Absolute properties of BG Ind – a bright F3 system just leaving the main sequence*

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ABSTRACT

We present photometric and spectroscopic analysis of the bright detached eclipsing binary BG Ind. The masses of the components are found to be $1.428 \pm 0.008$ and $1.293 \pm 0.008 M_\odot$ and the radii to be $2.290 \pm 0.017$ and $1.680 \pm 0.038 R_\odot$ for primary and secondary stars, respectively. Spectra and isochrone fittings coupled with colour indices calibration yield $[\text{Fe/H}] = -0.2 \pm 0.1$. At an age of $2.65 \pm 0.20$ Gyr, BG Ind is well advanced in the main-sequence evolutionary phase – in fact, its primary is at TAMS or just beyond it. Together with three similar systems (BK Peg, BW Aqr and GX Gem), it offers an interesting opportunity to test the theoretical description of overshooting in the critical mass range $1.2–1.5 M_\odot$.

Key words: binaries: eclipsing – stars: evolution – stars: fundamental parameters.

1 INTRODUCTION

The 6th magnitude star BG Ind was classified as an F3 dwarf by Malaroda (1975), and several years later it was established as an eclipsing binary by Manfroid & Mathys (1984) and Mathys, Manfroid & Renson (1986), who, based on $u_b v_y$ data from 1984, identified it as a detached system with partial eclipses and a period of 1.464 047 d. The first radial velocity measurements of BG Ind were performed by Andersen, Jensen & Nordström (1984). Although their data were rather scarce (just two spectra), the resulting estimates of masses and radii of the components ($m_1 \sim 1.4 M_\odot$, $R_1 \sim 2.0 R_\odot$ and $m_2 \sim 1.2 M_\odot$, $R_2 \sim 1.5 R_\odot$) proved to be remarkably accurate. Additional Strömgren photometry was collected in 1986 by Van Hamme & Manfroid (1988; hereafter VHM) who also solved the $v_b v_y$ light curves of the system and found an improved value of the period ($P = 1.464 069$ d). For the fixed mass ratio $q = 0.85$ taken from Andersen et al. (1984), they obtained $m_1 = 1.41 M_\odot$, $R_1 = 2.22 R_\odot$ and $m_2 = 1.20 M_\odot$, $R_2 = 1.60 R_\odot$.

Revised data of Mathys et al. (1986) and VHM, together with additional points from 1987, were catalogued by Manfroid et al. (1991) and Sterken et al. (1993) as a part of the ‘Long Term Photometry of Variables’ programme conducted at European Southern Observatory (ESO). BG Ind was monitored by Hipparcos satellite (Perryman et al. 1997) and robotic telescopes ASAS (Pojmanski 2001) and Pi of the Sky (Małek et al. 2010); it is also included in ‘The Geneva-Copenhagen survey of the solar neighbourhood’ (Holmberg, Nordström & Andersen 2009). Recently, a spectroscopic solution of BG Ind based on data collected in 2006 has been published by Bakış et al. (2010), who for $P = 1.464 069$ d and $i = 74.14$ found by VHM obtained $m_1 = 1.47 \pm 0.01 M_\odot$, $m_2 = 1.31 \pm 0.01 M_\odot$, and a semimajor axis $a = 7.64 \pm 0.04 R_\odot$.

With so much data available, BG Ind may seem to be well explored and hence of little interest. However, there are at least three reasons to investigate it more thoroughly than in the papers mentioned above. First, VHM encountered problems with phasing, and they recommended ‘further monitoring of this binary system for minimum times in order to obtain improved ephemeris, and to allow a study of the behaviour of its orbital period’. Secondly, systemic radial velocity measurements gave diverging results: $v_r = 39.8 \pm 4$ km s$^{-1}$ (VHM) and $59.4 \pm 5$ km s$^{-1}$ (Bakış et al. 2010). To make the confusion even larger, from the three velocity components of BG Ind with respect to the Sun listed by Holmberg et al. (2009) in the recent version of their GCS catalogue (cdsarc.u-strasbg.fr/viz-bin/Cat?V/130&) one obtains a total velocity of 20.3 km s$^{-1}$.

