Photometry of four binary subdwarf B stars and the nature of their unseen companion stars

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ABSTRACT

We present light curves of four binary subdwarf B stars (sdB), Ton 245, Feige 11, PG 1432+159 and PG 1017–086. We also present new spectroscopic data for PG 1017–086 from which we derive its orbital period, 0.073 d, and the mass function, f_m = 0.0010 ± 0.0002 M⊙. This is the shortest period for an sdB binary measured to date. The values of P and f_m for the other sdB binaries have been published elsewhere. We are able to exclude the possibility that the unseen companion stars to Ton 245, Feige 11 and PG 1432+159 are main-sequence stars or subgiant stars from the absence of a sinusoidal signal, which would be caused by the irradiation of such a companion star, i.e. they show no reflection effect. The unseen companion stars in these binaries are likely to be white dwarf stars. In contrast, the reflection effect in PG 1017–086 is clearly seen. The lack of eclipses in this binary combined with other data suggests that the companion is a low-mass M-dwarf or, perhaps, a brown dwarf.

Key words: binaries: close – stars: horizontal branch – stars: individual: Feige 11 – stars: individual: Ton 245 – stars: individual: PG 1017–086 – stars: individual: PG 1432+159.

1 INTRODUCTION

Subdwarf B (sdB) stars dominate surveys for extremely blue stars brighter than B ≈ 16 (Green, Schmidt & Liebert 1986; Downes 1986; Kilkenny et al. 1997). Their effective temperatures (T_eff = 20 000–40 000 K) and surface gravities (log g = 5.5–6.5) place the majority of sdB stars on the extreme horizontal branch (EHB), i.e. they appear in the same region of the T_eff–log g plane as evolutionary tracks for core helium burning stars with core masses of ~0.5 M⊙ and extremely thin (~0.02 M⊙) hydrogen envelopes (Heber 1986; Saffer et al. 1994). The extremely low mass of the hydrogen envelope in sdB stars is thought to be caused by extensive mass loss when the star was a red giant near the tip of the red giant branch (RGB), i.e. just prior to ignition of helium in the degenerate helium core. If mass loss occurs while the red giant is near the tip of the red giant branch, the core can go on to ignite helium, despite the dramatic mass loss, and may then appear as an EHB star (d’Cruz et al. 1996). The cause of the extensive mass loss has been a matter of some debate, but a recent survey for short-period binary EHB stars by Maxted et al. (2001) has shown that in at least two out of three EHB stars, interactions with companion stars are responsible. In this scenario, the expanding red giant star comes into contact with its Roche lobe and begins to transfer mass to its companion star. This mass transfer is highly unstable, so a ‘common envelope’ forms around the companion and the core of the red giant. The drag on the companion orbiting inside the common envelope leads to extensive mass loss and dramatic shrinkage of the orbit (Iben & Livio 1993).

The properties of sdB stars, for example, their orbital period distribution, are a strong test of population synthesis models for binary stars because the common envelope phase that produced the sdB star must have occurred in a star with a degenerate helium core at the tip of the red giant branch. This places useful limits on the mass and radius of the star at the onset of the common envelope phase. Another property of these binaries which can, in principle, be compared with population synthesis models is the relative number of degenerate and non-degenerate companions, i.e. the fraction of sdB stars with main-sequence or subgiant companions compared with the fraction with white dwarf companions. In this paper we outline a simple method to determine the nature of the companion in practice and apply the method to four sdB binaries with known orbital periods.

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2 THE METHOD

In those cases where the companion to an sdB star is not seen directly in the optical spectrum, some other method must be found to determine the nature of the companion star. A sensitive method for detecting main-sequence or subgiant companions is to obtain an accurate light curve and to look for the effect of the irradiation of one side of the companion star by the hot sdB star. This produces an easily detectable signal with the same period as the orbital period with an approximately sinusoidal shape because the binary appears brightest when we see the irradiated hemisphere face-on and is fainter half an orbit later when we see more of the non-irradiated hemisphere. This sinusoidal distortion to the light curve is known as the reflection effect.

2.1 The reflection effect

It is useful to estimate the amplitude of the reflection effect we expect from a cool, faint companion to an sdB star using the following assumptions and approximations. If the sdB star has an effective temperature of $T_1$ and a radius of $R_1$, the flux intercepted by a companion star of radius $R_c$ at a distance $a$, is $\pi R_c^2 \sigma T_1^4 (R_1/a)^2$, where $\sigma$ is the Stefan–Boltzmann constant. If all of the irradiating flux is re-emitted by the heated face, the effective temperature of the heated face is $T_h = T_1 (R_1/\sqrt{2a})^{1/2}$, where we have assumed the intrinsic luminosity of the companion star to be negligible. The amplitude of the reflection effect at a given wavelength depends on the spectrum of the sdB star and the spectrum of the reprocessed light from the heated face of the companion star. The spectrum of the reprocessed light we observe will change with the orbital phase because the temperature varies across the heated face and the light will not be radiated isotropically from the heated face. The model we describe later takes account of these effects, but for the purposes of estimating the amplitude of the reflection effect we can calculate the maximum flux observed from the heated star using the approximation that it appears as a star of radius $R_h$ and effective temperature of $T_h$. For observations at most optical and near-infrared wavelengths, the Rayleigh–Jeans limit of a blackbody spectrum is a good approximation for the spectrum of the sdB star, i.e. the intensity is proportional to the effective temperature. In the case of strong irradiation, $T_h$ will also be sufficiently high for this approximation to apply to the spectrum of the heated face of the companion.

