The δ Scuti star BI Canis Minoris (≡ HD 66853): pulsational behaviour and a critical discussion of physical parameter determination*

L. Mantegazza\textsuperscript{1} and E. Poretti\textsuperscript{2}
\textsuperscript{1} Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Via Bassi 6, I-27100 Pavia, Italy
INTERNET: mantegazza@vaxpv.pv.infn.it
\textsuperscript{2} Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-22055 Merate, Italy
INTERNET: poretti@astmim.mi.astro.it

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Abstract. A two site photometric campaign on the δ Scuti star BI CMi (2302 V observations over 16 nights) has allowed us to detect unambiguously four pulsation frequencies (\(\nu_1=8.246\), \(\nu_2=8.865\), \(\nu_3=7.433\) and \(\nu_4=8.515\) c/d) with amplitudes between 22 and 5 mmag. The data also show the presence of the nonlinear coupling term \(\nu_1 + \nu_2\), the \(2\nu_1\) term and the possible presence of two other frequencies with amplitudes of 2–3 mmag. Other components with further smaller amplitudes are probably present, but the data do not allow reliable identifications. We discuss the identification of the pulsation modes in terms of nonradial p modes, and we also point out the uncertainties on these identification associated to the physical parameter estimates.

The possible microvariability of HD 67028, one of the two comparison stars, is also discussed.

Key words: methods: data analysis – techniques: photometric – δ Scu – stars: individual: HD 66853 – stars: individual: HD 67028 – stars: oscillations

1. Introduction

The light variability of BI CMi(≡ HD66853 ≡ SAO116327 ≡ BD + 2°1867) was discovered by Kurpinski & al. (1988), who used it as a comparison for the study of the eclipsing binary YY CMi. The star showed a light curve with a changing shape and a maximum amplitude of about 0.1 mag. The authors derived a period of 0.119466 d (8.371 c/d) from the times of maxima, and both from the light curve characteristics and from the spectral type they classified it as a δ Scuti star. Since according to these data the star is a medium amplitude δ Scuti variable with a dominant frequency, we decided to put it into our observing program (Poretti & Mantegazza 1992).

2. Observations

BI CMi has been observed in a two site campaign from European Southern Observatory (La Silla, Chile) and from Merate Observatory (Italy) in the period January 16–February 5, 1991. The ESO observations cover 14 consecutive nights (from J.D. 2448280 to JD 2448293) while the Merate ones are distributed over 8 nights (from J.D. 2448273 to J.D. 2448291). We have contemporaneous observations from the two sites for 5 nights; in these nights we were able to monitor the star consecutively for almost 12 hours. Since on these nights there is a partial superimposition of the observations from the two sites for almost two hours, it was possible to get an excellent alignment between the two data sets.

We have done differential photometry in the V band with respect to two comparison stars: HD 66925 (CP) and HD 67028 (CK) following the cycle: CP-BI-CK-CP. Since the eclipsing binary YY CMi falls in the field of the variable, we also included this star too in the observing sequence one time each five cycles. The data regarding YY CMi will be published elsewhere. As a result we obtained 2032 differential measurements of BI CMi with respect to HD 66925 (1390 from La Silla and 642 from Merate).

The comparison of the differential magnitudes between CP and CK has shown, as expected, a different accuracy between the data gathered at La Silla and at Merate: the former have a mean standard deviation of 4.4 mmag for each measurement, against 8.6 mmag for the latter. The latter value is quite high due to the unfavourable declination of the variable star with respect to the latitude of Merate Observatory. However the Merate observations proved very useful in the subsequent data analysis because they considerably improved the spectral window and the frequency resolution.
Fig. 1. Differences of V magnitudes between Bi CMi and HD 66925 for the nights with observations from Merate Observatory only. The solid line represents the fit of the data with the four sinusoid model.

