The complex photometric behaviour of the δ Scuti star HD 224639*

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Abstract. HD 224639 was photometrically observed for 20 h in 1989 and 120 h in 1991 (454 and 2567 datapoints, respectively). The star shows a very complex pulsational content with 3 components with semi-amplitudes of about 15 mmag and many other terms with a smaller semi-amplitude. The 1991 dataset allowed us to single out 11 components in the frequency range between 5 and 12 c d⁻¹, but many more are probably present since the residual rms of the fit is 8.6 mmag, while the noise level is expected to be 3.7 mmag. By subdividing the 1991 dataset into two parts and by comparing the results of the frequency analysis with those obtained from the 1989 dataset we found independent evidence in support of the reliability of four frequencies: 6.21, 8.49, 9.54 and 11.42 c d⁻¹. Since most of the 11 components are nonradial modes, their identification is hampered by the high rotational velocity (v sin i = 110 km s⁻¹) which very probably produces the splitting of an ℓ mode into a multiplet (−ℓ ≤ m ≤ +ℓ) and, in any case, causes an appreciable shift in frequency of the central value (m=0).

Key words: methods: data analysis – stars: individual: HD 224639 – stars: oscillation – stars: δ Scu

1. Introduction

Some years ago, we included in our programme devoted to the study of multimode pulsators the star HD 224639 (7.3, F0), discovered to be a short period pulsator by Manfroid & Renson (1983). As a variable star, HD 224639 is now named BH Psc. This star was observed for 9 nights in November 1989 with the ESO 50-cm telescope at La Silla Observatory. The stars HD 224638 (7.2, F0) and HD 224945 (6.9, F0) were chosen as comparison stars.

Beyond the presence of several pulsational modes in HD 224639 (Mantegazza & Poretti 1990), the data reduction yielded evidence of variability at least for one of the two comparison stars, with an amplitude of a few hundredths of mag and a time scale of several hours. Such a variability in the comparison stars made a conclusive light curve interpretation impossible and a new intensive observing campaign was planned and performed in September and October 1991.

2. Observations and reduction

HD 224639 and its comparison stars were observed by differential photometric photometry with the 50-cm telescope at La Silla Observatory: the measurements were performed with the Johnson B filter. In order to find out which of the two comparison stars was variable we adopted HD 225086 (8.0, F2) as a new comparison star. A preliminary reduction of the first observing night made it clear that both HD 224638 and HD 224945 were in fact variable (Mantegazza & Poretti 1991) and therefore one more comparison star was adopted. As a first selection, HR 11 (6.43, B8 IIIp) was chosen and used for four observing nights but it was subsequently replaced with HD 200 (8.0, F8), whose colour is more similar to that of the variable stars.

HD 225086, HR 11 and HD 200 were found to be constant within a few thousandths of a magnitude. In particular the standard deviation of the 681 differential measurements of HD 200 with respect to HD 225086 (distributed over 15 nights) is 3.7 mmag and the resulting power spectrum does not show any significant peak. This value is assumed to be an estimate of the mean external error of our datapoints. The light variability of HD 224638 and HD 224945 was discussed by Mantegazza et al. (1994).

The observations above as well as others carried out at the same epoch at La Silla Observatory were found to be affected by a rapid variation of the atmospheric extinction with a timescale of a few hours. This phenomenon was related to the eruption of the Pinatubo volcano in the Philippines (June 1991). In order to avoid spurious effects due to this variability (of a particular importance in our case, owing to the small amplitude of the components of the light curve), a method which allows to calculate instantaneous values of the extinction coefficient was developed (Poretti & Zerbi 1993) and successfully applied in the data reduction.
Fig. 1. Light curve of HD 224639 obtained from the measurements collected in 1991. Solid line: solution with the 11 frequencies reported in Table 2.
Differential photometry versus HD 225086 yielded 2567 measurements of HD 224639 covering about 120 hours of survey on 18 nights over a 35 night baseline. A first observing run spanning 14 nights was followed by a second run spanning 10 nights: between them, there is a 10 d gap. The light curves are reported in Fig. 1; the differential measurements have been deposited in the Comm. 27 IAU Archives of Unpublished Observations, File 296E, and can also be requested from the authors.

