praesepe

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Abstract

The present paper provides a general overview of the asteroseismic potential of $\delta$ Scuti stars in clusters, in particular focusing on convection diagnostics. We give a summarise of the last results obtained by the authors for the Praesepe cluster of which five $\delta$ Scuti stars are analysed. In that work, linear analysis is confronted with observations, using refined descriptions for the effects of rotation on the determination of the global stellar parameters and on the adiabatic oscillation frequency computations. A single, complete, and coherent solution for all the selected stars is found, which lead the authors to find important restrictions to the convection description for a certain range of effective temperatures. Furthermore, the method used allowed to give an estimate of the global parameters of the selected stars and constrain the cluster.

Introduction

The main idea of the work here outlined is to compare ranges of observed and predicted unstable modes and analyse them in terms of ranges of radial modes. That methodology was conceived and used in Michel et al. (1999), hereafter M99, and here is revisited. The use of radial modes is justified because driving and damping in $\delta$ Scuti stars takes place predominantly in the He II ionisation zone, which is rather close to the stellar surface, where the vertical
scale is much less than the horizontal scale of the oscillations and when \( \ell \) is low the modal inertia is quite insensitive to degree \( \ell \). We consider the following stars belonging to the Praesepe cluster: BW Cnc, BS Cnc, BU Cnc and BN Cnc (already included in the sample considered by M99), which were observed by several campaigns of the STEPHI network (Michel et al. 1995), and a fifth star, BV Cnc, which was observed by Frandsen et al. (2001).

The present work intends to search for one particular solution that explains the whole set of observations, instead of sets of individual solutions for each star (methodology followed by M99 whose results are considered here as the reference domain of possible solutions). To do so, refined techniques for modelling intermediate mass stars are required, in particular those taking different effects of rotation into account. This requirement is fulfilled in this work with modern techniques that largely improve those adopted in M99 and other precedent works. One of the major improvements is the use the complete second-order formalism (including near degeneracy effects) developed by Suárez et al. (2006) based on the works by Dziembowski & Goode (1992) and Soufi et al. (1998), which, in addition, takes the effect of the star deformation due to rotation into account.

**Procedure**

Firstly, we calculate the fundamental parameters of each selected star. To do so we apply the method by Pérez Hernández (1999) which corrects the photometric observables for the effect of rotation. That method is model-dependent, so that solutions are obtained by adjusting some typically free parameters. The best solution given by the correction for the effect of rotation was obtained for \( \alpha_{\text{MLT}} = 1.614 \) and \( d_{\text{ov}} = 0.2 \). This best solution correspond to an age of the cluster of 650 Myr (±20 – 40 Myr). The age uncertainty of 20–40 Myr can be neglected in terms of global characteristics of the non-rotating co-partners (see the influence of age on photometric corrections for rotation in different open clusters in Suárez et al. 2002).

The fundamental parameters obtained are then used to build representative asteroseismic models for each star, consisting of pseudo-rotating equilibrium models and their corresponding adiabatic oscillation spectra. Theoretical adiabatic oscillation spectra are computed with the oscillation code FILOU (Tran Minh & Lon 1995, Suárez 2002) which uses the complete treatment of second-order effects of rotation by Suárez et al. (2006), based on the formalisms by Dziembowski & Goode (1992) and Soufi et al (1998). These asteroseismic models are then used to determine the observed radial orders ranges, which, as it was done in M99, are then confronted with mode instability predictions obtained from a linear stability analysis.
Unstable radial modes are calculated by means of linear stability computations which are carried out in the manner of Balmforth (1992). We adopt the nomenclature of M99, i.e. $\alpha_{NL} = l/H_p$ is the mixing-length parameter of the non-local convection model used in the stability computations. The non-local mixing-length parameter $\alpha_{NL}$ is calibrated to the same depth of the outer convection zone as suggested by the evolutionary computations which use the standard mixing-length formulation by Böhm-Vitense (1958) and a local mixing-length parameter $\alpha_{MLT} = 1.614$, for which the equivalent calibrated value of $\alpha_{NL} = 1.89$ is obtained. As in M99, a second series of stellar models with $\alpha_{NL} = 1.50$ in order to analyse the impact of varying the mixing-length on mode stability.

Comparison between observed and predicted ranges of unstable radial modes

We compare ranges of observed and predicted radial orders $n$ of unstable modes for two values of $\alpha_{NL}$: 1.89 and 1.50. This comparison is shown in Fig. 1 in which an uncertainty of $\pm 1 \ n$ in the determination of the range of radial orders (see Suárez et al. (2007) for a detailed explanation of uncertainty sources). For each star, we have two representative models corresponding to considering $\pm 10\%$ of the observed $V\sin i$ value, so we calculate four radial order ranges are calculated per object. It is found that, in general, the observed ranges are in good agreement with the theoretical predictions using $\alpha_{NL} = 1.50$, whereas with $\alpha_{NL} = 1.89$ the predicted ranges are in grave disagreement with the observations for the intermediate mass stars BW Cnc and BS Cnc, which present a temperature range of $\log T_{\text{eff}} = 3.87 - 3.88$. For these stars a smaller mixing-length parameter $\alpha_{NL}$ is then required than suggested from a calibrated solar model. The need of a smaller value for $\alpha_{NL}$ than that from a calibrated solar model was also reported by Daszyńska-Daszkiewicz et al. (2005) for the $\delta$ Scuti star FG Vir. For the massive objects, BU Cnc and BN Cnc, the predicted unstable ranges are compatible with the observed results ($\pm 1 \ n$), for both $\alpha_{NL} = 1.50$ and $\alpha_{NL} = 1.89$. The results for both objects are thus not sensitive to the value of $\alpha_{NL}$. This is to be expected because these more massive stars have shallower outer convection zones and thus their structures are less sensitive to the assumed value of the mixing-length parameter. Finally, for the less massive object, BV Cnc, the values for $\alpha_{NL}$ cannot be distinguished. Nevertheless, the observed ranges agree with the theoretical predictions within $\pm 1 \ n$. Therefore, in general, these results constitute a consistent solution in terms of physics and cluster membership, and the observed and theoretical ranges of radial orders are in reasonable agreement for all the stars considered in this work.

