Orbital periods of the binary sdB stars PG 0940+068 and PG 1247+554

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ABSTRACT
We have used the radial velocity variations of two sdB stars previously reported to be binaries to establish their orbital periods. They are PG 0940+068 (\(P = 8.33\) d) and PG 1247+554 (\(P = 0.599\) d). The minimum masses of the unseen companions, assuming a mass of 0.5 M\(_\odot\) for the sdB stars, are 0.090 ± 0.003 M\(_\odot\) for PG 1247+554 and 0.63 ± 0.02 M\(_\odot\) for PG 0940+068. The nature of the companions is not constrained further by our data.

Key words: binaries: close – binaries: spectroscopic – stars: individual: PG 0940+068 – stars: individual: PG 1247+554 – subdwarfs.

1 INTRODUCTION
Subdwarf B (sdB) stars are thought to be core-helium-burning stars with core masses of about 0.5 M\(_\odot\) and extremely thin (≤0.02 M\(_\odot\)) hydrogen envelopes (Heber 1986; Saffer et al. 1994). It is thought that the eventual fate of an sdB star is to cool to form a white dwarf with a mass of about 0.5 M\(_\odot\), which is low compared with the typical mass for white dwarfs (Bergeron, Saffer & Liebert 1992). The formation of low-mass white dwarfs, and by implication sdB stars, is thought to involve a common envelope phase, in which a companion to a red giant star in engulfed by the expanding outer layers. The resulting friction results in the companion spiralling in towards the core of the red giant, ejecting the envelope at the expense of orbital binding energy (Iben & Livio 1993). This provides a natural mechanism for the loss of the surface hydrogen layers in sdB stars.

The binary fraction of sdB stars is expected to be high given the scenario outlined above. Allard et al. (1994) found that 31 of their sample of 100 sdB stars show flat spectral energy distributions, which indicate the presence of companions with spectral types in the range late-G and early-M. They infer a binary fraction for main-sequence companions of 54–66 per cent, although the companions in their survey are over-luminous compared to normal main-sequence stars. A similar conclusion was reached by Jeffery & Pollacco (1998) based on the detection of spectral features arising from cool companions. Companions to sdB stars can also be detected in eclipsing systems such as HW Vir (Wood & Saffer 1999), PG 1336 – 018 (Kilkenny et al. 1998) and the sdB – white dwarf binary KPD 0422 + 5421 (Koen, Orosz & Wade 1998). Saffer, Livio & Yungelson (1998) found that at least seven of their sample of 46 sdB stars show radial velocity variations. Several of these binaries have subsequently had their orbital periods determined (Moran et al. 1999), although further observations are required to determine the nature of the companions in these binaries.

In this paper we present two new orbital period determinations from radial velocity measurements for binary sdB stars from the survey of Saffer et al. (1998).

2 OBSERVATIONS AND REDUCTIONS
Most of the data for this study come from observations obtained with the 2.5-m Isaac Newton Telescope (INT) on the island of La Palma. Spectra were obtained with the intermediate dispersion spectrograph (IDS) using the 500-mm camera, a 1200 line mm\(^{-1}\) grating and a TEK CCD (charge coupled device) as a detector.

Additional spectra of PG 0940+068 were obtained using three other instruments. Ten spectra were obtained with the grating spectograph on the 1.9-m telescope at the South African Astronomical Observatory (SAAO). Grating No. 5 (1200 line mm\(^{-1}\)) and a 1.2-arcsec slit were used with the SIT1 CCD detector. Four spectra were obtained with the RGO spectrograph and 82-cm camera on the Anglo-Australian Telescope (AAT). Full details of these spectra can be found in Maxted & Marsh (1999).

Two additional spectra of PG 1247+554 were obtained with the dual beam spectrograph ISIS on the 4.2-m William Herschel Telescope (WHT) on the island of La Palma. We used a 1200 line mm\(^{-1}\) grating on the red arm to obtain spectra of H\(_\alpha\) and He\(_i\) 6678. The detector was a TEK CCD and the slit width was 1.2 arcsec.

For all these instruments and detectors, sensitivity variations were removed using observations of a tungsten calibration lamp. Bias images show no signs of any structure in the region of the spectrum, so a constant bias level determined from a clipped-mean value in the overscan region was subtracted from all the images. The exposure times used varied from 300 to 1200 s.

