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Discovery of blue companions to two southern Cepheids: WW Car and FN Vel

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ABSTRACT
A large number of high-dispersion spectra of classical Cepheids were obtained in the region of the Ca II H + K spectral lines. The analysis of these spectra allowed us to detect the presence of a strong Balmer line, H\(\epsilon\), for several Cepheids, interpreted as the signature of a blue companion: the presence of a sufficiently bright blue companion to the Cepheid results in a discernible strengthening of the Ca II H + He\(\epsilon\) line relative to the Ca II K line. We investigated 103 Cepheids, including those with known hot companions (B5-B6 main-sequence stars) in order to test the method. We could confirm the presence of a companion to WW Car and FN Vel (the existence of the former was only suspected before) and we found that these companions are blue hot stars. The method remains efficient when the orbital velocity changes in a binary system cannot be revealed and other methods of binarity detection are not efficient.

Key words: binaries: spectroscopic – stars: individual: FN Velorum – stars: individual: WW Carinae – stars: variables: Cepheids.

1 INTRODUCTION
Classical Cepheids are radially pulsating F-G supergiants. Their regular variability makes them ideal standard candles in establishing the cosmic distance scale via the period–luminosity (\(P–L\)) relationship. The calibration of this relationship has a century-long history, and there is still need for improving the zero-point (Freedman & Madore 2010).

Cepheids which are members of binary systems can be suitable calibrators only if the luminosity of the Cepheid component can be disentangled from the luminosity of the companion star: if the companion remains unrevealed, its photometric effect can falsify the luminosity determination of the Cepheid. Because the incidence of binaries exceeds 50 per cent among classical Cepheids (Szabados 2003b), studying the binarity of individual Cepheids is an important task which is impeded by the fact that the companions are usually much fainter than the supergiant Cepheids.

Companions to Cepheids can be discovered by all conventional methods used for revealing binarity involving spectroscopy, photometry, and astrometry. There are some specific photometric methods only applicable for Cepheids summarized by Szabados (2003a).

Because most of the detectable companions are early-type main-sequence (or slightly more evolved) stars whose flux dominates the ultraviolet part of the binary spectrum, UV spectroscopy with the IUE satellite was especially successful in disclosing the binarity of Cepheids (Evans 1992). In the absence of UV spectra, there is a complementary method based on a specific portion of the optical spectrum for detecting blue secondary stars efficiently.

This method, referred to as the calcium-line method, is based on the spectrophotometry of the 3900–4000 Å part of the visible region. This interval covers the Ca II H (3968.47 Å) and the Ca II K (3933.68 Å) lines as well as the He\(\epsilon\) (3970.07 Å) line of the hydrogen Balmer series. The Ca II H and K lines in spectra of normal Cepheids without bright companions have practically equal depths (or residual flux). (We refer to the line profiles of Cepheids not accounting for narrow overlapping interstellar lines.) If, however, a hot companion is present, the He\(\epsilon\) line from the secondary star is superimposed on the Ca II H line and the resulting blend of these two lines is deeper than the Ca II K line (see Fig. 1). This technique of ‘intensity reversal’ was first used by Miller & Preston (1964a,b) for Cepheids. Later on, Evans (1985) showed that this method can be applied for detecting companions hotter than A3V spectral type stars.

In the last three decades this method was neglected. In view of the fact that there is no dedicated space mission for obtaining UV spectra, we decided to perform an optical spectroscopic survey of...
of telluric lines where necessary. The S/N exceeding that of the programme stars to enable cancellation in excess of 150. Each night we observed a broad-lined B star with an S/N value of 48 000. Typical maximum S/N values (per pixel) for the spectra are 10 000. The length range from 3800 to 8700 Å with a resolving power of about 50 000. The spectra cover a continuous wavelength range from 3800 to 8700 Å with a resolving power of about 48 000. Typical maximum S/N values (per pixel) for the spectra are in excess of 150. Each night we observed a broad-lined B star with an S/N exceeding that of the programme stars to enable cancellation of telluric lines where necessary.