In Sect. 5 the probable presence in the light curve of HD 67028 of a microvariability with an amplitude of about 1 mmag will be discussed. During the first two nights of the La Silla observations, HD 66829 was used as a check star. This star proved to be stable within a few mmag.

Both the magnitude differences Bi CMi minus HD 66925 and the magnitude differences HD 67028 minus HD 66925 have been deposited in the Comm. 27 IAU Archives of Unpublished Observations, File 263E. They can also be requested from the authors.

Figures 1, 2 and 3 show respectively the observations of Bi CMi for the 3 nights with measurements from Merate Observatory only, for the 5 nights with measurements from both sites, and for the 9 nights with measurements from La Silla Observatory only.

3. Data analysis

The frequency analysis was performed by means of the least-squares power spectrum defined by Vaniček (1971), which is

Fig. 2. Differences of V magnitudes between Bi CMi and HD 66925 for the nights with observations from both the two sites. The solid line represents the fit of the data with the four sinusoid model.
particularly suited for the study of multiperiodic light curves (Antonello et al. 1986; Andreasen 1987; Mantegazza et al. 1993) because it avoids performing any data prewhitening.

This analysis has allowed us to unambiguously identify and extract four frequencies: $\nu_1=8.246$, $\nu_2=8.865$, $\nu_3=7.433$ and $\nu_4=8.515$ c/d. The corresponding power spectra are shown in Fig. 4, where the spectra, even if computed in the interval 0–30 c/d, are shown up to 20 c/d only for clarity. Please note also that the ordinate scales are different for each spectrum, and that for each panel they indicate the fractional reduction of the residual variance, i.e. they are normalized with respect to the variance left after the removal of the previously detected periodic components.

These four frequencies can explain most of the data variance (about 89.0% of all the data, and 91.8% of La Silla data), but only part of the residual variance is attributable to noise. The rms residual on the La Silla data is 6.2 mmag, while the one expected from white noise level is of 4.4 mmag. This is also seen in the last panel of Fig. 4 where the four frequencies have been given as known constituents; even if the highest peaks cannot explain more than about 5% of the residual variance, however there is considerably more power at frequencies below 20 c/d than at higher values.

If we push forward the spectral analysis we find that there are several components with semi-amplitudes between 2–2.5 mmag. Following the order according to which they are detected in the successive spectra they are: 11.27, 0.66, 9.44, 17.10, 16.50 and 0.15 c/d. The 9.44 c/d peak has an alias with almost the same height at 10.44 c/d.

In order to check this result the data were analyzed with the CLEAN algorithm (Roberts et al. 1987). We would like here to emphasize the fact that we consider this algorithm less reliable than the multiple least square sinusoid fitting for the analysis of complicate multiperiodic time series such as those generated by $\delta$ Scuti stars. This is because of its entirely automatic iterative data deconvolution, which in some cases can lead to the splitting of one mode power among two or more 1 c/d aliases. However, it can supply a useful independent check of the results obtained with the least squares method.

The two first panels of Fig. 5 show the spectrum after the deconvolution from the window, the second panel has been added to show the low amplitude components. We can see that the re-
The result is almost identical to the one derived from the least-square analysis. The four dominant terms coincide, and among the lower amplitude peaks in the CLEAN spectrum there are the following previously found with the other technique: 0.15, 0.66, 10.44 (alias of 9.44), 11.27 and 17.10 c/d, and 16.50 c/d. We can see that among the low amplitude terms the one at 16.499 c/d is very close to the first Fourier harmonic of the dominant term (≈ 2 × 8.246), while the one at 17.100 c/d is coincident within the uncertainties with the non-linear coupling term between the two strongest modes (≈ 8.246 + 8.865). We can say nothing certain about the two low frequency terms: the one close to 0.66 c/d could be connected to the non-linear coupling between the two strongest modes (ν_2 - ν_1 = 0.62 c/d); however since some low frequency noise is also present in the spectrum derived from the differential magnitudes of the two comparison stars (see lower panel of Fig. 5) these terms could be ascribed both to noise due to atmospheric effects or to the comparison star. A strong hint that at least part of the low frequency power can be due to noise effects is got from the fact that by analyzing the La Silla data only, even if there is again some power in this spectral region, its contribution to the total data variance is considerably lower than when considering the whole dataset (i.e. the one also including Merate observations).