If we consider a binary, which is seen nearly edge-on but is not eclipsing, we find that the difference in magnitude when we see the irradiated and non-irradiated faces $\delta m$, is

$$\delta m = 2.5 \log_{10} \left[ 1 + \left( \frac{R_h}{R_1} \right)^2 \left( \frac{R_1}{\sqrt{2a}} \right)^{1/2} \right]$$

$$\approx \left( \frac{R_h}{R_1} \right)^2 \left( \frac{R_1}{a} \right)^{1/2}$$

if $\delta m$ is small.

Although this expression is approximate, it does enable us to estimate the amplitude of the reflection effect we might expect from an sdB star with a main-sequence companion. More importantly, it shows that $\delta m \propto R_h^2$, so a typical white dwarf with a radius of 0.01 $R_\odot$ will produce a reflection effect that is at least 100 times less than a typical M-dwarf with a radius of 0.1 $R_\odot$. The actual difference will be much larger than this if the white dwarf is not exceptionally cool but has a more typical effective temperature for white dwarfs of 10–20 000 K, because the temperature contrast between the heated and unheated hemispheres would then be much less. For example, an sdB star with $T_{\text{eff}} = 30 000$ K and a radius of 0.2 $R_\odot$, with a cool companion 1–$R_\odot$ distant ($P \sim 4$ h) will show a reflection effect of $\sim 0.1$ mag, which is easily detectable with differential charge-coupled device (CCD) photometry. In contrast, a white dwarf with a radius of 0.01 $R_\odot$ at the same distance gives rise to a reflection effect of no more than 0.001 mag. Even if the inclination of the binary reduced the amplitude of the reflection effect by an order of magnitude, it would be straightforward to distinguish the nature of the companions in these two hypothetical binary sdB stars using the presence or absence of a reflection effect in the light curve.

2.2 Our model

We have used a simple model to produce synthetic light curves for the sdB binaries we have observed, which is based on numerical integration over the visible surface of the heated star. The visible surface of the irradiated star is defined by a Roche potential. The effective temperature at the integration points on the heated face, $T_h$, is calculated from $T_h = (T_1^4 + f'(\alpha))^{1/4}$, where $T_1$ is the mean effective temperature of the unheated face and $f'$ is the irradiating flux over that region of the star allowing for the angle between the normal to the surface and the direction of the sdB star. The other parameters of our model are the radius of the sdB star in units of the orbital separation, $r_1$; the radius of the companion star in units of the distance between its centre and the inner Lagrangian point measured along the same axis (the filling-factor), $i$; the inclination of the orbit, $\hat{p}$; the mass ratio, $q = M_2/M_1$; the orbital period, $P$; the effective temperature of the sdB star, $T_1$. The observed flux at a given wavelength and orbital phase can then be estimated by assuming that both stars radiate as blackbodies. We also include limb darkening and gravity darkening in the calculation of the reflection effect. The details of the treatment of these effects in our model has a negligible effect on the predicted amplitude of the reflection effect so we do not describe them here. Our model does not include any contribution to the light curve caused by the distortion of the sdB star by its companion, i.e. the ellipsoidal effect from the sdB star is ignored. This effect is negligible for Ton 245, Feige 11 and PG 1432+159 but not for PG 1017–086.

Our calculation of the effective temperature over the surface of the companion star is equivalent to assuming that the bolometric albedo of the companion star, $\alpha$, is 1. There is good observational evidence for cool companions to hot subdwarf stars having high bolometric albedos, at least for short-period binaries. For example, Dorchsel et al. (2001) have presented B and R light curves of the eclipsing sdB star HS 0705+6700 which has an M-dwarf companion and an orbital period of $P = 2.3$ h. They used the Wilson–Devinney code (Wilson & Devinney 1971) to model the light curve and found that to achieve satisfactory fits to the light curves a value of $\alpha = 1$ was required. The fits were improved by using a value of $\alpha = 1.1$, which is unrealistic and is a consequence of using a monochromatic light curve model based on blackbody radiation to model broad-band light curves of an irradiated star where the spectrum is certainly very different to a blackbody. Our model is also affected by this problem. Similarly, Hilditch, Harries & Hill (1996) analysed the light curves of HW Vir, KV Vel (sdO + M, $P = 8.6$ h) and AA Dor (sdO + M, $P = 6.3$ h) with the light curve model LIGHT2 (Hill & Rucinski 1993) and also found $\alpha = 1$ or more is required to reproduce the reflection effect. Wood, Zhang & Robinson (1993) confirmed the requirement for a high albedo in HW Vir by using the Wilson–Devinney code to analyse their $UBVR$ light curves of HW Vir.
Although our model is quite simple, it is able to predict the amplitude of the reflection effect in sdB binaries with faint companions with an accuracy of ~50 per cent. To demonstrate this, we have calculated the amplitude of the reflection effect for two sdB stars with faint companions, HW Vir and PG 1336–018 and the sdOB binary V477 Lyr. These three stars are eclipsing binaries, so the properties of the stars can be determined independently. This is shown in Table 1, where we compare the observed amplitude of the reflection effect in the $V$ and $I$ bands, $\delta V$ and $\delta I$, to the values calculated using our model. We also list the properties of each binary in Table 1 that have the greatest effect on the values of $\delta V$ and $\delta I$ predicted by our model. In all three cases we see that the amplitude in the $V$ band is predicted correctly to within 50 per cent. For HW Vir where the amplitude has also been measured in the $I$ band, the amplitude predicted by our model agrees very well with the observed value.