We used IRAF to perform CCD processing, scattered light subtraction, and echelle order extraction. For these spectra two extractions were done, one uses a zero-order (i.e. the mean) normalization of the flat-field which removes the blaze from the extracted spectra. The second one uses a high-order polynomial to normalize the flat-field which removes the blaze from the extracted spectrum. The latter spectrum reflects more accurately the true counts along the orders. A Windows-based graphical package (ASP) developed by R. Earle Luck was used to process the blaze removed spectra. This included Beer’s law removal of telluric lines, smoothing with a fast Fourier transform procedure, continuum normalization, and wavelength calibration using template spectra. Echelle orders show significant S/N variations from edge to maximum due to blaze efficiency. To maximize the S/N in these spectra, we have co-added the order overlap region using as weights the counts from the second data extraction. The co-added spectra were then inspected and the continua sometimes modified by minor amounts in the overlap regions.

Table 1. Cepheids with anomalous profiles of the Ca II H + K lines.

<table>
<thead>
<tr>
<th>Cepheid</th>
<th>P (d)</th>
<th>(V)</th>
<th>Sp(Cep)</th>
<th>R_{KH}</th>
<th>Sp(comp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KN Cen</td>
<td>34.0296</td>
<td>9.87</td>
<td>G8.5ab</td>
<td>2.09</td>
<td>B6.0 V</td>
</tr>
<tr>
<td>V659 Cen</td>
<td>5.6218</td>
<td>6.60</td>
<td>F0/F7 Ib</td>
<td>1.61</td>
<td>B6.0 V</td>
</tr>
<tr>
<td>AX Cir</td>
<td>5.2733</td>
<td>5.88</td>
<td>F8II</td>
<td>1.67</td>
<td>B6.0 V</td>
</tr>
<tr>
<td>BP Cir</td>
<td>2.3984</td>
<td>7.56</td>
<td>F2/F3II</td>
<td>1.27</td>
<td>B6.0 V</td>
</tr>
<tr>
<td>V1334 Cyg</td>
<td>3.3350</td>
<td>5.87</td>
<td>F1III</td>
<td>1.86</td>
<td>B7.0 V</td>
</tr>
<tr>
<td>S Mus</td>
<td>9.6599</td>
<td>6.12</td>
<td>F6.0</td>
<td>1.44</td>
<td>B3.5 V</td>
</tr>
<tr>
<td>SY Nor</td>
<td>12.6457</td>
<td>9.51</td>
<td>F9.0</td>
<td>1.92</td>
<td>B4.5 V</td>
</tr>
<tr>
<td>V636 Sco</td>
<td>6.7968</td>
<td>6.65</td>
<td>F7/F8II</td>
<td>1.29</td>
<td>B9.5 V</td>
</tr>
</tbody>
</table>

New binaries:
- WW Car 4.6768 9.75 F9II 1.35 ?
- FN Vel 5.3242 10.29 F9II 1.42 ?

binary Cepheids, not all spectra show anomalous behaviour of the Ca II H + K lines, either because the companion is too faint, or it is of late spectral type.

3 EFFECT OF A BLUE COMPANION ON THE CA II H + K LINES

3.1 Cepheids with known blue companion

Cepheids with known blue companions have been selected from the list of Galactic Cepheids in binary systems (http://www.konkoly.hu/CEP/nagytab3.html). These target Cepheids are listed in the upper section of Table 1 whose subsequent columns give the name of the Cepheid, the pulsation period (in days), the mean V brightness, the spectral type of the Cepheid, the ratio of the residual fluxes defined below, and the spectral type of the blue companion. The relevant part of the observed spectra is shown in Fig. 2. It is clearly seen that the blend of the Ca II H and He lines is stronger than the Ca II K line.

