PG 1018–047: the longest period subdwarf B binary

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ABSTRACT

About 50% of all known hot subdwarf B stars (sdBs) reside in close (short period) binaries, for which common envelope ejection is the most likely formation mechanism. However, Han et al. (2003) predict that the majority of sdBs should form through stable mass transfer leading to long period binaries. Determining orbital periods for these systems is challenging and while the orbital periods of ~100 short period systems have been measured, there are no periods measured above 30 days. As part of a large program to characterise the orbital periods of subdwarf B binaries and their formation history, we have found that PG 1018–047 has an orbital period of 760 ± 6 days, easily making it the longest period ever detected for a subdwarf B binary. Exploiting the Balmer lines of the subdwarf primary and the narrow absorption lines of the companion present in the spectra, we derive the radial velocity amplitudes of both stars, and estimate the mass ratio $M_{MS}/M_{sdB} = 1.6 ± 0.2$. From the combination of visual and infrared photometry, the spectral type of the companion star is determined to be mid K.

Key words: binaries: close – binaries: spectroscopic – subdwarfs – stars: evolution – stars: individual: PG 1018-047

1 INTRODUCTION

Subdwarf B stars (sdBs) are core-helium burning stars with thin hydrogen envelopes. They are situated between the main sequence and the white dwarf cooling track at the blueward extension of the horizontal branch, the so-called Extreme or Extended Horizontal Branch (Heber et al. 1984; Heber 1986; Saffer et al. 1994). Subdwarf B stars have colours and spectral characteristics corresponding to those of a B star, but the Balmer lines are abnormally broad for the colour compared with population I main-sequence B stars due to their high surface gravities ($\log g \simeq 5.0 - 6.0$). Subdwarf B stars have a typical mass of 0.5 $M_\odot$ (Heber et al. 1984) and can be found in all Galactic populations. They are thought to be the dominant source for the UV-upturn in early type galaxies (Ferguson et al. 1991; Brown et al. 2000). A fraction of sdBs pulsate (Charpinet et al. 1999; Kilkeneny et al. 1997), giving great opportunities to derive fundamental parameters (e.g. the stellar mass) and study their internal structure in detail (Green et al. 2003; Fontaine et al. 2008; Østensen 2009, 2010). Subdwarf B stars are also suggested to be very useful as age indicators using evolutionary population synthesis (Brown et al. 1997), or as distance indicators (Kilkenny et al. 1999). Since a large fraction of sdBs are members of binary systems (Maxted et al. 2001) and because they are intrinsically bright and ubiquitous, they are therefore an ideal population in which to study binary star evolution. For a comprehensive review on hot subdwarf stars we refer the reader to Heber (2009).

Han et al. (2003) describe in detail the formation and evolution of sdBs by using binary population synthesis models. They find that sdBs form via five main evolutionary channels: the first and second common envelope channels, the first and second stable Roche lobe overflow channels and the helium white dwarf merger channel. This last channel is the only one that results in the formation of single sdBs. They find that the contribution of the second Roche lobe overflow channel is not significant, leaving only three channels to form sdB binaries. Each of these three binary formation channels predicts a different orbital period distribution for the population of sdBs. The binaries formed through the first common envelope channel should display orbital periods between 0.5 and ~40 days and the companions to the sdBs will be main sequence stars. Binaries formed via the second common envelope channel...
are expected to have white dwarf companions and their range of orbital periods will be wider, extending further into the short periods but not to long periods. Note as well that these common envelope phases are not very well understood. Nelemans et al. (2000) have concluded from the observed double white dwarf population that its outcome may not always be a strong reduction of the orbital separation. Finally, sdB binaries formed through the first stable Roche lobe overflow channel will have main sequence companions and will display orbital periods between 0.5 and ~2000 days. Han et al. (2003) conclude that their set 2 of simulations is the model that best describes the observed sample of short period sdB binaries (Morales-Rueda et al. 2003). In this particular model (and also in 9 out of the 12 models they describe) the majority of sdB binaries, between 60 and 70 percent of the total, are formed via the first stable Roche lobe overflow channel. At the same time, this is the channel most affected by observational selection effects decreasing the number of observable sdB binaries formed through this channel. These observational effects are primarily that sdBs with companions that are brighter than the sdB itself will not be identified as sdBs at all. The second effect has to do with observational limitations: it is easier to detect radial velocity variations from a short orbital period system than from a long one, as these are smaller and take longer to determine in the second case.