### 3 Observations and Reductions

#### 3.1 Photometry

We used the 1-m Jacobus Kapteyn telescope (JKT) on the Island of La Palma to obtain $V$-band images and $I$-band images of PG 1432+159 (57 $V$ images, 52 $I$ images), Feige 11 (80 $V$ images, 85 $I$ images) and Ton 245 (29 $V$ images, 40 $I$ images) on the nights of 1998 August 2–10. Additional observations of Ton 245 (nine $V$ images and nine $I$ images) were acquired on the night of 1999 January 3. The detector used was a TEK charged-coupled device (CCD) with 1024 x 1024 pixels giving an image scale of 0.34 arcsec pixel$^{-1}$. Exposure times varied between 10 and 120 s and the deadtime between exposures was 60 s. We obtained 40 $V$-band images of PG 1017–086 with the same telescope using a STTe CCD with 2048 x 2048 pixels giving an image scale of 0.34 arcsec pixel$^{-1}$ on the night of 2001 May 3. The exposure times were 70 or 120 s and the deadtime between exposures was 110 s. We also acquired 45 $V$-band images of PG 1017–086 with the SAAO 1-m telescope using a STTe CCD with 1024 pixels giving an image scale of 0.31 arcsec per pixel on the night 2001 May 7. The exposure time was 90 s and the deadtime between exposures was 73 s.

The bias level in every image was determined from the overscan regions and was subtracted from the image before further processing. Images of the twilight sky devoid of any bright stars were used to determine flat-field corrections by forming the median image of three to five twilight sky images in each filter, one for the data of each night. We used optimal photometry (Naylor 1998) to determine instrumental magnitudes of the stars in each frame. We checked for variability in the stars other than the target star in each frame before calculating differential magnitudes between the target star and the total flux in the comparison stars. The positions and approximate $V$ magnitudes of the targets and comparison stars are given in Table 2. The coordinates and identification numbers (in parentheses) in Table 2 were taken from Guide Star Catalogue-II.1 We have used published Strömgren $y$ magnitudes for PG 1432+159 and PG 1017–086 in place of $V$ – the difference for these blue stars is small ($\pm$0.05 mag). The magnitude of the comparison stars given in Table 2 was calculated from the published target magnitude given and the median magnitude difference from our own photometry.

#### 3.2 Spectroscopy

We obtained low-resolution spectra of Ton 245 using the red arm of the ISIS double-beam spectrograph on the 4.2-m William Herschel Telescope on the Island of La Palma on the night of 2001 February 22. We also obtained spectra with the same instrument of the K3V star GL 250 A and the M1.5V star GL 220. We used a 158 line mm$^{-1}$ grating and a TEK CCD with a 1-arcsec wide slit to obtain spectra with a resolution of 5–6Å and a mean dispersion of 2.9 Å pixel$^{-1}$. We applied a flux calibration to these spectra.

### Table 1

| Name       | $P$ (d) | Spec. type | $T_1$ (K) | $M_1$ | q   | $i$ (deg) | $f$  | $r_1$ | $\delta V$ Cal. | $\delta I$ Cal. | Ref. |
|------------|--------|------------|-----------|-------|-----|----------|------|-------|----------------|----------------|------|
| HW Vir     | 0.117  | sdB + M    | 28.500    | 0.5   | 0.3 | 81       | 0.34 | 0.205 | 0.26           | 0.24           | 0.30 | 0.30 | 1.2 |
| PG 1336−018| 0.101  | sdB + M5   | 33.000    | 0.5   | 0.3 | 81       | 0.53 | 0.19  | 0.20           | 0.27           | 0.20 | 0.20 | 3  |
| V477 Lyr   | 0.471  | sdOB + M   | 60100     | 0.51  | 0.29| 80.5     | 0.54 | 0.077 | 0.78           | 0.65           |      |      | 4  |