To test the presence of a possible hot companion, we used the ratio of residual fluxes, \( R_{KH} = r(\lambda_2)/r(\lambda_1) \). A typical value of the ratio for Cepheids without hot companions is \( R_{KH} = 1.00 \pm 0.03 \). As expected, the ratios for the stars with known hot companions show larger values ranging from 1.29 to 2.09 (see Table 1).

3.2 Cepheids with newly revealed blue companion

A similar intensity reversal was searched for in the spectra of other Cepheids, and it was found that WW Car and FN Vel have a formerly unrevealed blue companion. Indeed, the \( r_1(K)/r_1(H) \) ratio has a value of 1.35 in the case of WW Car and of 1.42 in the case of FN Vel, well above 1.00. The basic data on these two Cepheid variables are listed in Table 2 and their spectra near the Ca II H+K lines are shown in Fig. 3.

4 DISCUSSION

All information on both WW Car and FN Vel available in the literature was collected for two main reasons, viz.:

(i) to find additional evidence of binarity;
(ii) to determine the accurate value of the pulsation period in order to calculate the phase of the spectral observation.

The updated period was determined by the O − C diagram method (Sterken 2005). The newly determined ephemerides can be used when planning any future observations of these Cepheids.
Figure 2. Spectra of eight classical Cepheids with known B type companion in the region of the Ca II H+$\lambda$K lines.

Table 2. New binary Cepheids with blue companions. The accurate value of the pulsation period (col. 2) is from Section 4. The Julian Date of the spectral observation (col. 7) and the corresponding phase (col. 8) have been calculated from the newly determined ephemerides. The mean $V$ brightness (col. 3) and $B-V$ colour index (col. 4) in the Johnson photometric system are from Berdnikov, Dambis & Vozyakova (2000); the colour excess, $E(B-V)$ (col. 5) and the atmospheric iron content $[\text{Fe/H}]$ (col. 6) are both from Luck et al. (2011).

<table>
<thead>
<tr>
<th>Cepheid</th>
<th>Period (d)</th>
<th>$\langle V \rangle$ (mag)</th>
<th>$\langle B-V \rangle$ (mag)</th>
<th>$E(B-V)$ (mag)</th>
<th>$[\text{Fe/H}]$</th>
<th>JD 240 0000+</th>
<th>phase</th>
<th>Exp. (s)</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW Car</td>
<td>4.676 818</td>
<td>9.748</td>
<td>0.899</td>
<td>0.379</td>
<td>−0.07</td>
<td>552 82.603</td>
<td>0.849</td>
<td>1200</td>
<td>218</td>
</tr>
<tr>
<td>FN Vel</td>
<td>5.324 170</td>
<td>10.292</td>
<td>1.186</td>
<td>0.588</td>
<td>0.06</td>
<td>552 83.591</td>
<td>0.224</td>
<td>2100</td>
<td>251</td>
</tr>
</tbody>
</table>

All published photometric observations of WW Car and FN Vel were re-analysed in a homogeneous manner to determine seasonal moments of the chosen light-curve feature. The relevant data listed in Tables 3 and 4, respectively, are as follows.

(i) Column 1: the heliocentric moment of the selected light-curve feature (moment of maximum brightness);
(ii) Column 2: the epoch number, $E$, as calculated from equations (1) and (2), respectively:

$C = 2453.047.7725 + 4.676.818 \times E$

$\pm 0.0032 \pm 0.000002$

(1)

$C = 2453.775.6587 + 5.324.170 \times E$

$\pm 0.0022 \pm 0.000005$

(2)

(These ephemerides have been obtained by the weighted linear least-squares fit to the $O-C$ differences for both Cepheids);

(i) Column 3: the corresponding $O-C$ value;
(ii) Column 4: the weight assigned to the $O-C$ value (1, 2, or 3 depending on the quality of the light curve leading to the given difference);
(iii) Column 5: the source of the data.