3. Frequency analysis

The frequency analysis was performed by means of the least squares power spectrum defined by Vaniček (1971), which consists in the simultaneous least-squares fit of \( n + 1 \) sinusoids: \( n \) is the number of previously identified terms (known constituents, hereafter k.c.) and \( n + 1 \) is the sinusoid corresponding to the trial frequency. This technique is particularly suited to the study of multiperiodic light curves (Antonello et al. 1986; Andreasen 1987; Mantegazza et al. 1993) because it does not require any prewhitening of the data. This is because the amplitudes and phases of the frequency terms previously identified, when searching for a new frequency term, are recalculated for this new trial frequency. Only the frequencies of k.c. are kept constant, but their values are refined by a non-linear least-squares fit after each new periodic constituent has been detected. The y-ordinates of the spectra show the reduction factor

\[
RF = 1 - \frac{\sigma_{\text{res}}^2}{\sigma_{\text{in}}^2}
\]

where \( \sigma_{\text{res}} \) is the residual variance before considering the new trial frequency and \( \sigma_{\text{in}} \) is the residual variance after considering it.

3.1. 1991 observations

We calculated the spectra of the 1991 dataset inside the 0-20 c d\(^{-1}\) passband with a step of 0.0034 c d\(^{-1}\) (equivalent to (10\(\Delta T\))\(^{-1}\), where \(\Delta T\) is the time baseline, i.e. ten times smaller than the spectral resolution): the spectrum without any k.c. is shown in Fig. 2.

From Fig. 2 we see that the main contribution to the data variance is given by a signal around 9.5 c d\(^{-1}\), showing a double-peak structure (9.49 and 9.54 c d\(^{-1}\)). A strong peak at 8.49 c d\(^{-1}\) is also clearly visible. The higher reduction factor at \(f=9.49\) c d\(^{-1}\) with respect to the 8.49 c d\(^{-1}\) signal would suggest attributing physical meaning to the former and considering the latter as its own alias at \((f-1)\) c d\(^{-1}\). However, the presence of two very close peaks can alter the distribution of variance reduction between the two signals, due to the convolution of the signal with the spectral window. Therefore a scenario with a meaningful signal at \(f=8.49\) c d\(^{-1}\) and its alias at \(f+1=9.49\) c d\(^{-1}\), whose height is enhanced by the nearby signal at 9.54 c d\(^{-1}\), has also to be taken into account.

Beyond this group of frequencies a peak at 6.21 c d\(^{-1}\) is visible in the spectrum and, as will be discussed later on, is confirmed by subsequent least-squares analysis. In Fig. 3 we present the spectral window of these data (Deeming 1975): it is quite clean with only two quite strong aliases at \(\pm 1\) c d\(^{-1}\) from the central peak.

Taking into account the possible interactions between nearby modes or their strongest aliases which can modify the peak amplitudes we made a complete spectral analysis of the data by computing spectra with an increasing number of k.c. and with most of the possible combinations of frequencies. Indeed, in the case of a complicated power spectrum structure characterized by strong aliases (typically at \(\pm 1\) c d\(^{-1}\) from the central value), the choice of the right peak is not an easy task. The problems related to this kind of analysis were discussed by Mantegazza et al. (1993): if we select an alias instead of the real frequency, then we should expect the real frequency (or one of its aliases) to appear as the dominant peak in a subsequent spectrum. If this happens, we know that we are on the wrong way, so we can stop the analysis and repeat the whole procedure again, substituting a value differing by 1 c d\(^{-1}\) from the rejected frequency. The application of this procedure to the measurements of HD 224639 led us to the parallel analysis whose scheme is shown in Table 1. The task is complicated by the presence of three terms at 8.49, 9.54 and 10.57 c d\(^{-1}\), i.e. roughly spaced by about 1 c d\(^{-1}\). However, in this case also we can see from Table 1 that if we introduce an alias of the true value among the k.c, then the subsequent analysis evidences another alias or the true value itself in a subsequent spectrum. For example, when considering 6.21, 8.49, 9.54 and 10.57 c d\(^{-1}\), the analysis yielded 7.55 c d\(^{-1}\) as \(f_9\), i.e an alias of the true value 10.57 c d\(^{-1}\); when considering 6.21, 8.49+1=9.49, 9.54 and 9.57 c d\(^{-1}\) the analysis yielded the true value 8.49 c d\(^{-1}\) as \(f_9\). Only when considering 6.21, 8.49, 9.54 and 10.57 c d\(^{-1}\) we obtained 11 independent frequencies, reported in Table 2 with their amplitudes and phases; the interpolating curve is a cosine series.