Thirdly, and most importantly, both components of BG Ind belong to the interesting mass range of $1.2–1.5 M_\odot$ in which convective cores begin to develop, affecting evolutionary tracks and isochrones via overshooting-related uncertainties. Moreover, their masses are remarkably similar to those of BK Peg – a main-sequence binary recently studied by Clausen et al. (2010). Since the metallicity is

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similar in both cases, and smaller stellar radii observed in BK Peg ($R_1 = 1.987 \pm 0.008 R_\odot$, $R_2 = 1.473 \pm 0.017 R_\odot$) indicate a slightly less advanced evolutionary stage, these two systems are a potential source of valuable information concerning the end phases of core hydrogen burning in stars somewhat more massive than the Sun. Bearing this in mind, we decided to re-analyse BG Ind with the aim to determine its precise physical parameters and evolutionary status.

Our paper is based on photometric and spectroscopic data described in Section 2. The analysis of the data is detailed in Section 3, and its results are discussed in Section 4.

2 OBSERVATIONAL MATERIAL AND DATA REDUCTION

2.1 Photometry

Our photometric solutions are based on six sets of photometric measurements listed in Table 1, spanning a period from 1986 May to 2009 November [points with $\Delta m > 0.1$ mag, where $\Delta m$ stands for the deviation from the preliminary fit (see Section 3.2), were rejected from the original ASAS and Pi data sets]. We found that all photometric data from Table 1 neatly phase with the ephemeris

$$P = 1.46406335 \pm 0.0000002 d,$$

$$I_0 = \text{HJD} 24447876.3792 \pm 0.0004$$

(see Fig. A1 in Appendix A), and we are rather confident that the period of BG Ind remained constant for over 23 yr. The only indication suggesting a possible period change comes from the earliest observations of this system (runs 1 and 2 of VHM, not included in our analysis). To obtain the ephemeris, we first found $P$ using the analysis of variance method, and then we adjusted $I_0$ so as to maximize the symmetry of the minima with respect to phases 0.0 and 0.5.

Available online are also Hipparcos $B_T$ and $V_T$ light curves (Perryman et al. 1997), and Strömgren $u$ light curve of Manfroid et al. (1991) and Sterken et al. (1993). Their quality was too poor to use them for photometric solutions; however, $B_T$ and $V_T$ data yielded a useful estimate of the temperature of the hotter component (see Section 3.2). We note here that according to Suchkov, Makarov & Voges (2003), the Strömgren $(b - y)$ excess of BG Ind amounts to 0.001 only, so that reddening effects can be neglected.

| Label | Filter | First day | Last day | Number of data points |
|-------|--------|-----------|----------|-----------------------|
| MSb   | Strömgren $b$ | 44582 | 47070 | 165 |
| MSv   | Strömgren $v$ | 46382 | 47070 | 172 |
| MSy   | Strömgren $y$ | 46582 | 47070 | 172 |
| HipH  | Hipparcos $H$ | 47888 | 49054 | 142 |
| ASV   | Johnson $V$ | 51997 | 55167 | 576 |
| PiR   | Cousins $R$ | 53902 | 54933 | 828 |

References: 1 – Manfroid et al. (1991); 2 – Sterken et al. (1993); 3 – Perryman et al. (1997); 4 – Pojmanski (2001); 5 – Malek et al. (2010).

Pi of the Sky observations were done without filters, but the combined sensitivity of optical system and detector closely matched that of Cousins $R$ filter.

2.2 Spectroscopy

Because of problems with the systemic velocity of BG Ind mentioned in Section 1 we decided to use our own spectral data, collected in 2007 September/October with the fibre-fed Giraffe spectrograph on the 1.9-m Radcliffe telescope at the South African Astronomical Observatory. The seeing oscillated between 1.5 and 2.5 arcsec. A 2.7-arcsec entrance window provided a resolution of almost $R = 40000$ at $\lambda = 4470 \AA$. During the observations, pairs of scientific spectra were taken, separated by an exposure of a thorium–argon hollow-cathode lamp. The exposure times per spectrum ranged from 400 to 900 s.