Extraction of the spectra from the images was performed automatically using optimal extraction to maximize the signal-to-noise ratio of the resulting spectra (Horne 1986). Every spectrum
was bracketed by observations of the internal arc lamp at the position of the star. The arcs associated with each stellar spectrum were extracted using the profile determined for the stellar image to avoid possible systematic errors arising from tilted spectra. The wavelength scale was determined from a polynomial fit to measured arc-line positions. Uncertainties on every data point calculated from photon statistics are rigorously propagated through every stage of the data reduction.

Finally, a single spectrum of PG0940+068 was obtained with the cross-dispersed echelle spectrograph UCLES on the AAT. Details of the reduction of these spectra are similar to those described in Gatti et al. (1997).

Details of all these instruments, the dates of all the observing runs and the resolution and sampling obtained are given in Table 1.

### Table 1. Summary of the spectrograph/telescope combinations used to obtain spectra for this study. The slit width used in each case is approximately 1 arcsec.

| Date   | Telescope | Spectrograph | Resolution (Å) | Sampling (Å) |
|--------|-----------|--------------|----------------|--------------|
| Jun 97 | INT       | IDS          | 1.0            | 0.4          |
| Feb 98 | INT       | IDS          | 1.0            | 0.4          |
| Mar 98 | SAAO 1.9m |              | 0.8            | 0.4          |
| May 98 | AAT       | UCLES        | 0.10           | 0.04         |
| Jun 98 | AAT       | RGO          | 0.7            | 0.3          |
| Feb 99 | INT       | IDS          | 1.0            | 0.4          |
| Jul 99 | WHT       | ISIS         | 0.73           | 0.4          |

### 3 PG 0940 + 068

This star was first noted as a potential binary by Bragaglia et al. (1990) and later confirmed as such by Saffer et al. (1998). Saffer et al. also noted the presence of the He I 6678 absorption line in their spectra which identifies this star as an sdB star rather than a white dwarf.

To measure the radial velocities 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 which varies between spectra. The resolution of each instrument is accounted for in the fitting process. Only data within 2000 km s\(^{-1}\) of the H\(_{\alpha}\) line are included in the fitting process. We first normalize the spectra using a linear sine fit to the radial velocities to fix the position of the H\(_{\alpha}\) line. We used a least-squares fit to a single spectrum to establish the shape of an initial 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 yields an initial set of radial velocities. The periodogram of these velocities shows the best period to be near 8.33 d. Other peaks in the periodogram are much less significant. We used a sine fit to the radial velocities to fix the position of the H\(_{\alpha}\) line in each spectrum in a simultaneous least-squares fit to all the spectra to establish an optimum model line profile. We then re-measured the radial velocities of each spectrum using this optimum model line profile. The quality of the model line fits to the spectra estimated by eye and from the \(\chi^2\) statistic were generally good. These are the radial velocities given in Table 2.

The parameters of a circular orbit fit to the radial velocities are given in Table 3. The value of \(\chi^2\) is rather high. This is, perhaps, not surprising given the diverse sources of spectra on which this orbit is based, but might also suggest that there are additional sources of uncertainty in our measured radial velocities, e.g., image motion within the slit, instrument flexure and telluric absorption lines. We have adjusted the uncertainties in the measured parameters accordingly, i.e., multiplied them by \(\sqrt{141.1/(41 - 4)}\). The measured radial velocities and the circular orbit fit are shown in Fig. 1.

We also established the parameters of the orbit by fitting all the spectra simultaneously using a least-squares fit in which the position of the absorption line is determined by a circular orbit. The parameters of the orbit and the model line profile are all free parameters in the fitting process. This gives essentially the same result as fitting the individual radial velocities. We also subtracted the model profiles from the observed spectra to look for spectral features arising from a companion star, but without success.

### 4 PG 1247 + 554 (GD 319)

This star was first noted as a potential binary by Saffer et al. (1998), who also noted the strong He I 6678 line which suggests that this star is a blue horizontal branch (BHB) star or low-gravity