A least squares fit of the La Silla data with the above mentioned ten components gives a rms residual of 5.36 mmag (6.53 mmag for the whole sample), which is again too high, and suggests the presence of several further components with amplitudes below 2 mmag. The least squares solution for all these frequencies is summarized in Table 1, where they are listed in order of detection (which does not necessarily coincide with the order of the amplitudes). Finally the observations with the interpolating light curve are shown in Figs. 1, 2 and 3. The interpolating curves have been computed with the 4 dominant frequencies only; the addition of other terms only supplies marginal graphical improvements.

In order to test the significance of the low amplitude components we performed the conservative test proposed by Breger et al. (1992), i.e. from the amplitude spectrum of the residuals obtained by prewhitening for the components listed in Table 1 we derived a noise amplitude of 0.344 mmag from the average amplitude in the 20–30 c/d range, which seems quite free from other components. The ratios between the amplitude of each component and that of the noise is reported in column 4 of Table 1. According to Breger & al. (1992) if this ratio is larger than 4.0 there is quite a large probability that the corresponding component is due to pulsation. We can see that all the selected
Table 1. Multifrequency solution for BI CMi

<table>
<thead>
<tr>
<th>Frequency c/d</th>
<th>Ampl. mmag</th>
<th>S/N</th>
<th>Epoch (HJD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.246</td>
<td>95.44</td>
<td>22.0</td>
<td>63.9</td>
</tr>
<tr>
<td>8.865</td>
<td>102.60</td>
<td>18.9</td>
<td>54.9</td>
</tr>
<tr>
<td>7.433</td>
<td>86.03</td>
<td>5.5</td>
<td>16.0</td>
</tr>
<tr>
<td>8.515</td>
<td>98.55</td>
<td>5.3</td>
<td>15.4</td>
</tr>
<tr>
<td>11.269</td>
<td>130.43</td>
<td>2.8</td>
<td>8.1</td>
</tr>
<tr>
<td>0.659</td>
<td>7.63</td>
<td>1.8</td>
<td>5.2</td>
</tr>
<tr>
<td>9.441</td>
<td>109.27</td>
<td>2.1</td>
<td>6.1</td>
</tr>
<tr>
<td>17.100</td>
<td>197.92</td>
<td>2.0</td>
<td>5.8</td>
</tr>
<tr>
<td>16.499</td>
<td>190.96</td>
<td>2.0</td>
<td>5.8</td>
</tr>
<tr>
<td>0.149</td>
<td>1.72</td>
<td>1.9</td>
<td>5.5</td>
</tr>
</tbody>
</table>

$\bar{V}_{BI\ space\ CMi} - V_{HD\ space\ 66925} = 2.4247$

Table 2. Standard colour indices

<table>
<thead>
<tr>
<th>Star</th>
<th>(b − y)</th>
<th>c1</th>
<th>m1</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>BI CMi</td>
<td>0.226</td>
<td>0.707</td>
<td>0.203</td>
<td>2.734</td>
</tr>
<tr>
<td>HD 66925</td>
<td>0.015</td>
<td>1.040</td>
<td>0.135</td>
<td>2.860</td>
</tr>
<tr>
<td>std. dev.</td>
<td>±0.005</td>
<td>±0.007</td>
<td>±0.005</td>
<td>±0.007</td>
</tr>
</tbody>
</table>

components pass this test, therefore they cannot be ascribed to random noise.