The observations were reduced within the IRAF$^1$ ECHELLE package. After bias and flat-field correction, each pair of the frames was combined into a single frame, allowing for the rejection of cosmic ray hits. Altogether, 23 reduced spectra were obtained. For further analysis, a wavelength range extending from 4300 to 5800 Å was used, in which most of the spectra had $20 < S/N < 40$ with a few cases of lower quality.

Our method of radial velocity measurements, based on the broadening function formalism introduced by Rucinski (2002), is described by Kaluzny et al. (2006).$^2$ The spectrum of HD 200163 (spectral type F3V), obtained in the same observing period and with the same instrumental set-up, served as a template. The resulting barycentric radial velocities are listed in Table 2. The mean error, estimated from velocity-curve fitting, is $\pm 0.63$ km s$^{-1}$. The zero-point of the velocity scale was fixed by the velocity of HD 200163, equal to 4.6 km s$^{-1}$ (Wilson 1953).

Table 2. Barycentric radial velocities of BG Ind phased according to the ephemeris given by equation (1).

| HJD 2454000 | Phase | $v_1$ (km s$^{-1}$) | $v_2$ (km s$^{-1}$) |
|-------------|-------|---------------------|---------------------|
| 363.39889   | 0.833 | 134.234             | -83.756             |
| 363.420815  | 0.848 | 127.712             | -76.513             |
| 366.299933  | 0.808 | 142.702             | -91.436             |
| 368.315269  | 0.191 | -78.691             | 152.746             |
| 368.335724  | 0.205 | -83.175             | 157.484             |
| 368.365740  | 0.225 | -87.252             | 161.310             |
| 369.244426  | 0.825 | 136.888             | -85.218             |
| 369.263211  | 0.838 | 131.761             | -79.637             |
| 371.249086  | 0.195 | -80.656             | 153.364             |
| 371.266822  | 0.207 | -82.224             | 157.092             |
| 371.284471  | 0.219 | -85.197             | 159.509             |
| 371.315563  | 0.240 | -86.278             | 161.496             |
| 371.328299  | 0.249 | -86.007             | 162.845             |
| 371.344954  | 0.260 | -86.568             | 162.832             |
| 371.361949  | 0.272 | -85.781             | 160.540             |
| 371.379099  | 0.283 | -83.505             | 158.200             |
| 371.395454  | 0.295 | -82.164             | 157.302             |
| 371.412749  | 0.306 | -79.292             | 153.182             |
| 372.255302  | 0.882 | 112.450             | -57.583             |
| 372.275909  | 0.896 | 104.275             | -48.576             |
| 372.292410  | 0.907 | 96.605              | -41.796             |
| 372.308893  | 0.918 | 89.945              | -33.640             |
| 376.386726  | 0.221 | 144.054             | -92.932             |

Notes:

$^1$ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation (NSF).

$^2$ The software used in this paper is available at http://users.camk.edu.pl/pych/BF/

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The binary spectrum of BG Ind was disentangled using the code of Konacki et al. (2010) with the aim to estimate the temperature of the components. Unfortunately, because of strong rotational broadening and blending of the lines, the only method we could apply was a direct comparison to synthetic spectra (see Section 3.2).

3 ANALYSIS

The components of BG Ind have masses in the range 1.2–1.5 M\(_\odot\) (VHM; Bak\&ul et al. 2010), so that their envelopes should be convective. Consequently, we adopted gravity darkening exponents \(g_1 = g_2 = 0.32\) and bolometric albedos \(A_1 = A_2 = 0.5\). Just in case, we also obtained a solution with radiative envelopes \((g_1 = g_2 = A_1 = A_2 = 1.0)\) to find that all ‘radiative’ parameters but one did not differ by more than 0.1 per cent from the ‘convective’ ones. The exception was the radius of the primary \(R_1\) which in the radiative case was by 5.6 per cent smaller.