Details of the procedure, model characteristics, as well as the detailed com-
Figure 1: Observed and predicted (using linear stability analysis) ranges of unstable radial modes for the selected δ Scuti stars ($n_1$ is the lowest value, and $n_2$ the largest value of the radial order of the unstable modes) displayed for the selected δ Scuti stars. Filled circles represent the observed ranges. Rhombus and squares correspond to predicted radial order ranges for $\alpha_{NL} = 1.89$ and $\alpha_{NL} = 1.50$, respectively. Each diagonal-dashed line represents the width (in radial orders) of the represented ranges. Taken from Suárez et al. (2007)
parison between the present results with those of M99 are given in a forthcoming paper Suárez et al. (2007). We note that, as in M99, the instability predictions are carried out using equivalent envelope models which do, however, not take the effect of rotation into account. This is so because, up to date, there are no reliable theories available which describe the effect of rotation on mode stability. Nevertheless, in a forthcoming paper Suárez et al. (2007), a crude estimate of this effect is addressed, which assumes that mode stability depends predominantly on the effective temperature of the model (Pamiatnykh 1975). As well, in that work, more details on the procedure, the characteristics of models, and a detailed comparison between the present results with those of M99 are provided.

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Analysis of $\Pi_{1/0}(\Omega)$ period ratios in the presence of near degeneracy

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Abstract

In the present work we provide the preliminary results obtained when analysing the rotational Petersen diagrams when including the effects of near degeneracy. We found that near degeneracy affects significantly the fundamental-to-first overtone period ratios, $\Pi_{1/0}(\Omega)$, showing wriggles in the Petersen diagrams. Analysis of such wriggles reveals that they are mainly caused by the avoided-crossing phenomenon. The size of wriggles seems to increase with the rotational velocity and could, in certain cases, invalidate any accurate mass and/or metallicity determinations. Nevertheless, deep analysis of near degeneracy effects may allow us to obtain additional information on the mode identification of the radial modes and their corresponding coupled pairs, which would allow us to constrain the modelling.

Introduction

In a previous work (Suárez et al. 2006b, hereafter SGG06), we showed the importance of taking the rotation effects into account (even for relatively slow rotating stars, as double-mode pulsators) especially when accurate metallicity and/or mass determinations are required. In that paper, 10 period ratios were calculated for different rotational velocities (RPD) and metallicities and then compared with standard non-rotating Petersen diagrams (PD). The difference in period ratios was shown to increase with the rotational velocity for a given metallicity. Differences in the period ratios were found to be equivalent to differences in the metallicity.

The present work intends to complete SGG06’s work by including the effects of near degeneracy in the computations of oscillations. Mode identification is
essential for the correct use of PD. As shown by Soufi et al. (1998) and Suárez et al. (2006c), near degeneracy effects cannot be neglected for asteroseismic studies of slowly-to-moderately rotating stars. Near degeneracy affects the small separations since it occurs for close modes (under certain selection rules, $\Delta \ell = 0, \pm 2$, and $\Delta m = 0$). However, such an effect is far from being trivial and deserves special attention.

We examine in detail the effect of rotation on mass and metallicity diagnostics based on Petersen diagrams, focusing on the influence of the near degeneracy effects on the period ratios of radial modes. Indeed, important effects are expected to be found when near degeneracy is taken into account (Pamyatnykh 2003). In that work, very large and non-regular perturbations of such ratios were expected to occur. We found such perturbations under the form of wriggles in the RPD. However such wriggles seem to be regular. A short discussion on the possible origin of these wriggles is here provided.

The $\Pi^{d}_{1/0}(\Omega)$ period ratios

In order to study the effect of near degeneracy on RPD, we construct tracks of asteroseismic models for different mass, metallicity and rotational velocity. Equilibrium models are computed with the evolutionary code CESAM (Morel 1997) for which a first-order effect of rotation is taken into account in equilibrium equations. Uniform rotation and global conservation of the total angular momentum is assumed. Such models are the so-called ‘pseudo-rotating’ models (see Soufi 1998, Suárez et al. 2006c). Although the non-spherical components of the centrifugal acceleration are not considered, they are included as a perturbation in the oscillation frequencies computation. Computation of the oscillation spectra is carried out using the oscillation code FILOU (Tran Minh & Lon 1995, Suárez 2002) which is based on a perturbative analysis and provides adiabatic oscillations, corrected for the effects of rotation up to the second order (centrifugal and Coriolis forces), including near degeneracy effects.

In order to determine how near degeneracy affects mass and metallicity determinations using RPD, we selected several evolutionary tracks with different metallicities and two different initial rotational velocities $\Omega_{i} = 25, 50$, for a fixed mass of $1.8 M_\odot$. For each model we then computed the corresponding $\Pi^{d}_{1/0}(\Omega)$ period ratio, i.e., the 1O period ratios including near degeneracy effects.

In Fig. 1 we show RPD displaying such period ratios, from top bottom, for tracks computed for $\Omega_{i} = 25$ to $50 \text{ km s}^{-1}$ respectively. As expected, near degeneracy does not modify the general behaviour of the 1O period ratios with the metallicity, i.e., $\Pi^{d}_{1/0}(\Omega)$ increases when increasing rotational velocities. This is equivalent to decrease the metallicity in standard PD (see SGG06). However, the presence of wriggles may inverse this situation in the regions where
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Figure 1: Theoretical RPD showing the $\Pi_{1/0}^d(\Omega)$ period ratios for a set of evolutionary 1.8, $M_\odot$ tracks obtained for different metallicities. Tracks for two initial rotational velocities are considered: 25 and 50 km s$^{-1}$ (from top to bottom). For convenience, the following symbols are used: asterisks, representing models evolved with $\Omega_i = 25$ km s$^{-1}$; diamonds and those evolved with $\Omega_i = 50$ km s$^{-1}$.
the curves cross each other. Wriggles are found larger for increasing rotational velocities and they become significant (in the context of RPD) degrading substantially the accuracy of period ratios \( \Pi_{1/0}^{2} (\Omega) \), which can reach up \( 3 \cdot 10^{-3} \).