4.1 WW Carinae

The variability of WW Carinae was discovered by Henrietta Leavitt (Pickering 1906). The period determined somewhat later by Arville Walker (Pickering 1912), $P = 4.676$ d, is correct but no type of variability was assigned to the star. Szlagowski (1926) published a series of photographic observations covering the years 1924–1926. In his paper, WW Car is already considered as a Cepheid. The available photoelectric and more recent CCD photometric data involve those by Walraven, Muller & Oosterhoff (1958), Irwin (1961), Pel (1976), Pojmanski (2002), Berdnikov (2008), as well as the observations by the Hipparcos satellite (ESA 1997), and Optical Monitoring
are listed in Table 3. The brightness of WW Car have been obtained from the ephemeris 1, −1, and the O−C values of WW Car (see the description in the text).

Table 3. O−C values of WW Car (see the description in the text).

<table>
<thead>
<tr>
<th>JD⊙</th>
<th>E</th>
<th>O−C</th>
<th>W</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>240 0000 +</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>238 91.5175</td>
<td>−6234</td>
<td>0.0284</td>
<td>1</td>
<td>Szeligowski (1926)</td>
</tr>
<tr>
<td>242 85.4022</td>
<td>−6150</td>
<td>0.0604</td>
<td>1</td>
<td>Szeligowski (1926)</td>
</tr>
<tr>
<td>346 72.5746</td>
<td>−3929</td>
<td>0.0200</td>
<td>1</td>
<td>Walraven et al. (1958)</td>
</tr>
<tr>
<td>352 38.4720</td>
<td>−3808</td>
<td>0.0224</td>
<td>2</td>
<td>Irwin (1961)</td>
</tr>
<tr>
<td>410 47.0296</td>
<td>−2566</td>
<td>−0.0279</td>
<td>3</td>
<td>Pel (1976)</td>
</tr>
<tr>
<td>443 72.2203</td>
<td>−1855</td>
<td>−0.0548</td>
<td>3</td>
<td>Berdnikov (2008)</td>
</tr>
<tr>
<td>482 49.3296</td>
<td>−1026</td>
<td>−0.0276</td>
<td>3</td>
<td>Hipparcos (ESA 1997)</td>
</tr>
<tr>
<td>487 17.0190</td>
<td>−926</td>
<td>−0.0200</td>
<td>3</td>
<td>Hipparcos (ESA 1997)</td>
</tr>
<tr>
<td>505 78.3901</td>
<td>−528</td>
<td>−0.0225</td>
<td>3</td>
<td>Berdnikov (2008)</td>
</tr>
<tr>
<td>519 48.7159</td>
<td>−235</td>
<td>−0.0044</td>
<td>3</td>
<td>ASAS (Pojmanski 2002)</td>
</tr>
<tr>
<td>523 69.6325</td>
<td>−145</td>
<td>−0.0014</td>
<td>3</td>
<td>ASAS (Pojmanski 2002)</td>
</tr>
<tr>
<td>527 29.7555</td>
<td>−68</td>
<td>0.0066</td>
<td>3</td>
<td>ASAS (Pojmanski 2002)</td>
</tr>
<tr>
<td>530 47.7826</td>
<td>0</td>
<td>0.0101</td>
<td>3</td>
<td>ASAS (Pojmanski 2002)</td>
</tr>
<tr>
<td>531 50.6862</td>
<td>22</td>
<td>0.0237</td>
<td>3</td>
<td>INTEGRAL OMC</td>
</tr>
<tr>
<td>534 54.6642</td>
<td>87</td>
<td>0.0085</td>
<td>3</td>
<td>ASAS (Pojmanski 2002)</td>
</tr>
<tr>
<td>537 96.0799</td>
<td>160</td>
<td>0.0165</td>
<td>3</td>
<td>ASAS (Pojmanski 2002)</td>
</tr>
<tr>
<td>542 02.9568</td>
<td>247</td>
<td>0.0103</td>
<td>3</td>
<td>ASAS (Pojmanski 2002)</td>
</tr>
<tr>
<td>542 12.3011</td>
<td>249</td>
<td>0.0009</td>
<td>1</td>
<td>INTEGRAL OMC</td>
</tr>
<tr>
<td>545 35.0003</td>
<td>318</td>
<td>−0.0003</td>
<td>3</td>
<td>ASAS (Pojmanski 2002)</td>
</tr>
<tr>
<td>548 76.4254</td>
<td>391</td>
<td>0.0171</td>
<td>3</td>
<td>ASAS (Pojmanski 2002)</td>
</tr>
<tr>
<td>549 18.5119</td>
<td>400</td>
<td>0.0122</td>
<td>3</td>
<td>INTEGRAL OMC</td>
</tr>
<tr>
<td>553 18.1264</td>
<td>494</td>
<td>0.0058</td>
<td>3</td>
<td>AA VSO</td>
</tr>
</tbody>
</table>