We can see that the parallel analysis tends to favour the choice of 8.49 c d\(^{-1}\) and 9.54 c d\(^{-1}\) as real physical terms. How-
Table 1. The selection of the real frequency in many power spectra is complicated by the alias structure; however, when selecting a wrong value, an its own alias appears in a subsequent spectrum. In this table all the possibilities of identifying the $f_5$, $f_3$ and $f_4$ terms are indicated: in one case only the analysis does not show an alias value of a previous term (indicated by an “X”)  

<table>
<thead>
<tr>
<th>$f_1$</th>
<th>6.21</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_2$</td>
<td>8.49</td>
</tr>
<tr>
<td>$f_3$</td>
<td>8.54 9.54 9.54 10.54</td>
</tr>
<tr>
<td>$f_4$</td>
<td>8.57 10.57 9.57 10.57</td>
</tr>
<tr>
<td>$f_5$</td>
<td>10.56 10.24 10.24 7.11</td>
</tr>
<tr>
<td>$f_6$</td>
<td>X 7.11 11.41 10.24</td>
</tr>
<tr>
<td>$f_7$</td>
<td>11.41 7.12 11.42</td>
</tr>
<tr>
<td>$f_8$</td>
<td>8.63 7.55 9.54</td>
</tr>
<tr>
<td>$f_9$</td>
<td>8.94 X X</td>
</tr>
<tr>
<td>$f_{10}$</td>
<td>10.45</td>
</tr>
<tr>
<td>$f_{11}$</td>
<td>5.92</td>
</tr>
</tbody>
</table>

Table 2. Most reliable least–squares solution for the 1991 dataset

<table>
<thead>
<tr>
<th>Mode [c d$^{-1}$]</th>
<th>Amplitude [mmag]</th>
<th>Phase [0.2π]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.215</td>
<td>17.2</td>
<td>4.42</td>
</tr>
<tr>
<td>9.543</td>
<td>15.9</td>
<td>5.86</td>
</tr>
<tr>
<td>8.488</td>
<td>14.8</td>
<td>2.15</td>
</tr>
<tr>
<td>10.565</td>
<td>9.8</td>
<td>3.12</td>
</tr>
<tr>
<td>10.241</td>
<td>8.7</td>
<td>5.18</td>
</tr>
<tr>
<td>7.120</td>
<td>7.2</td>
<td>0.14</td>
</tr>
<tr>
<td>11.419</td>
<td>6.4</td>
<td>5.74</td>
</tr>
<tr>
<td>8.944</td>
<td>5.9</td>
<td>0.24</td>
</tr>
<tr>
<td>10.454</td>
<td>5.8</td>
<td>1.08</td>
</tr>
<tr>
<td>8.633</td>
<td>4.4</td>
<td>1.04</td>
</tr>
<tr>
<td>5.918</td>
<td>3.3</td>
<td>2.70</td>
</tr>
</tbody>
</table>

Residual r.m.s. 8.6 mmag

$T_0$ = HJD 2448505.000

However, the choice of 8.49 c d$^{-1}$ instead of 9.49 c d$^{-1}$ is not conclusive (see Table 1); we shall investigate this point again when discussing the 1988 measurements. We can notice that even with a high number of k.c. the residual rms (8.6 mmag) remains consistently above the mean external error (3.7 mmag); i.e. there remains a part of the signal that has to be accounted for, and since the amplitudes of the new terms are below 4 mmag, it means that there should be a lot of such terms.