In terms of metallicity, this implies uncertainties reaching up to 0.50 dex (for the largest rotational velocity considered) which is critical for Pop. I HADS. This new scenario would invalidate, a priori, the PD as diagnostic diagrams. However, wriggles in period ratios do not seem to be located randomly in PD. They depend on the frequency evolution of the quadrupole modes coupled with the radial ones which are mainly dominated by the avoided-crossing phenomenon, and they seem nearly independent of the rotational velocity and metallicity. If these results are confirmed, it would be possible to provide some clues for the mode identification of the fundamental radial mode, the first overtone, and their corresponding quadrupole coupled modes, only using white light photometry. We will provide a complete study of the effect of near degeneracy on RPD, for different metallicities, masses and rotational velocities in a forthcoming paper (Suárez et al. 2006a), in which we show that wriggles in period ratios may imply differences of about \( 10^{-2} \) (for rotational velocities around \( 50 \) km s\(^{-1}\)) when comparing with non-rotating PD. In that work we also examine certain properties of the near degeneracy effects, namely the mode contamination i.e., the weight of the original individual spherical harmonics describing the oscillation mode in the resulting coupled mode; and the coupling strength, i.e., the effect of near degeneracy on the oscillation frequencies. Analysis of these properties seem to be a promising procedure, not only to retrieve the usefulness of PD, but also to provide additional information for the complete mode identification, the rotational velocity and the inclination angle of the star.

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Revised instability domains of SPB and $\beta$ Cephei stars

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Abstract

The excitation of pulsation modes in $\beta$ Cephei and Slowly Pulsating B stars is known to be very sensitive to opacity changes in the stellar interior where $T \sim 2 \times 10^5$ K. In this region differences in opacity up to $\sim 50\%$ can be induced by the choice between OPAL and OP opacity tables, and between two different metal mixtures (Grevesse & Noels 1993 and Asplund et al. 2005). We have extended the non-adiabatic computations presented in Miglio et al. (2007) towards models of higher mass and pulsation modes of degree $\ell = 3$, and we present here the instability domains in the HR- and log $P$-log $T_{\text{eff}}$ diagrams resulting from different choices of opacity tables, and for three different metallicities.

Introduction

The detection of B-type pulsators in low metallicity environments (see e.g. Kołaczkowski et al. 2006 and references therein), and the large number of pulsation modes detected in B stars, are now revealing new discrepancies between theory and observations that challenge standard stellar models. For instance, the two $\beta$ Cep stars 12 Lacertae and $\nu$ Eridani present low order p-modes with frequencies higher than those predicted by pulsation models, as well as high-order g-modes (SPB type oscillation) (Jerzykiewicz et al., 2005; Handler et al., 2006, and references therein).

The interpretation of observations in the framework of standard stellar models must take into consideration the uncertainties in the basic input physics. In fact, pulsations modes in SPBs and $\beta$ Cep stars are excited by the $\kappa$-mechanism (see e.g. Dziembowski et al., 1993) due to the Fe-group opacity bump at $T \sim 2 \times 10^5$ K, and in the last three years there have been two important
updates of the basic physics that can affect the study of B-type pulsators: 

(i) the revised solar metal mixture (Asplund et al., 2005) that implies a 25% larger Fe mass fraction for a given metallicity $Z$; and 

(ii) the new Fe data included in OP opacity computations that lead to an opacity in the Z-bump increased by 18% with respect to the previous values (Badnell et al., 2005).

Miglio et al. (2007) (hereafter Paper I) and Pamyatnykh & Ziomek (2007) showed that the combination these updates have a remarkable effect on the instability domains of SPB and $\beta$ Cephei pulsators compared to the results obtained using OPAL opacities (Iglesias & Rogers, 1996) and Grevesse & Noels (1993) metal mixture.

In Paper I we analyzed the role of chemical composition and opacity computations on the instability strip of B-type pulsators and on the frequency domain of expected excited modes. In the present paper we have extended the computations presented in Paper I by considering stellar masses up to 18 $M_\odot$ instead of 12 $M_\odot$, and by carrying out the non-adiabatic analysis also for $\ell = 3$ modes. Only throughout comparisons with observations we will be able to assess if, and to which extent, the current uncertainties on opacity calculations and on the assumed metal mixture are able to explain the discrepancies between recent observations and standard stellar models. For this purpose we present in the following sections the instability strips in the HR ($\log L$-$\log T_{\text{eff}}$) and in the period-effective temperature ($\log P$-$\log T_{\text{eff}}$) diagrams resulting from the non-adiabatic calculations presented in Paper I and extended as mentioned above.

Stellar models and opacities

We computed stellar models with the code CLES (Code Liégeois d’Evolution Stellaire, Scuflaire et al. 2007). The main physical inputs are: OPAL2001 equation of state (Rogers & Nayfonov, 2002) and Caughlan & Fowler (1988) nuclear reaction rates with Formicola et al. (2004) for the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ cross-section. Convective transport is treated by using the classical Mixing Length Theory of convection (Böhm-Vitense, 1958), and a convective overshooting parameter of 0.2 pressure scale height was assumed in all the models. For the chemical composition we have considered: Grevesse & Noels (1993) (GN93) and Asplund et al. (2005) corrected with the Ne abundance determined by Cunha et al. (2006) (AGS05+Ne). We have computed models with: 

(i) OPAL opacity tables with GN93 and 

(ii) AGS05+Ne chemical composition, then models with 

(iii) OP opacity tables assuming GN93 and 

(iv) AGS05+Ne mixtures. All the opacity tables are completed at $\log T < 4.1$ with the corresponding GN93 and AGS05 low temperature tables by Ferguson et al. (2005).

The masses considered span from 2.5 to 18 $M_\odot$, and the chemical com-
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The positions considered are: $X = 0.70$ for the hydrogen mass fraction, and three different metal mass fractions: $Z = 0.02, 0.01$ and $0.005$. For all the models the evolution was followed from the Pre-Main Sequence.

We recall that the differences between opacities computed with OPAL, OP and with the metal mixtures considered can reach nearly 50% in the region where the driving of pulsations occurs ($T \sim 2 \times 10^5$ K) for a typical $\beta$ Cep star (see Paper I for a detailed comparison). Though not included in the calculations presented here, it is worth recalling that the effect of considering the Asplund et al. (2005) metal mixture without the higher Neon abundance proposed by Cunha et al. (2006) is to further increase the Fe relative mass fraction by $\sim 5\%$. In a 10 $M_\odot$ model (and for a given value of $Z$) this induces a further increase of the opacity at $T \sim 2 \times 10^5$ K up to 7%, that only slightly modifies the instability strips presented here.