4. Pulsational model

4.1. $uvby\beta$ photometry and theoretical models

In order to discuss the pulsational characteristics of the star it is useful to know its physical parameters. To this end we get from La Silla some measurements during a few nights in the $uvby\beta$ system by observing it differentially with respect to 4 close standard stars chosen from the Catalogue of Hauck & Mermilliod (1990). The indices obtained after transformation into the standard system both for BI CMi and HD 66925 are reported in Table 2 with the estimated mean external standard deviations. From these colours and by means of Crawford’s (1979) calibration and using the codes kindly supplied by Dr. Dworetsky, we derived the following intrinsic colours for BI CMi: E(b − y) = 0.013, (b − y)0 = 0.213, c0 = 0.704, m0 = 0.207, $\delta m_1 = -0.028$. The value of $\delta m_1$ indicates the presence in the spectrum of metal line blocking similar to that of some $\delta$ Del or Am stars. Kurtz (1979) has shown that in such cases the c1 index is an inadequate luminosity indicator; however Guthrie (1987) has derived a correction to $\delta c_1$ in order to get correct absolute magnitudes in these cases too. The equation to be used is:

$$M_V = M_V(ZAMS, \beta) - f \cdot \delta c_1 + 0.1$$

where

$$\delta c_1 = c_0 - c_0(ZAMS, \beta) - 1.2 \delta m_1 - 1.1 \cdot 10^{-6} (V \ sin i)^2$$

and $f = 9.1$. The projected rotational velocity of BI CMi is unknown, but its contribution to $M_V$ is small, and we can neglect it.

At the same time Dworetsky & Moon (1986) have evaluated the correction to be added to the log g values obtained from their ($\beta, c_1$) grid (Moon & Dworetsky 1985), in order to get reliable gravities for stars with peculiar chemical abundances:

$$\log g = \log g(grid) + 3.442 \delta m_1$$

With these improvements we get the following physical parameters for BI CMi: $T_{eff} = 3852$, $\log g = 3.84$ and $M_V=2.03$ (corresponding to a spectral type F1 III-IV) and in turn $M_{bol}=2.04$ and $M = 1.35\ M_\odot$. This photometric mass is a bit low with respect to the evolutionary mass ($\geq 1.5\ M_\odot$, Straizis & Kuriliene 1980), but however compatible with it if we take into account all the uncertainties involved in its derivation. Starting from these parameters we can compute the pulsational constants associated to the various detected modes, and compare them with the theoretical ones. By doing this we discover that the four dominant modes could only be associated with non radial g modes (for example for the longest period mode we derive $Q=0.045\ d$, to be compared with the value of 0.033d expected for the fundamental radial mode). Similar modes are not frequent among the $\delta$ Scuti stars. To the authors’ knowledge there is only one object for which it has been suggested that they are excited: 63 Her (Mangeney et al. 1991). The same conclusion about the excited modes can be reached if we apply the empirical relationship derived by López de Cea et al. (1990) for the fundamental mode in $\delta$ Scuti stars:

$$\log v_0 = 0.300 M_{bol} + 3.195 \log T_{eff} - 11.90$$

which supplies $v_0 = 10.37\ c/d$ for BI CMi, to be compared with the shortest frequency found to be 7.43 c/d from our analysis. However this result may just be an artifact due to the uncorrected working of absolute magnitude calibration. In fact if we hypothesize that the shortest frequency corresponds to the fundamental radial mode and that the $T_{eff}$ estimate is reliable (being essentially based on the $\beta$ index which is only marginally sensitive to peculiar abundances), then $M_{bol}$ should be 1.56. In order to bring into consistency photometric, pulsational and evolutionary data (if we do not accept the possibility of $g$ modes) we should therefore decrease $M_{bol}$. We can check this result by means of Bell’s $uvby\beta$ synthetic colours, (Bell 1988; VandenBerg & Bell 1985) since we can see that the reddened colours of BI CMi are quite similar to those of the solar composition model with $T_{eff} = 7000\ K$ and $\log g = 3.75$. First of all we can see that the agreement between temperature and gravity derived from the Kurucz’s (on which the Moon & Dworetsky’s calibration is based) and Bell’s atmospheric models is quite good. We observe however that the $f$ coefficient derived by Bell is higher than the one used in equation (1). From Bell’s models we can estimate for $\beta = 2.734$: $M_V(ZAMS) = 3.18,$
to the uncertainties connected to the physical parameters it is difficult to give more precise identifications, in particular, since colour information is not available, the \( l \) values cannot be derived. However from the period ratios there is some evidence that these modes should have the same \( k \) value (probably close to 1) and different \( l \) values.