### Table 2. Radial velocity measurements for PG0940+068.

| HJD (−245 0000) | Velocity (km s\(^{-1}\)) | HJD (−245 0000) | Velocity (km s\(^{-1}\)) | HJD (−245 0000) | Velocity (km s\(^{-1}\)) | HJD (−245 0000) | Velocity (km s\(^{-1}\)) |
|-----------------|--------------------------|-----------------|--------------------------|-----------------|--------------------------|-----------------|--------------------------|
| 852.4349        | +47.6 ± 2.5              | 855.4455        | −58.2 ± 2.9              | 882.3250        | −75.5 ± 7.7              | 969.8409        | 34.6 ± 4.1               |
| 852.4463        | +60.0 ± 2.6              | 855.4511        | −61.8 ± 3.1              | 882.3323        | −56.7 ± 8.1              | 1238.4055       | −64.2 ± 7.1              |
| 852.4589        | +43.8 ± 2.2              | 855.4561        | −62.9 ± 3.1              | 882.3397        | −71.4 ± 8.4              | 1240.3832       | −69.3 ± 2.0              |
| 852.6349        | +39.7 ± 2.6              | 855.4611        | −58.3 ± 3.1              | 882.3484        | −49.2 ± 9.2              | 1240.4840       | −61.9 ± 1.8              |
| 852.6434        | +34.9 ± 3.4              | 855.5102        | −61.6 ± 3.2              | 882.3567        | −59.2 ± 8.6              | 1240.6304       | −56.5 ± 3.4              |
| 853.5760        | +11.2 ± 2.2              | 855.5151        | −62.7 ± 3.1              | 882.3640        | −57.8 ± 10.8             | 1241.3896       | −27.4 ± 2.1              |
| 853.5847        | +3.5 ± 3.2               | 881.3208        | −131.8 ± 18.1            | 941.8613        | −13.4 ± 1.6              | 1241.5396       | −15.4 ± 1.9              |
| 853.6816        | +6.4 ± 2.5               | 882.2942        | −92.5 ± 8.3              | 968.8381        | 41.9 ± 3.4               | 1241.6821       | −13.8 ± 3.2              |
| 853.6912        | +3.1 ± 2.4               | 882.3016        | −71.5 ± 9.0              | 968.8419        | 43.1 ± 3.2               | 1242.3831       | 17.0 ± 2.1               |
| 854.4479        | −26.4 ± 3.8              | 882.3089        | −72.7 ± 8.1              | 969.8371        | 36.4 ± 3.4               | 1242.6059       | 20.5 ± 1.9               |

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sDB star. There is a K-star companion 2.7 arcsec away but this was shown to be unrelated to PG 1247+554 by McAlister et al. (1996), i.e., it is an optical double star.

We acquired 11 spectra of this star and its nearby companion star over four nights of 1999 March, covering the Hα line and the He i 6676 line, four spectra over two nights of 1997 June covering the Hα line only and two spectra covering the Hα line and the He i 6676 line on a night of 1999 July.

We used the same procedure described above for PG 0940+068 to establishing a model line profile and to measure the radial velocities from the Hα line. These are given in column 2 of Table 4. We also measured radial velocities from the He i 6678 line in our 1999 spectra using a similar procedure but using only two Gaussian profiles to model the line. The velocities are given in column 3 of Table 4.

The parameters of a circular orbit fit to the radial velocities measured from both spectral lines are given in Table 3 and the fit is shown in Fig. 2. The value of \( \chi^2 \) is, again, rather high so we have adjusted the uncertainties in the measured parameters accordingly, i.e., multiplied them by \( \sqrt{45.3/(30-4)} \). A simultaneous fit to all the spectra to determine the orbit gives essentially the same results and there is no trace of a companion star in the residual spectra.

5 DISCUSSION

If we assume a canonical mass of 0.5 M⊙ for the visible components of these binaries (Saffer et al. 1994), we can calculate a minimum mass of 0.63 ± 0.02 M⊙ for the unseen companions to PG 0940+068 and 0.036 ± 0.003 M⊙ for PG 1247+554. If the
unseen companion to PG 0940+068 was a main-sequence star it would have an absolute magnitude, $M_V = 8.3 \pm 0.9$ (Henry & McCarthy 1993), where the uncertainty reflects the error in the mass and the scatter in the mass – luminosity relation. On average, the absolute magnitude of an sdB star is $M_V = 4.5 \pm 0.8$, so a main-sequence companion is likely to contribute at least 1 per cent of the light at $V$. While this would not have been seen in our spectra, it should allow the nature of the companion to be established through high signal-to-noise ratio spectroscopy, perhaps around the Ca ii IR triplet as in Jeffery & Pollacco (1998).

6 CONCLUSION

We have measured the orbital periods for two sdB binary stars and calculated the minimum mass of the companion star. The orbital period of PG 0940+068 is 8.33 d and the minimum mass of the companion is 0.087 $\pm$ 0.003 $M_\odot$. If the companion to PG 0940+068 is a main-sequence star, it will contribute 1 per cent of the light at $V$, which may make it directly detectable.

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