Results: Updated SPBs and $\beta$-Cep instability domains

We carry out a pulsational stability analysis of main-sequence models from our grid using the non-adiabatic code MAD (Dupret et al., 2003). As mentioned above, in these computations we fixed the overshooting parameter $\alpha_{ov}$ at 0.2 and the initial hydrogen mass fraction $X$ at 0.70. For discussion about the effect of assuming different $\alpha_{ov}$ or $X$ on the stability domain, as well as for the stability study in post-MS models, we refer to the work by Pamyatnykh (1999). We checked the stability of radial modes and of non-radial p- and g-modes of degree $1 \leq \ell \leq 3$.

The location of the instability strip in the HR diagram and the frequency of the excited modes are determined by the properties of the metal opacity bump. The effects of the choice of the metal mixture (GN93 or AGS05+Ne) and of the opacity computations (OPAL or OP) on the HR location of instability domains are shown in figures 1, 2, and 3 for models with metallicity $Z = 0.02, 0.01$, and $0.005$, respectively. The combined effects on the excited modes of OP opacity and AGS05+Ne metal mixture, compared with the standard OPAL with GN93, are also shown by means of the Period-$T_{\text{eff}}$ diagram in Fig. 4.

The results presented in these figures can be summarized as follows:

1. Since the region where $\kappa_T = (\partial \log \kappa_R / \partial \log T)_{\rho}$ increases outwards is found deeper in the star, with respect to the models computed with OPAL tables, the blue borders of the instability strips are hotter with OP models compared to OPAL ones.

2. The $T_{\text{eff}}$ domain for which we find SPB pulsators using OP opacities is $\sim 3000$ K larger than for OPAL models. As a consequence, the number of expected hybrid $\beta$ Cep–SPB objects is also larger for OP models.
3. The impact of the different OP–OPAL opacities is more important for low metallicity. As shown in Fig. 2, while OPAL–GN93 models with $Z=0.01$ are hardly able to produce a narrow instability strip at the end of MS, with excited modes only for $\ell > 1$, the OP models present $\ell = 0–3$ excited modes already for an evolutionary state corresponding to $X_c \simeq 0.3$.

4. The Fe-mass fraction enhancement in the AGS05+Ne mixture, compared with GN93, has the main effect of extending towards higher overtones the range of excited frequencies.

5. Furthermore, while the different profile of $\kappa$ in OP and OPAL computations modifies the blue border of the instability strip, a larger Fe-mass fraction in the metal mixture provides a slightly wider instability bands, and this effect increases as the metallicity decreases. Thus, the number of $\beta$ Cep pulsators expected with AGS05+Ne is more than three times larger than with GN93.

6. Computations for the lowest metallicity considered ($Z=0.005$), show that none of the different OP/OPAL and GN93/AGS05+Ne evolutionary tracks for masses up to $18 M_\odot$ predicts $\beta$ Cep pulsators, whereas we find SPB-type modes excited when considering OP with AGS05+Ne.

The instability strips presented in this work will be made available to the community via the HELAS (European Helio- and Asteroseismology Network) website\(^1\) and are also available upon request to the authors.

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\(^1\)http://http://www.helas-eu.org
Revised instability domains of SPB and $\beta$ Cephei stars

Pamyatnykh, A. A. & Ziomek, W. 2007, CoAst 150, 207
Figure 1: Instability strips of $\beta$ Cep- and SPB-type pulsations in the HR diagram for $Z=0.02$. Evolutionary tracks are represented by dotted lines.
Figure 2: Same as Fig. 1 but for $Z=0.01$
Figure 3: Same as Fig. 1 but for $Z=0.005$
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Figure 4: Instability strips represented in a log $T_{\text{eff}}$-log $P$ diagram for $Z=0.02,0.01$ and different degree $\ell$. In each panel, the two regions of unstable modes represent $\beta$ Cep- and SPB-type pulsations.
Near infrared spectroscopy of the HADS stars V703 Sco and 1 Mon: First steps towards the use of near-IR spectroscopy for the study of $\delta$ Scuti stars

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Abstract

Intermediate results from an on-going programme to study the possibilities of near-infrared spectroscopy are presented for the always difficult task of providing information on the mode identification of pulsating stars. High-resolution spectroscopy taken with CRIRES shows, for the first time, stellar absorption lines in the near-IR varying with the pulsation cycle in the high amplitude $\delta$ Scuti star 1 Mon.$^1$

Introduction

Near-infrared, high-resolution spectrographs will be readily available at medium to large telescopes in the next decade. Existing instruments like PHOENIX and CRIRES, and next generation instruments like, for instance, NAHUAL (Martín et al., 2004), are possible due in part to the improvement in performance of near-IR detectors, now available in larger formats and with lower readout noise.

This region of the spectrum has rarely been used in the study of main-sequence classical pulsators, probably due to the lower flux emitted at these wavelengths by hot stars compared with that in the optical. This, together with the high temporal resolution and high S/N needed for the study of pulsations, had become a strong impediment for the use of these type of data. With the advent of new, more efficient spectrographs at large telescopes, this difficulty can be surmounted and this methodology included in the battery of techniques.

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$^1$Based on observations collected at the European Southern Observatory at La Silla and Paranal, Chile (CRIRES science verification program 60.A-9086)
used in asteroseismology. This method will thus provide a large wavelength baseline for modal identification, which greatly improves the significance of the identification, as shown by Balona et al. (2001) for the optical $V$ and $I$ wavebands, when applying the photometric mode identification technique (e.g., Garrido, 2000). In this and future analyses, the same principle will be applied to spectroscopic data, and the first steps will be given towards the use of near-IR, high-resolution spectroscopy for the study of main sequence pulsating stars.

The main aim of this investigation is the detection of pulsations in the radial velocity (RV) curve or in the measurements of the equivalent width (EW) of the hydrogen lines in the low-resolution data provided by SofI, and in the variations of the line profiles in the high-resolution data provided by CRRES. An attempt to provide physical parameters of the stars from near-IR spectroscopy alone has also been carried out for V703 Sco (Amado et al., 2007) and is being attempted for 1 Mon.

V703 Sco and 1 Mon

Our target stars are High Amplitude Delta Scuti (HADS) pulsators, which are defined as $\delta$ Sct stars with a total amplitude in their visual light curves greater than 0.3 mag. This sample was selected for this study because of their high amplitude, their visibility and the number of periodicities already detected in their light curves.