1. Wood & Saffer (1999); 2. Kiss et al. (2000); 3. Kilkenny et al. (1998); 4. Pollacco & Bell (1994).

### Table 2

| Target       | $\alpha$(J2000) | $\delta$(J2000) | $V$ | Ref. |
|--------------|----------------|----------------|-----|------|
| Ton 245     | 15 40 35.4      | +26 47 42      | 13.89 | 1   |
| (N1330313366)| 15 40 43.1      | +26 46 52      | 15.79 | 2   |
| (N1330313095)| 15 40 37.4      | +26 48 21      | 18.17 | 3   |
| (N13303130109)| 15 40 32.5      | +26 48 43      | 17.36 | 4   |
| Feige 11    | 01 04 21.7      | +04 13 37      | 12.06 | 5   |
| (N320132243) | 01 04 28.0      | +04 11 55      | 14.47 | 6   |
| (N320132247) | 01 04 28.4      | +04 11 25      | 13.80 | 7   |
| PG 1432+159 | 14 35 19.2      | +15 40 14      | 13.90 | 8   |
| (N1313121947)| 14 35 16.0      | +15 39 59      | 15.94 | 9   |
| (N1313121769)| 14 35 13.7      | +15 36 41      | 15.61 | 10  |
| (N1313121359)| 14 35 11.9      | +15 36 45      | 14.82 | 11  |
| (N13131213083)| 14 35 26.3      | +15 39 17      | 16.55 | 12  |
| PG 1017−086 | 20 10 14.5      | −08 53 46      | 14.43 | 13  |
| (S1212232199)| 20 10 08.5      | −08 50 58      | 13.11 | 14  |

1. Iriarte (1959); 2. Landolt (1983); 3. Wesemael et al. (1992).
using observations of G191-B2B and the tabulated fluxes of Oke (1990). We have made no correction for slit losses in this calibration.

We observed PG 1017−086 using the 2.5-m Isaac Newton Telescope on the Island of La Palma. A total of 22 spectra were acquired on the nights of 2000 April 11, 2001 March 8–11 and May 6. Spectra were obtained with the intermediate dispersion spectrograph using the 500-mm camera, a 1200 line mm\(^{-1}\) grating and a TEK CCD as a detector. The spectra cover 400 Å around the H\(\alpha\) line at a dispersion of 0.39 Å pixel\(^{-1}\). The slit width used was 0.97 arcsec, which gave a resolution of \(\sim 0.9\) Å. The exposure time per spectrum was 600 or 900 s. We also obtained a continuous series of 26 spectra of PG 1017−086 on the night 2001 March 12 using the 235-mm camera, a 900 line mm\(^{-1}\) grating and an EEV CCD. The spectra cover the wavelength range 3700–5400 Å at a dispersion of 0.63 Å pixel\(^{-1}\) with a resolution of \(\sim 1.6\) Å and the exposure time per spectrum was 300 s.

We extracted the spectra from the images using optimal extraction to maximize the signal-to-noise ratio (Marsh 1989). We observed arcs before and after all observations of PG 1017−086. The arcs associated with each stellar spectrum were extracted using the same weighting determined for the stellar image to avoid possible systematic errors caused by the tilt of the spectra on the detector. The wavelength scale was determined from a fit to measured arc line positions and in each case the standard deviation of the fit is much less than 1 pixel. The wavelength scale for an individual spectrum was determined by interpolation to the time of mid-exposure from the fits to arcs taken before and after the spectrum to account for the small amount of drift in the wavelength scale owing to flexure of the instrument. Statistical errors on every data point calculated from photon statistics are rigorously propagated through every stage of the data reduction.

### Table 3. Measured heliocentric radial velocities for PG 1017−086.

| HJD−2450000 | Radial velocity (km s\(^{-1}\)) | Spectrum |
|-------------|----------------------------------|----------|
| 1646.4502   | −63.4 ± 7.1                     | Red      |
| 1646.4614   | −1.9 ± 6.4                      | Red      |
| 1977.4525   | −27.7 ± 12.3                    | Red      |
| 1977.4595   | −25.4 ± 12.0                    | Red      |
| 1977.4665   | −36.9 ± 13.2                    | Red      |
| 1977.4735   | −54.1 ± 10.9                    | Red      |
| 1978.5806   | −31.5 ± 8.2                     | Red      |
| 1978.5910   | 0.9 ± 9.3                       | Red      |
| 1979.5198   | −60.5 ± 6.6                     | Red      |
| 1979.5302   | −13.3 ± 6.3                     | Red      |
| 1979.5786   | −53.4 ± 7.2                     | Red      |
| 1979.5891   | −49.6 ± 7.0                     | Red      |
| 1980.4757   | −37.7 ± 7.1                     | Blue     |
| 1980.4793   | −12.0 ± 7.2                     | Blue     |
| 1980.4829   | −6.2 ± 7.4                      | Blue     |
| 1980.4864   | 23.6 ± 7.5                      | Blue     |
| 1980.4900   | 25.8 ± 7.0                      | Blue     |
| 1980.4936   | 42.1 ± 6.4                      | Blue     |
| 1980.4971   | 43.1 ± 6.5                      | Blue     |
| 1980.5007   | 38.6 ± 6.7                      | Blue     |
| 1980.5043   | 42.1 ± 6.9                      | Blue     |
| 1980.5078   | 27.4 ± 6.8                      | Blue     |
| 1980.5129   | 15.3 ± 7.0                      | Blue     |
| 1980.5164   | 5.5 ± 6.9                       | Blue     |
| 1980.5200   | −29.6 ± 7.0                     | Blue     |
| 1980.5236   | −40.3 ± 7.0                     | Blue     |
| 1980.5272   | −48.2 ± 6.7                     | Blue     |
| 1980.5307   | −54.1 ± 6.6                     | Blue     |
| 1980.5343   | −67.6 ± 6.7                     | Blue     |
| 1980.5379   | −44.0 ± 6.5                     | Blue     |
| 1980.5414   | −53.6 ± 6.6                     | Blue     |
| 1980.5450   | −59.9 ± 6.7                     | Blue     |
| 1980.6119   | −49.6 ± 7.0                     | Blue     |
| 1980.6155   | −45.2 ± 6.5                     | Blue     |
| 1980.6191   | −32.5 ± 6.6                     | Blue     |
| 1980.6226   | −21.9 ± 7.2                     | Blue     |
| 1980.6262   | −22.6 ± 7.6                     | Blue     |
| 1980.6298   | −1.3 ± 7.4                      | Blue     |
| 2036.3872   | −26.6 ± 25.7                    | Red      |
| 2036.3948   | −3.7 ± 21.5                     | Red      |
| 2036.4024   | 6.1 ± 14.9                      | Red      |
| 2036.4100   | 28.2 ± 13.6                     | Red      |
| 2036.4180   | 37.9 ± 15.6                     | Red      |
| 2036.4256   | 3.1 ± 14.4                      | Red      |
| 2036.4332   | −20.9 ± 17.6                    | Red      |
| 2036.4407   | −46.5 ± 19.6                    | Red      |
| 2036.4483   | −57.6 ± 44.0                    | Red      |