Since the dataset is naturally subdivided into two parts separated by a gap of 10 days, we analysed separately the two subsets in order to confirm the results given above. In both of them we found the term at 6.21 c d$^{-1}$. Introducing this term as a k.c. we found the spectra shown in Fig. 4. We see that the dominant peaks are respectively at 8.49 and 9.54 c d$^{-1}$. By introducing these frequencies as k.c. we found 9.54 and 8.49 c d$^{-1}$ as a third component in the first and second subsets respectively. Due to the limited frequency resolution of the two subsets (0.07 and 0.09 c d$^{-1}$ to be compared to 0.03 c d$^{-1}$ for the complete dataset) and to the complexity of the stellar frequency spectrum, it is not possible to perform an analysis as complete as the one performed on the complete dataset. However, a least–squares fit using the 11–component solution derived in the previous section shows that the three dominant components have the same amplitudes in the two subsets. This result supports their identification as real excited frequencies in the light curve of HD 224639.

3.2. 1989 observations

As already described in the Introduction, previous observations of HD 224639 were taken at La Silla Observatory by differential photometry in the Johnson B band. HD 224638 and HD 224945 were used as comparison stars: the data reduction provided 454 measurements. The observations cover 20 hours on 9 consecutive nights. The spectral window of these data is shown in the lower panel of Fig. 3. We see that it has a much worse appearance than the 1991 dataset, hence we can only try to get some confirmations of the previous findings from these data.

As already stated above, both comparison stars show an irregular variability with an amplitude of a few hundredths of mag and a characteristic timescale of the order of 1 d (Man-
tegazza et al. 1994). Due to this irregular behaviour it is not possible to remove this spurious signal from the differential magnitudes of HD 224639. However, since this variability essentially affects frequencies below 4 c d$^{-1}$ while the previous analysis has shown that the relevant pulsational terms have frequencies above 5 c d$^{-1}$ (see also Fig. 2), we can use these data to find some independent confirmations of the results given above. A least-squares analysis of the differences of magnitudes between HD 224639 and HD 224638 has therefore been performed. The spectrum with no k.c. is shown in Fig. 5 where we clearly see the low frequency peaks caused by the variability of the comparison star.

Following the procedure previously described we found the following terms in subsequent spectra: 11.43, 9.52 and 6.23 c d$^{-1}$. Because of the short time coverage during each night and the presence of the low frequency disturbance no more terms can be extracted with some confidence. As a consequence of the low spectral resolution (about 0.11 c d$^{-1}$), the peak at 9.52 c d$^{-1}$ results from the merging of the peak at 9.54 c d$^{-1}$ with the alias at 9.49 c d$^{-1}$ of the 8.49 c d$^{-1}$ peak. The amplitude of the 6.23 c d$^{-1}$ term is, within the uncertainties, identical to that of 1991 season. On the other hand, the amplitude of the 11.43 c d$^{-1}$ term seems considerably higher than the one measured in 1991, but this is probably a spurious effect due to the poor...
Table 3. Frequency content deduced from the CLEAN spectra of the 1991 observations

<table>
<thead>
<tr>
<th>Freq. [c d⁻¹]</th>
<th>CLEAN Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.543</td>
<td>3.16 · 10⁻⁵</td>
</tr>
<tr>
<td>6.214</td>
<td>2.75 · 10⁻⁵</td>
</tr>
<tr>
<td>8.487</td>
<td>1.85 · 10⁻⁵</td>
</tr>
<tr>
<td>10.565</td>
<td>8.05 · 10⁻⁶</td>
</tr>
<tr>
<td>10.239</td>
<td>7.74 · 10⁻⁶</td>
</tr>
<tr>
<td>7.121</td>
<td>4.81 · 10⁻⁶</td>
</tr>
<tr>
<td>5.237</td>
<td>3.34 · 10⁻⁶</td>
</tr>
<tr>
<td>8.945</td>
<td>2.69 · 10⁻⁶</td>
</tr>
<tr>
<td>7.322</td>
<td>2.50 · 10⁻⁶</td>
</tr>
<tr>
<td>11.418</td>
<td>2.41 · 10⁻⁶</td>
</tr>
<tr>
<td>8.786</td>
<td>1.65 · 10⁻⁶</td>
</tr>
<tr>
<td>3.845</td>
<td>1.54 · 10⁻⁶</td>
</tr>
<tr>
<td>10.454</td>
<td>1.33 · 10⁻⁶</td>
</tr>
<tr>
<td>12.391</td>
<td>1.30 · 10⁻⁶</td>
</tr>
</tbody>
</table>