Since BG Ind is a short-period system, and broadening-function fitting yielded \(v\sin i\) values close to those expected from the synchronous rotation for the radii obtained by VHM, we assumed full synchronization of both components. The effects of reflection were included, and a logarithmic limb-darkening based on tables by Van Hamme (1993) was used as implemented in PHOEBE 0.31a.

According to Holmberg et al. (2009), the system is slightly underabundant in metals ([Fe/H] = −0.3). However, their estimate is based on Strömgren photometry of the total light, and as such it cannot be 100 per cent reliable. As for the temperatures of the components, VHM assumed \(T_1 = 7000\) K for the primary and obtained \(T_2 = 6450\) K for the secondary from the fit. While these values are certainly reasonable, they may be too high for the radii obtained by VHM which indicate that at least the primary is about to leave the main sequence or even has left it. Moreover, upon comparing our phased velocity curve with phased light curves from Table 1, we found that the hotter component of BG Ind is the secondary (see Fig. 1).\(^3\) The same conclusion follows from the velocities measured by Bak\&ul et al. (2010), which also nicely phase with ephemeris (1), showing, however, a much larger scatter (the rms residual from our fit to their data is 4.6 km s\(^{-1}\), only slightly larger than 4.4 km s\(^{-1}\) found in the original paper).

\(^3\) The misidentification of VHM is entirely understandable when one remembers that they had just two velocity measurements and only an approximate value of the period.

Thus, while searching for an observational estimate of the temperature of BG Ind components, we decided to focus on the secondary. As it rotates significantly slower than the primary and must be less evolutionarily advanced, we expected it to be a more or less normal main-sequence star to which available colour–temperature calibrations could be reliably applied.

3.1 Preliminary solutions

We started the analysis from searching for solutions with \(T_2\) equal to 7000, 6500 or 6000 K, and [Fe/H] equal to 0.0 or −0.3. We used PHOEBE interface (PrSa & Zwitter 2005) to the Wilson–Devinney code (Wilson & Devinney 1971), solving for all light curves simultaneously. The essential aim of preliminary calculations was to check how strongly the gravitational acceleration of the secondary \(g_2\) and the contributions of the secondary to the total light in various wavebands at \(\varphi = 0.25\) vary in this parameter range. As detailed in the next section, the first of those parameters was needed for an estimate of \(T_2\) based on our spectra, while the remaining were needed for an independent estimate of \(T_2\) based on calibrations of colour indices.

There is no indication for a non-zero eccentricity in either light or velocity curves, but we included iterations of \(e\), just in case. The solutions yielded \(e = 0.0 \pm 0.0005\) and an almost constant \(\log g_2 = 4.14\)–4.15. The primary’s acceleration \(g_1\) was almost constant, but smaller by a factor of 2, i.e. appropriate for the beginning of the subgiant branch rather than for the main sequence.

3.2 The temperature of the secondary

With \(g_2\) fixed, we generated an array of synthetic spectra for 6000 K \(\leq T \leq 7000\) K and \(−1 \leq [\text{Fe/H}] \leq 0\) based on the library of Coelho et al. (2005). The respective spacings \(\Delta T\) and \(\Delta [\text{Fe/H}]\) were equal to 100 and 0.1 K. All spectra were rotationally broadened with \(v\sin i = 78\) km s\(^{-1}\) for the primary and 53 km s\(^{-1}\) for the secondary, consistently with the mean values of \(i\) and component radii obtained from preliminary fits (3.7, 2.35 and 1.61 R\(_\odot\), respectively). Next, for each synthetic spectrum the sum of squared deviations from its observed counterpart was calculated. In the case of the secondary, the smallest sum was obtained for \(T_2 = 6500\) K and [Fe/H] = −0.2 (see Fig. A2 for a comparison of the best-fitting spectrum to the observed one). In the case of the primary, no unique minimum was found, for which broad and/or blended lines are probably to be blamed (e.g. Mg \(\text{I}\) lines at 5167 and 5173 Å were observed as a single spectral feature). We estimate the uncertainties of temperature and metallicity at ±100 and ±0.1 K, respectively.