| T0 (HJD)   | 2452036.3940 ± 0.0005 |
| P (d)      | 0.0729938 ± 0.0000003 |
| y (km s\(^{-1}\)) | −9.1 ± 1.3 |
| K (km s\(^{-1}\)) | 51.0 ± 1.7 |
| \(\chi^2\) | 46.1 |
| N          | 47 |

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4 PG 1017−086

4.1 Radial velocities

We first observed PG 1017–086 as part of a survey for binary sdB stars (Maxted et al. 2001). The two spectra we obtained for that survey showed a change in radial velocity measured from the H\(\alpha\) line of \(\sim 60\) km s\(^{-1}\) over 0.5 h. We obtained further observations of the H\(\alpha\) line of PG 1017–086 to determine the orbital period and mass function. To measure the radial velocity we used least-squares fitting of a model line profile. This model line profile is the summation of three Gaussian profiles with different widths and depths but with a common central position that varies between spectra. Only data within 2000 km s\(^{-1}\) of the H\(\alpha\) line are included in the fitting process and the spectra are normalized using a linear fit to the continuum either side of the H\(\alpha\) line. We used a least-squares fit to one of the spectra to determine an initial shape for the model line profile. A least-squares fit of this profile to each spectrum in which the position of the line is the only free parameter gives an initial set of radial velocities. We used these initial radial velocities to fix the position of the H\(\alpha\) line in a simultaneous fit to all the spectra to obtain an improved model line profile. A least-squares fit of this profile to each spectrum yields the radial velocities given in Table 3 and are labelled ‘Red’. A similar process was used to measure radial velocities from the H\(\beta\)--He lines with two Gaussian profiles used to model each line. These are given in Table 3 and are labelled ‘Blue’. The uncertainties quoted are calculated by propagating the uncertainties on every data point in the spectra right through the data reduction and analysis.

The periodogram of the radial velocities given in Table 3 shows a single unambiguous orbital frequency at 13.70 cycle d\(^{-1}\). We used a least-squares fit of a sine wave of the form \(y + K \sin(T − T_0)/P\) to obtain the parameters given in Table 4, where \(y\) is the systemic velocity, \(K\) is the projected orbital speed, \(T\) is the time of mid-exposure of the spectrum and \(P\) is the orbital period. The measured