The star V703 Sco (HD 160589) is a HADS with periods of $P_1 = 0.14996$ d ($\nu_1 = 6.66844$ d$^{-1}$), $P_2 = 0.11522$ d ($\nu_2 = 6.67905$ d$^{-1}$), which might be due to the fundamental and first overtone modes, with a ratio of 0.768, and $P_3 = 0.09354$ d ($\nu_3 = 10.69061$ d$^{-1}$) (Ponsen, 1961; Oosterhoff, 1966; Koen, 2001). The rotational velocity is $v \sin i = 16$ km s$^{-1}$ and the spectral type is A9V (Houk, 1982).

The star 1 Mon (HD 40535) is also a HADS with periods $P_1 = 0.136$ d ($\nu_1 = 7.346$ d$^{-1}$; $\ell = 0$), $P_2 = 0.134$ d ($\nu_2 = 7.475$ d$^{-1}$) and $P_3 = 0.139$ d ($\nu_3 = 7.217$ d$^{-1}$). The last two periods belong to two $\ell = 1$ modes, as detected by Balona & Stobie (1980) and as identified by Balona et al. (2001) and Dupret et al. (2005). A fourth period $P_4 = 0.149$ d ($\nu_4 = 6.717$ d$^{-1}$) was detected by Breger & Kolenberg (2006). The star has also a low projected rotational velocity ($v \sin i = 18.8 \pm 1.5$ km s$^{-1}$; Solano & Fernley, 1997) and a spectral type F2V (Rodríguez et al., 1994).

Observations

V703 Sco was observed during two nights, on the 12th and the 14th of September 2005, with SofI on the NTT at La Silla, ESO. On each of these nights,
the star was observed in a consecutive sequence of 6 exposures in the mode “AutoNodOnSlit”, each one taken by nodding the star 60 arcsec on the slit. Exposure times were computed taking the average of 30 (NDIT) 12s (DIT) exposures with 3 integrations in position A (NINT=3) and another 3 in position B. The object frames were taken through a 0.6 arcsec slit to get the maximum possible resolution ($R \sim 1500$). The data were reduced with IRAF (Tody, 1986).

1 Mon was observed simultaneously in near-IR spectroscopy and in Strömgren photometry at the beginning of March 2007. The photometric data were continuously acquired from the 27th of February to the 3rd of March at the Observatorio de Sierra Nevada (OSN; Granada, Spain), except for the very same night when the star was observed by CRiRES. The spectroscopic observations were carried out with CRiRES at the VLT in Science Verification time during the night of March the 2nd. The target was monitored continuously during $\approx 3.5$ hours to cover one pulsation cycle. Observations were performed at three different settings with central wavelengths 1643.9, 1693.8 and 1732.7 nm. That configuration of the observations provided 12 pieces of the $H$-band spectrum starting at 1617 and ending at 1746 nm, covering, therefore, a total range in wavelength of $\sim 100$ nm (see Fig. 1, top panel). A slit width of 0.4 arcsec was used to obtain a resolution of $\sim 35 000$ measured from the FWHM of several isolated telluric absorption lines.

Correction of the telluric spectrum

Ground-based, near-IR spectra show, even within the well established photometric $J$, $H$ and $K$ bands, absorption features due to the Earth’s atmosphere. Classical methods for correcting the data from these variable absorption features are difficult to apply to observations based in the rapid and continuous acquisition of time series spectra. Observations of telluric standards are thus not that useful, as these time series take longer than the time scale of the atmospheric variations (of the order of a few to tens of minutes), and take the target to different airmasses than those at which the standars were observed.

The data presented in this paper, especially the low-resolution data, were acquired in order to check for the effect of not properly resolving the variable atmospheric absorption lines (intrinsically narrow $\sim 5$ km s$^{-1}$). The correction of the atmospheric absorption spectrum in low-resolution data is complicated by the enormous amount of blended lines and bands at this resolution, even if the $H$ band is affected the least compared with the $J$ or $K$ bands. In Fig. 1, an $H$-band synthetic spectrum with the physical parameters of V703 Sco is shown, together with a telluric spectrum of the same region at the resolution given by SofI (top, $\sim 1500$) and CRiRES (bottom, $\sim 35 000$). It can be seen that the
regions free of telluric absorption are very small in the low-resolution data and, even then, they coincide with regions of stellar absorption, such as the end of the hydrogen Brackett series or some of the broad H\textsc{i} Brackett lines. On the other hand, it can be seen that, at higher spectral resolution, it becomes easier to identify the sections of the spectrum where spectral information or stability is affected due to strong, saturated or variable telluric lines (for studies of these effects see, for instance, Vacca et al., 2003; Pontoppidan & van Dishoeck, 2004; Bailey et al., 2007). In principle, the effect in the normalisation of low-resolution spectra from lack of good continuum regions, due to the blending of the wings of the broad hydrogen lines with the telluric absorption features, should affect the measurements of the EW of the line.

Physical parameters from near-IR spectroscopy

For V703 Sco, synthetic spectra were computed from Kurucz’s model atmosphere grids, degraded to the resolution of the data and compared with the overall mean of the whole set of spectra. The best fit to the data is obtained for a model with \([\text{Fe}/\text{H}] = -0.5\), \(6250 < T_{\text{eff}} < 6750\) K and a \(\log g = 4.5\) (Amado et al., 2007) implying that V703 Sco is a SX Phe star. However, the high gravity derived from the synthetic spectra contradicts what would be expected from the periods of this star, which, interpreted as low radial order frequencies, imply an evolved status. Furthermore, the photometric indices and the space motions point towards a normal Pop. I HADS classification (Rodríguez, private communication). Therefore, some doubts still exist on the parameter determination for this star, even more taking into account that the LTE modelling of the near-IR hydrogen lines might fail to reproduce the strength of the lines (Przybilla & Butler, 2004).

Synthetic spectra will also be computed for 1 Mon and fitted to the observed metallic lines in order to determine the physical parameters, providing, for the first time, a metallicity determination for this star.

Effect of pulsation in the near-IR

As mentioned above, the idea behind observing HADS stars was to assure an amplitude of pulsation large enough to be easily recovered in our data at both low and high resolution. Below, some preliminary results are provided.