In all preliminary solutions with [Fe/H] = 0, the secondary-to-primary luminosity ratio \(L_2/L_1\) (found from the contribution of each component to the total light of the system at \(\varphi = 0.25\)) was almost constant in each of \(b, v\) and \(y\) bands, amounting, respectively, to 0.570–0.573, 0.598–0.606 and 0.551–0.553. Given the total apparent magnitudes of BG Ind at \(\varphi = 0.25\), we used these ratios to calculate the corresponding apparent magnitudes of the secondary, and we found its temperature from \((b - y) - T_{\text{eff}}\) calibration of Casagrande et al. (2010). The result for [Fe/H] = 0.0 was a remarkably constant \(T_2 = 6523–6528\) K. Solutions with [Fe/H] = −0.3 were only slightly more diverging, with \(T_2 = 6477–6487\) K. After averaging, we got \(T_2 = 6525 \pm 63\) and 6483 \pm 63 K, respectively, where the error includes inaccuracies of colour–temperature calibration and magnitude measurement at \(\varphi = 0.25\).

Independent calibrations of Holmberg, Nordström & Andersen (2007) produce \(T_2 = 6438\) and 6394 K, which due to larger errors...
Table 3. PHOEBE solutions with $T_2 = 6650$ K and [Fe/H] = −0.2.

| Light curve | $\text{rms}$ (mmag) | $i$ (°) | $a$ ($R_\odot$) | $m_1$ ($M_\odot$) | $m_2$ ($M_\odot$) | $R_1$ ($R_\odot$) | $R_2$ ($R_\odot$) | $T_1$ (K) | $L_1$ ($L_\odot$) | $L_2$ ($L_\odot$) |
|-------------|---------------------|--------|-----------------|-----------------|-----------------|-----------------|-----------------|-------------|----------------|----------------|
| MSb         | 7.0                 | 72.95  | 7.567           | 1.428           | 1.293           | 2.313           | 1.651           | 6312        | 7.37           | 4.62          |
| MSv         | 7.5                 | 72.95  | 7.567           | 1.428           | 1.293           | 2.303           | 1.663           | 6320        | 7.34           | 4.69          |
| MSy         | 7.9                 | 73.00  | 7.565           | 1.427           | 1.292           | 2.165           | 1.796           | 6443        | 7.00           | 5.47          |
| HipH        | 6.4                 | 73.12  | 7.560           | 1.424           | 1.289           | 2.226           | 1.723           | 6382        | 7.13           | 5.04          |
| ASV         | 16.1                | 72.72  | 7.577           | 1.434           | 1.298           | 2.395           | 1.637           | 6375        | 8.22           | 4.55          |
| PiR         | 11.4                | 73.03  | 7.567           | 1.428           | 1.293           | 2.340           | 1.610           | 6262        | 7.30           | 4.39          |

\begin{equation}
\langle x \rangle = \frac{\sum_{j=1}^{6} x_j / \sigma_j^2}{\sum_{j=1}^{6} 1 / \sigma_j^2}
\end{equation}

and

\begin{equation}
\sigma^2 = \frac{1}{\sum_{j=1}^{6} 1 / \sigma_j^2}.
\end{equation}

The final parameters with their errors are listed in Table 4.

### 4 DISCUSSION AND CONCLUSIONS

In Section 1, we outlined three problems which prompted us to analyse BG Ind: variability of the period; doubtful systemic velocity and the spectroscopic solution were found using the Torres code. Because the Torres code requires centre of mass velocities on input, it was necessary to correct the observed light centre velocities for effects caused by the distortion of the components. Additive phase-dependent corrections were calculated using the Wilson–Devinney code; their values ranged from −0.86 to 0.27 km s$^{-1}$.