### Table 4. Circular orbit fit to the measured radial velocities for PG 1017−086.

| T0 (HJD)   | 2452036.3940 ± 0.0005 |
| P (d)      | 0.0729938 ± 0.0000003 |
| y (km s\(^{-1}\)) | −9.1 ± 1.3 |
| K (km s\(^{-1}\)) | 51.0 ± 1.7 |
| \(\chi^2\) | 46.1 |
| N          | 47 |
radial velocities are shown in Fig. 1 as a function of orbital phase together with the sine wave determined from the least-squares fit. We rebinned all the spectra near Hα on to a common wavelength scale allowing for the measured radial velocity shifts and then formed the average spectrum, and similarly for the spectra of the bluer Balmer lines. There are no spectral features attributable to a cool companion star visible in either of these average spectra. We used the average blue spectrum to measure the effective temperature, $T_{\text{eff}}$, the surface gravity $\log g$ and the helium abundance by number, $y$, by fitting model spectra to the Balmer lines (H$\beta$ to H10), the He I lines (λ4026, 4388, 4471, 4713, 4922) and He II λ4686 lines using the procedure outlined in Saffer et al. (1994). We used the synthetic spectra derived from H and He line blanketed NLTE model atmospheres of Napiwotzki (1997). We find $T_{\text{eff}} = 30\,300 \pm 80\,K$, $\log g = 5.61 \pm 0.02$ and $y = 0.0016 \pm 0.0001$ from these fits, where the uncertainties are ‘internal errors’ from the fitting procedure and do not include uncertainties in the models themselves. The spectrum and fit are shown in Fig. 2. The synthetic spectra were convolved beforehand with a Gaussian profile of the appropriate width to account for the instrumental profile and with a broadening function to account for a projected rotational velocity, $V_{\text{rot}} \sin i$, of 118 km s$^{-1}$. This was determined from a least-squares fit to the Hα line of a synthetic line profile for the appropriate $T_{\text{eff}}, \log g$ and $y$ values convolved with a broadening function for various values of $V_{\text{rot}} \sin i$. From a plot of $\chi^2$ versus $V_{\text{rot}} \sin i$ we estimate a value of $V_{\text{rot}} \sin i = 118^{+12}_{-14}\,\text{km\,s}^{-1}$. The radius of a 0.5-M$_{\odot}$ sdB star with $\log g = 5.61$ is 0.19 R$_{\odot}$. If we assume that tidal forces have forced the sdB star to corotate with the binary, the rotational velocity of the sdB star is 132 km s$^{-1}$. The measured value of $V_{\text{rot}} \sin i$ would then imply that the inclination of the binary is $63^{\circ} \pm 8^{\circ}$.

4.2 The light curve and the nature of the companion

Our photometry of PG 1017–086 is shown in Fig. 3 as a function of the orbital phase calculated from the values of $T_{\text{eq}}$ and $P$ derived above. The reflection effect with an amplitude of $\sim 0.08$ mag can be clearly seen and maximum light is at a phase of zero as expected, i.e. when the sdB star is closest to the observer. The difference between the mean level of the light curves observed with the SAAO 1-m telescope and the JKT is caused by a difference in the sensitivity of the CCDs used at the bluest wavelengths passed by the V filter. This makes PG 1017–086 appear brighter than its redder companion star for the CCD with better blue sensitivity.

The minimum mass of the companion to a 0.5-M$_{\odot}$ sdB star for the values of $P$ and $K$ observed in PG 1017–086 is $0.0687 \pm 0.025$ M$_{\odot}$. The mass of the companion for the inclination of $63^{\circ} \pm 8^{\circ}$ calculated above is $0.078^{+0.005}_{-0.006}$ M$_{\odot}$. If we assume that the companion is a low-mass M-dwarf with a typical radius of 0.085 R$_{\odot}$, we find that our simple model for the reflection effect predicts an amplitude for the light curve of 0.074 mag, which is consistent with the amplitude observed (Fig. 3) given the uncertainties involved, i.e. $\sim 50$ per cent. The amplitude of the reflection effect seen in the light curve cannot be produced by a white dwarf companion. The lack of any eclipse sets an upper limit to the inclination of $72^{\circ}$ for the radius of sdB star we have calculated. The limit reduces to $63^{\circ}$ if we assume that the companion has a radius of 0.085 R$_{\odot}$, which is consistent with the

![Figure 1](https://academic.oup.com/mnras/article-abstract/333/1/231/1187294/fig1)

**Figure 1.** Radial velocities of PG 1017–086 measured from the Hα line (open circles) and from the H$\beta$–He lines (closed circles). The sine wave fit described in the text is also shown (solid line).

![Figure 2](https://academic.oup.com/mnras/article-abstract/333/1/231/1187294/fig2)

**Figure 2.** Synthetic spectrum fit to the blue Balmer lines and helium lines of PG 1017–086.

![Figure 3](https://academic.oup.com/mnras/article-abstract/333/1/231/1187294/fig3)

**Figure 3.** The V-band light curve of PG 1017–086 observed with the SAAO 1-m telescope (filled circles) and with the JKT (open circles). The solid lines are cosine functions with an amplitude of 0.083 mag.

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inclination used in the calculation of the reflection effect. Our model does not include the ellipsoidal effect caused by the sdB star, which is expected to be ≈0.01 mag. This is too small to be measured reliably from our light curves, but would be measurable with improved data, particularly at bluer wavelengths where the sdB star dominates. The size of the ellipsoidal effect depends strongly on the size of the star relative to its Roche lobe, so this measurement would usefully constrain the properties of the stars in PG 1017−086.

In summary, we can say that the companion to PG 1017−086 is a low-mass star or, perhaps, a brown dwarf, but is certainly not a white dwarf star.

5 TON 245, FEIGE 11 AND PG 1432+159

In this section we have to go through a fairly complex chain of logic in order to establish the final result, which is that the companions of the three stars Ton 245, Feige 11 and PG 1432+159 must all be compact as opposed to main-sequence stars or brown dwarfs. To help the reader, we now give an overview of the reasoning we employ.