Low resolution data

HADS objects show pulsation cycles with variations in \(T_{\text{eff}}\) of the order of 1000 K and in \(\log g\) of the order of 0.35 dex (Rolland et al., 1991; Rodríguez et al.,...
Figure 1: top panel: $H$-band synthetic spectrum computed with the physical parameters of V703 Sco (thick line) together with a telluric spectrum of the same region (thin line) at the resolution given by SofI ($\sim 1500$). Bottom panel: the same as for the top panel but at the resolution provided by CRiRES ($\sim 35000$). The wavelength region of this spectrum corresponds to one of the thin lines, delimiting the wavelength regions of our CRiRES data, plotted above the continuum in the top panel.
Near infrared spectroscopy of the HADS stars V703 Sco and 1 Mon

Figure 2: Normalised, synthetic stellar flux spectra for $T_{\text{eff}} = 6000$ (dashed line), 7000 (solid line) and 8000 K (dotted line), $\log g = 4.50$ and solar metallicity, in the near-IR region, at the resolution of SofI ($\sim 1500$).

In Fig. 2, Kurucz’s synthetic flux spectra with $T_{\text{eff}} = 6000$, 7000 and 8000 K, $\log g = 4.50$ and solar metallicity, are shown. These spectra were “normalised” by dividing them with a blackbody function of $T_{\text{eff}} = 7000$K, which had been previously fitted to a continuum region of the spectra around 1700 nm. This procedure was used with the observed low-resolution data of V703 Sco. It can be seen that the effect of increasing the temperature is basically a change in the depth of the hydrogen lines and in the shape of the spectral energy distribution (SED).

The dispersion in the RV and EW measurements in our data (taken at a high airmass) is too high to detect the pulsations. A small variation of the shape of the SED, of the same order as that mentioned above for the synthetic spectra, can be detected in the data. However, whereas the change in the depth of the hydrogen lines goes from 4% to 7% of the value of the continuum in the synthetic spectra, no change larger than around 1% is seen in H $\alpha$ (4-7)
in the observed spectra. In principle, a study of the pulsation cycle of V703 Sco would have been possible with these type of data if better quality spectra with a somewhat higher resolution had been used. Of course, a better temporal resolution is definitely needed.

High resolution data

The work on the CRiRES data is in progress but the preliminary results are encouraging.

In the 100 nm of the $H$-band spectrum covered by our observations, several lines are seen to vary in a standard deviation plot. Figure 3 shows one of these lines, corresponding to the Si\textsc{i} $\lambda1733.8551$ nm, averaged over the whole time series (top), the differences of the individual spectra with respect to this average (centre) and the standard deviation from the average of the intensity at each
Figure 4: Top panel: Observed Strömgren $v$ differential light curve for the four nights of the observing run, together with a theoretical light curve determined from the main frequencies found in the data. Bottom panel: Zoom on one of the nights, showing the theoretical light curve (solid line; no photometric observations taken) and the radial velocities measured from the CRiRES spectra (square symbols).

Pixel (bottom). Radial velocity measurements in this line are shown in Fig. 4, together with the Strömgren $v$ light curve collected at OSN. Unfortunately, no photometric data were acquired during the night of CRiRES observations and only an interpolation of the light curve computed with the detected frequencies can be provided. This preliminary RV curve appears in anti-phase with the light curve as expected, with an amplitude from maximum to minimum of 25.6 km s$^{-1}$, larger than those quoted by Smith (1982, 18 km s$^{-1}$) and Balona & Stobie (1980, 15 km s$^{-1}$) probably because of beating effects. An in-depth analysis of this dataset is being conducted and will be the subject of a future work.
Conclusions and future work

The results obtained for V703 Sco show that the low resolution provided by instruments like SofI ($R \sim 1500$) is not sufficient to produce RV curves of the required precision, or for the study of line-profile variations. Nevertheless, even at this resolution, it might be worth it to address the question of weather a study of EW time series might have been possible with higher quality data, resulting in precise enough curves from which to extract the amplitudes and phases of the modes, as done in the optical by Dall et al. (2003).

For the first time, variations in near-IR absorption lines due to pulsation have been detected and measured for a $\delta$ Scuti star. As demonstrated with CRIRES data, spectroscopic techniques already used in the optical (moments method, line profile fitting, Doppler imaging) can and will be applied to our data to extract information from this spectral region that can be used to constrain and help in the identification of the modes. The diagnostic potential of this region comes from the different sensitivity of the absorption lines to changes in $T_{\text{eff}}$ and $\log g$ with respect to the optical, and from the interplay between the pulsation and the limb-darkening effects. However, more theoretical work is needed, specially for the extension to this wavelength region of the well known amplitude-ratio and phase-difference plots used in modal discrimination.

In the near future, proposals to observe $\delta$ Scuti stars of various amplitudes with CRIRES and other near-IR spectrographs will be submitted. Moreover, simultaneous high-resolution spectroscopy in the optical and in the near-IR will be acquired for these studies.

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A new slowly pulsating subdwarf-B star: HD 4539

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Abstract

We report the spectroscopic discovery of slow pulsations in the subdwarf-B (sdB) star HD 4539. It is amongst the brightest sdB stars and, as such, has been well studied. Its temperature and gravity would place it squarely where the so-called “Betsy” stars (long-period sdB pulsators) are found, and this has been confirmed by the discovery of line-profile variations reported in this paper for the first time. As periodogram analyses of radial velocity curves obtained in 2005 and 2006 yield several significant frequencies, line-profile variations are very probably a consequence of pulsation.

Introduction

Subdwarf-B (sdB) stars are low-mass (∼ 0.5\(M_\odot\)) core helium burning objects that belong to the Extreme Horizontal Branch (EHB) (Heber 1986). They have a thin and mostly inert hydrogen-rich envelope, and remain hot (20 000 K ≤ \(T_{\text{eff}}\) ≤ 40 000 K) and compact (5 ≤ \(\log g\) ≤ 6.2) throughout their EHB lifetime (Saffer et al. 1994), before evolving towards the white dwarf cooling sequence without experiencing the Asymptotic Giant Branch and Planetary Nebula phases of stellar evolution. Yi et al. (1997) suggest sdB stars could be responsible for the ultraviolet-upturn seen in the energy distributions of elliptical galaxies and spiral galaxy bulges, and therefore understanding their formation may provide an important diagnostic for studying galaxy formation and evolution. Han et al. (2002, 2003) use binary population synthesis calculations to demonstrate the formation of sdB stars through several possible channels, but resulting models should still be compared with observation. This could be achieved thanks to the discovery that some subdwarf-B stars undergo non-radial pulsations, which means asteroseismology could be used to study their internal structure.
There are two main types of pulsating sdB stars: V361 Hya stars are short-period pulsators, and the so-called “Betsy” stars are long-period pulsators. Kilkenny et al. (1997) serendipitously discovered V361 Hya stars in the Edinburgh-Cape (EC) Blue Object Survey. Typically they undergo short-period (100 – 200 s) low-amplitude (a few mmag) multiperiodic pulsations, and they are rather hot and dense ($T_{\text{eff}} \sim 34 000$ K, $\log g \sim 5.8$). Independently from the observational discovery, pulsating sdB stars were predicted by Charpinet et al. (1996), based on the $\kappa$-mechanism. A local enhancement in the abundance of partially ionised iron in the envelope of sdB stars (due to diffusion in the form of gravitational settling and radiative levitation) causes a bump in the opacity that triggers pulsations. In V361 Hya stars, this results in low-order, low-degree pulsation modes that reach their highest amplitude near the star’s surface ($p$-modes).