resolution which blends the term at 11.42 c d⁻¹ with the alias at 11.45 c d⁻¹ of the term at 10.45 c d⁻¹.

3.3. Complete dataset: 1989 plus 1991 measurements

The double peak structure shown in the spectra of the 1991 observations (see above) can clearly be disentangled by increasing spectral resolution, i.e. increasing the time baseline. This can be done by grouping the 1989 and 1991 measurements into a single dataset. We remember that in the 1989 data there is a low frequency spurious signal due to the variability of comparison stars. However, the effect of this signal tends to be minimized by the fact that the 1991 dataset, which is by far the more conspicuous, does not contain this signal.

Since, as was said before, it was not possible to remove the variable contribution of the comparison star from the 1989 data, we aligned the zero-points of the two time-series by simply subtracting their averages. A possible residual difference in the two zero-points can affect only low frequencies and this can be considered as unimportant in our case. The complete dataset provides a baseline of 699 days and therefore a spectral resolution of 0.0015 c d⁻¹ (and consequently it requires also a very small step in the frequency analysis, thus making it quite cumbersome). The 6.21 c d⁻¹ term is surely present in both the 1989 and the 1991 datasets and it is obviously present in the complete dataset; we therefore introduced it in the analysis as the first k.c. even though it is not the highest peak in the power spectrum obtained with no k.c. (Fig. 6, upper panel). The subsequent power spectrum is shown in the middle panel of Fig. 6 and clearly shows a dominant peak at 9.54 c d⁻¹. Adding this term as the second k.c. the third spectrum shows the highest peak at 8.49 c d⁻¹ (Fig. 6, lower panel). We see that these spectra support the idea that the true terms are at 8.49 and 9.54 c d⁻¹.

Fig. 6. Least-squares spectra of HD 224639. Complete dataset. No k.c. (top panel), 6.21 c d⁻¹ as k.c. (medium panel), 6.21 c d⁻¹ and 9.54 c d⁻¹ as k.c. (bottom panel)

4. CLEAN analysis

In order to check the results listed above the 1991 data were also analysed with the CLEAN algorithm (Robert et al. 1987). This entirely automatic iterative data deconvolution is less reliable than a least-squares analysis, because it can, in some cases, split power between the signal and its aliases at a distance of ±1 c d⁻¹. However it offers a useful check, not influenced by human judgement (or personal prejudice) of the results obtained with other techniques.
5. Strömgren colours and $\nu$ sin $i$ measurements

In order to estimate stellar fundamental physical parameters, we collected, during the 1991 observations, a number of measurements in the $ugv$ filters. Strömgren’s color indices were obtained by observing the stars differentially with respect to some nearby standard stars. For HD 224639 we found $b - y = 0.212$, $m_1 = 0.154$, $c_1 = 0.846$ and $\beta = 2.713$.

Hence, we applied the same procedure used in the case of SAO 4710 (Mantegazza & Poretti 1990) and BI CMi (Mantegazza & Poretti 1994). By using the Moon & Dworesky (1985) calibration for $T_{\text{eff}}$ and log $g$ and the Crawford (1979) one for $M_V$ (taking also into account the corrections introduced by Guthrie (1987) for metallicity and rotation), we obtained the following parameters for HD 224639: $T_{\text{eff}} = 6860$ K, log $g = 3.24$ and $M_V = 0.84$. In turn, from these values we obtained $M = 2.3M_\odot$ and $R = 4.1R_\odot$. The star is located near the red edge of the instability strip and it is a little evolved object.