We detect no significant reflection effect in any of these stars and our task is to show that this is enough to say that they must have compact companions, most probably white dwarfs. The complicating factor is the unknown orbital inclination that also affects the reflection effect amplitude in the sense that the amplitude becomes small as orbits become more face-on. In fact, the reflection amplitude can also decrease at high inclinations because for a given radial velocity amplitude a high inclination implies a reduced companion star mass which, in turn, implies a reduced radius and, therefore, a reduced reflection effect. However, it is the reduction at low inclinations that is much more significant, for example, see Fig. 4. This essentially means that very low-mass companions are ruled out by the radial velocity amplitudes and therefore we cannot obtain a small reflection effect by appealing to brown dwarf companions for these three stars. Thus, the problem boils down to ruling out low inclinations as a way of getting low amplitudes. We can do so as follows.

From the spectra of the targets we can place upper limits upon the contribution of the companion stars to the sdB spectra. Given the luminosity of the sdB stars at that wavelength, the main-sequence mass–luminosity relation implies upper limits upon the companion star masses. For a given sdB mass, radial velocity amplitude and orbital period, an upper limit on the companion mass gives a lower limit upon the inclination (see Fig. 4). This in turn gives a lower limit upon the predicted amplitude of the reflection effect on the assumption of main-sequence companions. The loop is finally closed when we establish that this lower limit should have been detectable in each case, and therefore that the companions must be compact.

5.1 Upper limits to the luminosity ratios

In order to set upper limits on the contribution from any cool companion star to the spectra of Ton 245, Feige 11 and PG 1432+159, we have considered a region of the spectrum where we expect to see no features from the sdB star or the atmosphere of the Earth. We then subtract off varying amounts of cool star spectrum to find the luminosity ratio at which the combined spectrum no longer looks featureless, i.e. for which a low-order polynomial is no longer a good fit.

Figure 4. The amplitude of the reflection effect, $\delta m$, predicted by our model in $V$ (solid line) and $I$ (dashed line) and the luminosity ratio in the $V$ band, $L_V$, as a function of the inclination for a main-sequence companion.
For Feige 11 and PG 1432+159 we used the average spectra near Hα described in Moran et al. (1999). We compared these spectra with a spectrum of GL 69, a K5V star. All the spectra were shifted in wavelength so that spectral features appear at their rest wavelengths and then rebinned on to a uniform wavelength grid of 215 elements between 6365 and 6450 Å. There are no significant spectral features from the sdB star or the atmosphere of the Earth in this wavelength region. The spectra were normalized to give a continuum value of 1. We then calculated the $\chi^2$ statistic for a least-squares parabolic fit to the residual $f_{\text{sdB}} - L \times f_{\text{GL69}} + L$, where $f_{\text{sdB}}$ and $f_{\text{GL69}}$ are the normalized spectra of the sdB star and GL 69, respectively. The results are shown as a function of the luminosity ratio, $L$, in Fig. 5.

If $\chi^2_0$ is the value of $\chi^2$ for $L = 0$, then we can set an upper limit to $L$ by considering the minimum value of $L$ for which $\chi^2$ is significantly worse than $\chi^2_0$. We have chosen a conservative value of $\chi^2_0 + 3$ (91.6 per cent confidence limit) and find corresponding upper limits of $L < 0.0026$ for Feige 11 and $L < 0.009$ for PG 1432+159.

We applied the same technique to our low-resolution ISIS spectrum of Ton 245 and the K3V star GL 250 A in the spectral region 8350–8600 Å, which is also free of spectral features from the sdB stars or the atmosphere of the Earth. The rebinned spectra have 86 pixels in this case. The results are shown in Fig. 5, where it can be seen that $L < 0.043$. The limit on $L$ is less stringent than those calculated for Feige 11 or PG 1432+159 because there are fewer spectral features visible at lower resolution. We also applied the technique to Ton 245 and the M1.5V star GL 220 and found $L < 0.046$. Although the value of $\chi^2$ is slightly improved by subtracting 1–2 per cent of a cool star spectrum from the spectrum of Ton 245, this is not a significant improvement and it is probably caused by the cancellation of flat-fielding errors, sky subtraction problems and weak absorption features caused by the atmosphere of the Earth rather than any real detection of a cool companion.

5.2 The amplitude of the reflection effect from a main-sequence companion

In order to calculate the amplitude of the reflection effect from a main-sequence star and the luminosity ratio as a function of inclination, we proceed as follows. For a given orbital inclination, the semi-amplitudes and orbital periods given in Table 5 can be used to compute the mass of the companion star and the separation of the stars assuming a mass of 0.5 M⊙ for the sdB star. The radius of the sdB star can be estimated using the surface gravity given by Saffer et al. (1994). The radius, effective temperature and absolute visual magnitude of the companion star can be estimated from its mass using the tabulations of Zombeck (1990). We can then use our model for the reflection effect to predict the amplitude of the reflection effect as a function of the inclination. The luminosity ratio in the $V$ band can also be calculated given the absolute visual magnitude of the sdB star calculated from the radius and effective temperature of the sdB star combined with a surface brightness in the $V$ band from the model atmospheres described above. The results of these calculations are shown in Fig. 4. We can see from the right-hand panels of Fig. 4 that the upper limit to the luminosity
ratio calculated above sets a lower limit to the inclination of the binary if we assume the companion to be a main-sequence star.