Long-period sdB pulsators were discovered by Green et al. (2003). They cluster around $T_{\text{eff}} \sim 25 000$ K, $\log g \sim 5.4$, and vary on timescales of about 1 hour, with very low amplitudes, pointing to $g$-mode pulsations. Indeed, Fontaine et al. (2003) demonstrate that the same $\kappa$-mechanism that excites $p$-mode pulsations in V361 Hya stars can also trigger higher degree $g$-mode pulsations in the cooler, less dense “Betsy” stars. Randall et al. (2006a) suggest at least 75% of cool ($T_{\text{eff}} < 30 000$ K) subdwarf-B stars should pulsate with long periods, but so far, only PG 1716+426 (the class prototype), PG 1627+017 and PG 1338+481 have been the subjects of extensive observational efforts, by Reed et al. (2004) and Randall et al. (2006a, 2006b) respectively.

The magnitude of HD 4539 ($B \sim 10.12$) makes it one of the brightest known sdB stars, and it has been extensively studied in the past. For instance, Bascheck et al. (1972) estimate its atmospheric parameters to be $T_{\text{eff}} \sim 25 000$ K and $\log g \sim 5.4$, while Saffer et al. (1994) find values of $T_{\text{eff}} \sim 27 000$ K and $\log g \sim 5.46$. In any case, this star has surface parameters similar to those of “Betsy” stars. We first observed HD 4539 (2000.0 coordinates: $\alpha = 0^h 47^m 29.219^s, \delta = +09^\circ 58' 55.69''$) in August 2005 because inclement weather made it impossible to obtain data on fainter stars. When our spectra exhibited the presence of strong line-profile variations, we decided to perform follow-up observations in subsequent runs to confirm our discovery. In this paper, we therefore report the presence of slow pulsations in HD 4539.

Observations

Spectroscopic observations were made with the Grating Spectrograph and SITe CCD on the 1.9-m telescope at the South African Astronomical Observatory.

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1 These are still awaiting official nomenclature, but are informally known as “Betsy” stars, after their discoverer, Dr Elizabeth Green.
(SAAO) in Sutherland, in August 2005, August 2006 and November 2006. Table 1 lists the number of spectra obtained on each night as well as the exposure times.

The typical seeing during our observing runs was rarely better than 1.5", and, accordingly, the typical slit width used was 1.5" or lower. This setting allowed us to obtain a typical signal-to-noise ratio (SNR) of about 100, without compromising the spectral resolution. Photometry in B and I was also obtained in 2006 with the UCT CCD and the SAAO CCD on the 0.75-m and 1.0-m Sutherland telescopes respectively. A preliminary analysis shows $\Delta B \lesssim 0.02$ mag; the details will be reported in a subsequent paper.

Our 198 spectra cover a wavelength range of a little less than 900 Å (from 3950 Å to 4820 Å) with a resolution of 1 Å and were all obtained alternately with spectra of a Cu/Ar arc lamp for wavelength calibration purposes. Reduction was performed using a program specifically written to reduce our data sets automatically. This state-of-the-art code first flat-fields the images before extracting the spectra, then calibrates their wavelength dependence, correcting for the small tilt of the spectra (less than three pixels over a 1798-pixel long chip), and finally subtracts an extensive sky-window, while getting rid of cosmic ray hits and other undesirable effects. The results of our code were compared with reduction performed using IRAF, and the differences were negligible.

In Figure 1, we show a typical spectrum of HD 4539 obtained in August 2005, while Figures 2 and 3 demonstrate the kind of line-profile variations that came to our attention.

| Table 1: Observing log for HD 4539. |
|-------------------------------|-----------------|-----------------|-----------------|
| Date                          | JD              | Number of spectra | Integration      |
| 2005 August 23/24 2453606     | 1               | 200              |
| 27/28                         | 3610            | 16               | 400              |
| 28/29                         | 3611            | 11               | 400              |
| 29/30                         | 3612            | 28               | 400              |
| 2006 August 04/05 3952        | 8               | 400              |
| 05/06                         | 3953            | 7                | 400              |
| 06/07                         | 3954            | 8                | 400              |
| 08/09                         | 3956            | 23               | 400              |
| 09/10                         | 3957            | 29               | 400              |
| 10/11                         | 3958            | 23               | 400              |
| 15/16                         | 3963            | 9                | 400              |
| 2006 November 06/07 4046      | 10              | 500              |
| 07/08                         | 4047            | 25               | 500              |
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The fact that the O II and N II lines in the left-hand panels of Figures 2 and 3 exhibit different behaviours (one getting stronger while the other is getting weaker) is similar to the pattern observed by Telting & Østensen (2004) in the fast pulsator PG 1325+101, where He II lines are in anti-phase with the other lines. This is an effect of temperature variation due to pulsation, which, in the case of pulsating subdwarf-B stars, cannot be neglected.

Although line-profile variations can be caused by surface spots, this would be very surprising in the case of subdwarf-B stars. Spots can be associated with late-type stars where convection in the atmosphere is important for energy transport, but this is insignificant in sdB stars. It is also likely that abundance spots due to magnetic fields can be ruled out in subdwarf-B stars because they are slow rotators, typically having $v \sin i \lesssim 5$ km/s (Heber et al. 2000), which corresponds to a rotation period of the order of one day, while periods observed for HD 4539, and variable sdB stars in general, are an order of magnitude smaller and can therefore not arise through a non-uniform abundance distribution in the photosphere consequent upon a magnetic field. On the other hand, Fontaine et al. (2003) demonstrate that non-radial pulsations can be expected in cool subdwarf-B stars like HD 4539 and we investigate this as a possible cause of line-profile variations.
Figure 2: Variations in He I lines of HD 4539 observed on different nights in August 2005. The solid spectrum was obtained on HJD 2453611, and the dashed spectrum on HJD 2453612.