The moment of maximum brightness was determined for each star. Even the F0 spectral type given by the SIMBAD data base might be incorrect for a genuine Cepheid variable. In addition to the five radial velocity measurements obtained in 1983 (Pont et al. 1994), the atmospheric composition was studied by Luck et al. (2011), Luck & Lambert (2011), and Usenko et al. (2011).

4.2 FN Velorum

The brightness variability of FN Velorum was revealed by O’Connell (1951). He already classified this variable as a Cepheid and published a correct period. Then this Cepheid had been neglected for decades. More recent photometric data are available from the Hipparcos mission (ESA 1997), the ASAS sky survey (Pojmanski 2002), and the data base containing Berdnikov’s photometric observations of Cepheids (Berdnikov 2008). The seasonal normal maxima listed in Table 4 have been determined from these data. The O−C diagram is plotted in Fig. 5. The plot can be approximated by a constant period corresponding to the ephemeris 2 for the moments of the maximum brightness. The scatter of the points in Fig. 5 reflects the observational error and uncertainties in the analysis of the data.

Spectroscopic observations of FN Vel started only recently. Luck et al. (2011) studied the atmospheric chemical composition and determined [Fe/H] = +0.06. Moreover, Anderson (2013) revealed that FN Vel belongs to a spectroscopic binary system, and even the
spectroscopic orbit could be successfully determined from his own extensive radial velocity measurement series. The orbital period of the binary system is 471.654 d. This spectroscopic binarity is a strong evidence of the reliability of the method for binarity detection applied in this paper.

5 CONCLUSION

We used the so-called calcium-line method to investigate the presence of hot blue companions to 103 southern Cepheids. In this method, the strong Balmer line, $H_\epsilon$, of the companion superimposes on the Ca II H line of the Cepheid, resulting in the strengthening of the Ca II H line with respect to the Ca II K line in the compound spectrum of the binary system. (The Ca II H & K lines have practically equal depths in single Cepheids.)

The method allowed us to recover eight Cepheids with known blue companions in our sample and led to the discovery of hot companions for two more Cepheids, WW Car and FN Vel. In the case of FN Vel, this is an independent confirmation of binarity published by Anderson (2013) in his PhD thesis. WW Car has also been suspected in having a blue companion from photometry (Madore & Fernie 1980).

As Cepheids are used as standard candles in determining the cosmic distance scale, it is important to disentangle the luminosity of the Cepheids from that of their companion when calibrating the $P$-$L$ relationship. Therefore, the binarity of Cepheids should be studied on a star-by-star basis.

ACKNOWLEDGEMENTS

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REFERENCES

Berdnikov L. N., 2008, VizieR Online Data Catalog: II/285
ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Miller J., Preston G., 1964a, PASP, 76, 47
O’Connell D. J. K., 1951, Publ. Riverview Coll. Obs., 2, 100
Pocci E. G., 1976, A&AS, 24, 413
Pickering E. C., 1906, Harvard Circ., No. 115, 1
Pickering E. C., 1912, Harvard Circ., No. 170, 6

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