Although the luminosity ratio was calculated at redder wavelengths than the $V$ band, the cool companion is redder than the sdB star at these wavelengths, so this is a pessimistic assumption, i.e. we allow a greater range of inclinations by applying these upper limits calculated from the spectra to the $V$ band. In Table 5 we list the minimum amplitude of the reflection effect predicted by our model for the range of inclinations allowed by the upper limit to the luminosity ratio $L_{\text{max}}$.

5.3 The observed light curves

The light curves of Ton 245, Feige 11 and PG 1432+159 are shown in Fig. 6. Also shown are the results of a least-squares fit of a cosine wave to these data with the same period as the orbital period. The amplitude of these cosine waves, $\delta m$, is given in Table 6 together with the standard deviation of the residuals, $\sigma_{\delta m}$. We have also calculated periodograms for each light curve, i.e. the semi-amplitude...
of the sine wave fit by least squares as a function of frequency. The results are shown in Fig. 7. Almost all of the power in these periodograms occurs near 1 cycle d^{-1} or its aliases and is caused by a combination of the window function and differential extinction between the target and comparison stars. It is clear that there is no significant variability in these light curves with the same period as the orbital period and that any reflection effect in these binaries has an amplitude of less than \( \sim 0.01 \) mag. We compare these measured semi-amplitudes with the minimum semi-amplitudes for the reflection effect from a main-sequence calculated above by calculating the ratio \( \delta m_{\text{min}}/2 \), where \( \delta m_{\text{min}} \) is the uncertainty in \( \delta m \). We see that in all three cases the minimum predicted semi-amplitude exceeds the observed semi-amplitude by an order of magnitude more than its uncertainty.

We have also considered the sources of uncertainty in our analysis. The uncertainties in the properties of the sdB star, i.e. mass, radius and temperature, affect the value of \( \delta m_{\text{min}} \) by no more than a few hundredths of a magnitude. Another source of uncertainty is the scatter in the mass-radius relation for M-dwarfs, which is \( \sim 12 \) per cent (Caillault & Patterson 1990), but this also has a small effect on \( \delta m_{\text{min}} \). The largest source of uncertainty in our analysis is the error introduced by the assumptions and approximations used in our model of the reflection effect. These are difficult to quantify but we have shown that for sdB binaries similar to those we are studying but with M-dwarf companions, the model is able to predict the amplitude of the reflection effect to within 50 per cent. Even if we are pessimistic and assume that the uncertainties in the models used to derive \( \delta m_{\text{min}} \) are a factor of a few, it is clear that the amplitude of any reflection effect in the light curves of Ton 245 is a factor of at least \( \sim 4 \) lower than that expected from a main-sequence companion and an order of magnitude lower for the light curves of Feige 11 and PG 1432+159.

There is no evidence in any of our light curves of variability on time-scales of 90–600 s, which is the typical period range for pulsating sdB stars (Koen et al. 1999). However, our data are far from ideal for studying pulsations given the long exposure times used and poor data sampling so it is quite possible that one or more of the stars studied are pulsating sdB stars.

6 DISCUSSION

We can rule out the possibility that the companions to Ton 245, Feige 11 and PG 1432+159 are main-sequence stars because they do not show any reflection effect in their light curves. We can also rule out a subgiant companion in all three cases because a subgiant is, by definition, larger than a main-sequence star, so the reflection effect would be much larger. We conclude that none of these sdB stars has a main-sequence or subgiant companion. The companions to these sdB stars have masses \( \times 0.3 M_\odot \) (but must have radii much smaller than main-sequence stars to avoid the reflection effect being seen in the light curve. A white dwarf companion satisfies these constraints comfortably and sdB–white dwarf binaries are known to exist, for example, KPD 0422+5421 (Koen, Orosz & Wade 1998), KPD 1930+2752 (Maxted, Marsh & North 2000).

The orbital period we have measured for PG 1017−086 is the shortest period for an sdB binary measured to-date and is comparable with those of short-period cataclysmic variables. The time-scale for orbital shrinkage caused by the loss of gravitational waves is \( \sim 800 \) Myr, which is comparable with the lifetime of an sdB star. It is interesting to speculate what the binary will look like if mass transfer begins before the sdB star evolves into a low-mass
white dwarf. The stream of material from the M-dwarf will impact directly on to the surface of the sdB star, i.e. no accretion disc will form, so the effects of the mass transfer may not be immediately obvious.

7 CONCLUSION

We have presented light curves in two colours of three binary subdwarf B stars – PG 1432+159, Feige 11 and Ton 245. We have shown that there is no sign in these light curves of the sinusoidal variation that would be seen if the companion star were a main-sequence star or a subgiant. The most likely explanation is that all three sdB stars have white dwarf companion stars.

In contrast, the reflection effect in PG 1017–086 is clearly seen in the light curve. We have presented spectroscopy of this star from which we have measured the orbital period, mass function and projected rotational velocity. These observations show that PG 1017–086 is an sdB star with a low-mass M-dwarf or brown dwarf companion.

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