\textsc{jktebop} cannot deal with multiple light curves, so the final model fitting had to be performed separately for each of the photometric data sets listed in Table 1. We fixed $e = 0$ as indicated by preliminary solutions and started the final calculations from \textsc{phoebe} fits which produced six sets of parameters listed in Table 3 whose second column shows the rms deviation of observed points from the fit. Next, we calculated errors of inclination $i$ and relative radii of the components of $R_{1,2} = R_{1,2}/A$ using \textsc{jktebop}, and errors of $m_{1,2} \sin^2 i$ and $A \sin i$ using the Torres code. The errors were then transformed into errors of parameters returned by \textsc{phoebe} and assigned to respective \textsc{phoebe} solutions. Finally, weighted averages of \textsc{phoebe} parameters and the errors of those averages were found from the standard formulae

\begin{equation}
\langle x \rangle = \frac{\sum_{j=1}^{6} x_j / \sigma_j^2}{\sum_{j=1}^{6} 1 / \sigma_j^2}
\end{equation}

and

\begin{equation}
\sigma^2 = \frac{1}{\sum_{j=1}^{6} 1 / \sigma_j^2}.
\end{equation}

The final parameters with their errors are listed in Table 4.
lack of accurate parameters of the system. As mentioned in Section 2.1, we found that between 1986 and 2009 the period remained constant at 1.464 063 35 ± 0.000 000 02 d. The only indication that it might have changed comes from the earliest observations of BG Ind from 1981 and 1984 (runs 1 and 2 of VHM) which were not included in our data. As for the systemic velocity, our value of 31.2 ± 0.2 km s⁻¹ does not agree with any of those obtained by other authors. The value found by VHM (39.8 ± 4 km s⁻¹) was based on two measurements only, and its error was likely underestimated. 59.4 ± 5 km s⁻¹ of Bakš et al. (2010) is rather large for an F-type star in the Sun’s vicinity. The origin of such a large discrepancy with all remaining estimates is difficult to explain – we may only note that they did not observe any radial velocity standards, and it is conceivable that they reversed the sign of the heliocentric correction while reducing the data. Finally, according to the old version of the GCS catalogue (vizier.u-strasbg.fr/viz-bin/VizieR?-source=V per cent2F117A; marked as ‘obsoleted by V/130’), the low vₖₐₜ = 20.3 km s⁻¹ of Holmberg et al. (2009) results from just one velocity measurement, and as such it must have been contaminated by the orbital motion of the binary.

The parameters found in Section 3.3 are accurate enough for isochrone fitting. We used solar-scaled Dartmouth isochrones (Dotter et al. 2008) which include core overshooting defined as a product of the pressure scaleheight and a factor αₖₑₜ, which depends on stellar mass and composition (at nearly solar metallicities, it grows from 0.05 for 1.2 ≤ M ≤ 1.3 M⊙ through 0.1 for 1.3 < M ≤ 1.4 M⊙ to 0.2 for M > 1.4 M⊙). The convection itself is treated by mixing length parameter αₘᵢₓ = 1.938. What makes BG Ind particularly interesting is that the masses of the components fall at the beginning and at the end of the range where αₖₑₜ ramps up. First, we fitted isochrones calculated for −0.4 ≤ [Fe/H] ≤ 0 with a step of 0.1 to the most accurately determined parameters, i.e. masses and radii of the components.

We found that the respective ages were 2.27–2.43, 2.45–2.55, 2.60–2.67, 2.77–2.85 and 2.96–3.10 Gyr. Next, we checked how well these isochrones perform on M−log L and log Tₑₜ−log L planes. The best agreement was obtained for [Fe/H] = −0.2. The fit with [Fe/H] = −0.1 was almost equally good, that with [Fe/H] = −0.3 was still acceptable and those with [Fe/H] = 0 and −0.4 had to be rejected. Thus, the isochrone fitting confirmed our spectroscopic estimate of metallicity which we finally fixed at [Fe/H] = −0.2 ± 0.1. The corresponding age is 2.65 ± 0.20 Gyr.