Figure 3: Same as Figure 2, but the solid spectrum was obtained on HJD 2453958, and the dashed spectrum on HJD 2453952.
Radial velocity analysis

Radial velocities were derived using VCROSS (Hill 1982), an interactive cross-correlation program. VCROSS measures radial velocity differences between stars by cross-correlating stellar spectra with one appropriately chosen reference spectrum. Tests on synthetic data by Hill (1982) demonstrate no systematic errors should be expected, and excellent radial velocity determination should be achieved given a proper choice of reference spectrum.

First, we chose our highest signal-to-noise ratio spectrum for each separate night as a reference spectrum, and computed radial velocities for the corresponding nights. We then used the highest SNR spectrum of each run as reference spectrum and obtained radial velocities for each spectrum of the corresponding run. Finally, our best SNR spectrum overall was used to obtain radial velocities for all spectra. This consistency check allowed us to select the spectra with the best determination of radial velocities (about two-thirds of them). After correcting these spectra for the Earth’s orbital and diurnal motion, we shifted them to zero radial velocity and added them all together to produce a “super-template” with higher SNR. This template was used to derive new radial velocities for all spectra, and this procedure of shifting the spectra and deriving new radial velocities was to be repeated iteratively until the radial velocities converged (within the fitting errors quoted by VCROSS, that is, less than 0.07 km/s), which, in this particular case, happened after only three iterations. In Figure 4 we plot the radial velocities obtained using the aforementioned method and corrected for the Earth’s motion, for each observing night. These were used for the frequency analysis described in the next section.

Frequency analysis

We performed an extensive frequency analysis of our data set using the software package Period04, described by Lenz & Breger (2005), and SigSpec, a program providing a rigorous statistical analysis of the significance levels in an amplitude spectrum (Reegen 2007). SigSpec computes a significance spectrum for each detected signal so that, for instance, a significance level of 8 means the considered amplitude would be due to noise in one out of $10^8$ cases. It is ideal to deal with strongly aliased data such as ours, when the usual signal-to-noise criteria can become doubtful. Following Reegen’s (2007) Equation 31, a signal-to-noise ratio of 4 roughly corresponds to a significance level of 5.4575, and a signal-to-noise ratio of 3 to a significance of 3.0698.

When computing the significance spectrum of our data set, we found it be dominated by three low frequency signals (Figure 5, upper panel). This is not
Figure 4: Radial velocities in HD 4539 spectra for each observing night. In particular note the smooth radial velocity variation obtained on HJD 2454046 indicating a typical error of 2 km/s
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Figure 5: Significance spectra extracted from radial velocity curves of Figure 4, before (top) and after (bottom) removing the low-frequency signals. The horizontal dotted lines correspond to a SNR of 3 and 4. Vertical dotted lines indicate the frequencies of Table 2.

unusual in slowly pulsating subdwarf-B stars (see e.g. For et al. 2006, and Kilkenny et al. 2007), and in any case some of these low frequencies can be explained by the sampling of our data. There is however some obvious excess in the significance levels at $\sim 25$ c/d, $\sim 35$ c/d, $\sim 45$ c/d and $\sim 50$ c/d.

We therefore decided to analyse our data set after removing the three low frequency signals. After recomputing the significance spectrum, we found one frequency with a significance higher than 5.46, and three others well above the 3.07-significance level, as can be seen in Figure 5 (lower panel)\(^2\).

The values of these frequencies are summarised in Table 2 after having been optimised in a non-linear least-squares fit, taking into account the influence each frequency can have on the others (Schoenaers & Cuypers 2004).

In Table 2 we also quote three frequencies with lower significance. Although we cannot confirm whether they’re real, and would need additional data to do so, we still consider them as tentative identifications as the significance spectrum exhibits some excess power in these regions.

It is to be noted that we also divided our data set in three parts (one for each run), and analysed them separately. Even though it is obvious we do

\(^2\)The significance spectra were computed up to the Nyquist frequency but are only plotted up to 62 c/d because no power was found to be present at higher frequencies.
Table 2: Frequencies, amplitudes and phases of the variations found in the radial velocity curve of HD 4539. The errors quoted on the frequencies come from a Monte-Carlo simulation. The last column gives the significance level of the frequencies.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Period (s)</th>
<th>Amplitude (km/s)</th>
<th>Phase</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1$</td>
<td>1927</td>
<td>2.14</td>
<td>0.66</td>
<td>5.50</td>
</tr>
<tr>
<td>$f_2$</td>
<td>1692</td>
<td>1.86</td>
<td>0.35</td>
<td>4.47</td>
</tr>
<tr>
<td>$f_3$</td>
<td>9310</td>
<td>1.71</td>
<td>0.05</td>
<td>4.26</td>
</tr>
<tr>
<td>$f_4$</td>
<td>5304</td>
<td>1.46</td>
<td>0.57</td>
<td>3.23</td>
</tr>
<tr>
<td>$f_5$</td>
<td>3336</td>
<td>1.46</td>
<td>0.80</td>
<td>2.23</td>
</tr>
<tr>
<td>$f_6$</td>
<td>1548</td>
<td>1.40</td>
<td>0.48</td>
<td>3.09</td>
</tr>
<tr>
<td>$f_7$</td>
<td>2325</td>
<td>1.36</td>
<td>0.39</td>
<td>2.93</td>
</tr>
</tbody>
</table>

not have enough data points in the first and third runs to discriminate against some frequencies found in the second run just based on their absence in the first and/or third run, it is nevertheless a worthwhile check to compare the three frequency spectra. Radial velocities obtained in 2006 August gave the same frequencies as the complete dataset, with amplitudes and phases also in agreement within observational error.

Summary

After three observing runs in 2005 and 2006, we report the discovery of another member of the slowly pulsating subdwarf-B star class. HD 4539 undergoes at least four pulsations with periods ranging from 1692s to 9310s, and amplitudes up to 2.14 km/s. Being such a bright sdB star, it is an ideal target for an in-depth asteroseismological analysis, for example using the method outlined by Schoenaers & Lynas-Gray (2006). This will be the subject of a subsequent paper.

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Best regards from Vienna,
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