During an observing run devoted to another object (1992 November, Coudé Auxiliary Telescope), we collected a high-resolution spectrogram (4489–4526 Å, 0.035 Å/pixel) of HD 224639 in order to determine its $\nu$ sin $i$ value. The $\nu$ sin $i$ value was determined by a comparison between the FWHM of the observed lines and those obtained by computing the convolution of rotational line profiles having different velocities with an intrinsic profile which results from instrumental, thermal and microturbulent broadening; this procedure was successfully checked on rotational standard stars measured during the same observing run. The $\nu$ sin $i$ value turned out to be about 110 km s$^{-1}$.

6. Discussion

The frequency analysis has shown that the light curve of HD 224639 results from the superposition of at least 11 pulsational terms, and that their number should probably be much larger since a least–squares fit of the data with these 11 terms has a residual rms much higher than the one expected from observational noise (8.6 versus 3.7 mmag); this can also be seen in Fig. 1, since there are systematic deviations of the computed curve from the measurements. Owing to the complexity of the pulsational spectrum and to the ambiguity introduced by the alias peaks, it is difficult to detect the true values of these frequencies. However, the comparison of the results from two independent datasets (1989 and 1991) and the two 1991 subsets shows that 4 terms can be quite confidently singled out: 6.21, 8.49, 9.54 and 11.42 c d$^{-1}$. In the following, we shall limit ourselves to a discussion of the physical identification of these four terms only.

In order to understand which types of modes are responsible for the signals stated above, we first estimate the frequency of the fundamental mode by introducing the physical parameters derived above in the empirical relation

$$\log \nu_0 = 0.300 M_{\text{bol}} + 3.195 \log T_{\text{eff}} - 11.90$$

reported by López de Coca et al (1990). We obtain $\nu_0 = 4.14$ c d$^{-1}$.
The estimate of the physical parameters allows us to derive
\[ \log(Q/P) = -6.454 + 0.5 \log g + 0.1 M_{bol} + \log T_{eff} = -0.91 \]
where \( Q \) is the pulsational constant and \( P \) the period. The resulting
pulsational constants are reported in Table 4; we remember
that the uncertainties on these values are about 18% (Breger 1989). These values, though approximate, tells us that all the
pulsational terms obtained from the frequency analysis should
be radial or nonradial \( p \)-modes; the possibility that they are
nonradial \( g \)-modes is very unlikely.

The \( Q \) values can also be compared with the theoretical ones
predicted for a star with similar physical parameters (see e.g.
the model 2.0m50 by Fitch, 1981). Making allowance for the
uncertainties, we can see that there are several radial or nonradial
modes that can account for these \( Q \)-values. All that we can be
said is that these modes should have \( n \geq 2 \).

The difficulty in mode typing is increased by the fact that
this star has a high \( v \sin i \) (110 km s\(^{-1}\)), as we cannot neglect
the resulting frequency shift and the splitting of the pulsational
modes as measured in the observer’s reference frame. We made
several tests following Saio’s (1981) procedure, adopting values
between 6 and 10 c d\(^{-1}\) as rest frequencies, assuming for the
star the physical parameters given above and the plausible fact that,
given the quite high \( v \sin i \) value, the star is probably viewed
almost equator on. The results were quite instructive and as an
example we report in Table 5 the multiplets we found in two typi-
cal cases assuming 6.0 and 10.0 c d\(^{-1}\) as rest frequencies and
two \( p \)-modes with \( n = 1, \ell = 2 \) and \( n = 3, \ell = 3 \), respectively.
We see that the multiplets cover quite large frequency ranges,
in particular in the second case the multiplet almost covers the
complete range spanned by the observed terms and that some of
its terms bear a certain resemblance with the observed values.
We can also notice that the central values (corresponding to
\( n=0 \)) are largely shifted from the rest value.

These facts tell us that, on the one hand, the very complex
pulsational spectrum observed could result from the superposition
of few pulsational terms split by the high rotation, and that,
on the other hand, any attempt to typify modes through their \( Q 
\) values or their frequency ratios is hopeless.

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