The location of BG Ind on M−R, M−log L and log Tₑₜ−log L planes is shown in Fig. 2 together with \( t = 2.60 \) and 2.67 Gyr isochrones obtained for [Fe/H] = −0.2. One can see that the more massive primary has almost reached the beginning of the subgiant branch, while the secondary is still on its way to TAMS. The agreement between theoretical and observational data would be ideal if it were not for small discrepancies in \( R_2 \) and \( T_1 \) (by ∼3 and ∼1.5 per cent, respectively). The first one could originate from the fact that the eclipses of BG Ind are partial and the secondary is by almost 40 per cent smaller than the primary (and therefore less deformed). As a result, and because of rather poor quality of available photometric data, the accuracy of \( R_2 \) determination has to be somewhat lower than that of \( R_1 \). We turned our attention to the second discrepancy, at first glance rather insignificant, because it occurs precisely where the effects of overshoot treatment should be largest (the primary of BG Ind is a star with \( M > 1.4 M_\odot \) at TAMS). We decided to check if the same effect appears in other systems with similar masses and in similar evolutionary phase.

Based on a recent compilation of Clausen et al. (2010), we chose BW Aqr, BK Peg and GX Gem whose component masses range from 1.26 to 1.49 M⊙, and whose [Fe/H] indices are consistent with 0. The fitting of solar-scaled Dartmouth isochrones for [Fe/H] = 0 yielded respective ages of 2.15–2.45, 2.6–2.8 and 2.50–2.75 Gyr, placed roughly halfway between Yonsei–Yale and VRSS ages quoted in table 12 of Clausen et al. (2010). Figs 2 and 3 demonstrate that the temperature discrepancy, absent in the relativley unevolved secondary components of BG Ind and BK Peg, increases with the evolutionary advancement (whose best indicator is the distance from the sharp upturn of the isochrones on the M−log L plane) until it becomes clearly visible in GX Gem whose both components are at TAMS or have already left the main sequence. Note that luminosity errors are larger than those quoted by Clausen et al. (2010) – this is because we recalculated them according to the formula

\[
\delta \log L = \sqrt{\left(\frac{\delta R}{R}\right)^2 + \left(4 \frac{\delta T}{T}\right)^2}
\]

(4)
to make them consistent with ours.

The discrepancy is a 1σ effect and as such it may not be real; however, the fact that upon concluding their main-sequence phase all stars deviate consistently to the right from the best isochrones strongly suggests that there might be some physics behind. It is beyond the scope of our paper to identify physical factors or
Figure 3. Systems with similar evolutionary advancement as BG Ind. The lines are Dartmouth [Fe/H] = 0.0 isochrones for 2.60 and 2.80 Gyr (BK Peg), 2.10 and 2.45 Gyr (BW Aqr) and 2.45 and 2.70 Gyr (GX Gem).

assumptions potentially responsible for such effect. Whether anybody decides to look for them or not, improving the quality of photometric and spectroscopic solutions of all four systems is certainly a worthwhile task, although in the case of BG Ind it might prove rather difficult because of strong rotational broadening.

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APPENDIX A: LIGHT CURVES AND SPECTRUM OF BG IND

Figure A1. BG Ind light curves used in this paper (see Table 1 for the list), phased with ephemeris (1). Individual curves are normalized to magnitude 0 at maximum light. Phase 0 corresponds to the eclipse of the primary defined as the more massive component.

Figure A2. A section of the disentangled spectrum of the secondary (line) compared with the best-fitting synthetic spectrum, obtained for $T_{\text{eff}} = 6500$ K, $g = 4.15$, $[\text{Fe/H}] = -0.2$, and rotationally broadened with $v \sin i = 53$ km s$^{-1}$ (dots). The largest differences appear in deep lines and in overlap regions of echelle orders.

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