One could wonder if the three rather close components \( \nu_1, \nu_4 \)
and \( \nu_2 \) (i.e. 8.246, 8.515 and 8.865 c/d) could result from the
rotational splitting of the same nonradial mode \( \text{(same} \ l \ \text{but different} \ m \text{)} \). We notice that the observed separation between
adjacent lines increases with frequency, while from the rotational
splitting seen in the observer frame we should expect the opposite
behaviour. A possible explanation is that one line is missing
(i.e. its amplitude is too small to be observed). In such a case there
are several solution for these three lines \( \text{(e.g.} \ l = 2, m = 1, 0, -2; l = 2, m = 2, 1, -1; \text{and so on)} \), but none is able to fit all the
three frequencies within their observational accuracy. Hence the
presence of rotational splitting effects in the light curve of BI
CMi has yet to be proved.

As a conclusion we can say that among the four dominant
modes at least three should be nonradial, and they could be
ascribed to \( p \)-modes with \( k \approx 1 \) and probably with different \( l \)
values.

5. Light microvariability of HD 67028

If we look at the spectrum obtained from the magnitude
differences between the two comparison stars we can see that besides
the low frequency peaks there is also a relatively high peak at
19.322 c/d with an alias of about the same strength at 20.322
2/c/d. These peaks remain in the spectrum after the removal of
the low frequency signal, hence they could indicate the presence of
a weakly excited mode of HD 67028 (its semi-amplitude is of
1.1 mmag). We can see this peak in the CLEAN spectrum too
(see third panel of Fig. 5). We can attribute this peak to HD
67028 because in the spectrum of BI–CP data we have no peaks
of significant height at or around this frequency. We observe
that according to the criterion set by Breger et al. (1992) this
peak could be significant having a S/N amplitude ratio of about
4.4 (since we have a mean amplitude of the spectrum of 0.24
mmag in the region from 7 to 19 c/d).

From the Strömgren photometry of HD 67028 (Hauck &
Mermilliod 1990) we obtain the following physical parameters
\( \log T_{\text{eff}} = 3.912, \log g = 3.89 \) and \( M_V = 1.36 \); they place the
star close to the second overtone blue edge of the instability
strip (see e.g. Fig.1 by Fitch 1981). The physical characteristics
of this star are similar to those of HD 19279, a star in which
Mantegazza & Poretti (1993) have discovered a single pulsation
mode at 14.45 c/d with an amplitude of 2.0 mmag. From the
pulsational constant, assuming 19.32 c/d as the true frequency,
we can see that we could be in presence of the second or the
third radial mode.
6. Conclusions

The light curve analysis of BI CMi has allowed us to unambiguously evidence the presence of 4 pulsation modes. The dominant one is slightly non–sinusoidal and it is non–linearly coupled with the second one in strength. At least three of these 4 modes are nonradial p–modes, probably with different l values. Two more modes with smaller amplitudes have been detected and there is evidence that there should be other undetected modes with further smaller amplitudes.

While temperatures and gravities derived from different calibrations of the uvbyβ photometry supply comparable values, there seem to exist serious ambiguities on the calculation of the absolute magnitudes. Such ambiguities can lead to completely different mode identifications depending on the adopted calibration.

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