Despite extensive observational work, not a single system has been found in this long-period regime (first stable RLOF channel), whereas at present ~100 sdB binaries with short periods are confirmed (Geier et al. 2011 and Copperwheat et al. 2011). The orbital periods are mostly below 1 day, with a median period of 0.61 days. However, in this work we will report on PG 1018−047, the first truly sdB binary with a short orbital period. The presence of the companion in the spectrum prompted continued follow-up of the system in order to determine how such a binary could have formed in the first place. We present the results after more than a decade of monitoring.

### 2 OBSERVATIONS AND REDUCTION

We have observed PG 1018−047 spectroscopically with several different instrument setups over a period of ten years. In Table 1 we summarize the observing dates, the setup used in each case, the wavelength range covered and the number of spectra obtained during each epoch. The data were obtained using the Isaac Newton Telescope (INT), William Herschel Telescope (WHT), and Nordic Optical Telescope (NOT) on the Island of La Palma, the Radcliffe Telescope at the South African Astronomical Observatory (SAAO) and the Hobby-Eberly Telescope (HET) located at the McDonald Observatory in Texas. The different instrument setups were as follows:

For the INT-Red spectra the intermediate dispersion spectrograph (IDS) was used. It is a long-slit spectrograph mounted on the Cassegrain Focal Station of the INT. The 500 mm camera together with the high resolution R1200R grating and a windowed Tek5 CCD centered in $\lambda = 6560 \text{ Å}$ covered the $H_{\beta}$ region. A 1 arcsec slit was used.

INT-Blue: The INT with the IDS, equipped with the 235 camera, the R1200B grating and a windowed EEV10 CCD was used to obtain these blue spectra. The 2002-2007, 2008-2009 spectra were centered on respectively $\lambda = 4348 \text{ Å}$ and $\lambda = 4505 \text{ Å}$, covering as many Balmer lines to the blue as possible, including $H_{\beta}$ at 4861.327 Å. For all exposures a 1 arcsec slit was used.

The SAAO data were obtained using the Radcliffe 1.9 m telescope together with the grating spectrograph plus the SITE back-illuminated CCD. Grating 4, with 1200 grooves per millimeter was used to obtain spectra covering $H_{\gamma}$ and $H_{\beta}$ with a dispersion of 0.5 Å/pix and a resolution of 1 Å at 4600 Å. The slit width varied from 1.2 to 1.5 arcsec depending on the seeing.

WHT-Red: The WHT was equipped with the double arm intermediate dispersion Spectrograph and Imaging System (ISIS). The R1200R grating and the Red+ CCD were used to obtain the red spectra centered on $\lambda = 6560 \text{ Å}$ (2007 data) and on $\lambda = 6521 \text{ Å}$ (2009 data). A slit width of 1.2 arcsec was used for the 2007 observations and a 1 arcsec slit for the 2009 ones.

The setup WHT-Blue denotes WHT data obtained using the ISIS spectrograph with the R600B grating and the blue EEV10. The grating was centered on $\lambda = 4388 \text{ Å}$ with a 1 arcsec slit (2006 observations), on $\lambda = 4500 \text{ Å}$ with a 1.5 arcsec slit (2007 data), $\lambda = 4339 \text{ Å}$ with a slit width of 0.62 arcsec (2008) and on $\lambda = 4349 \text{ Å}$ with a 1.04 arcsec slit during the 2009 observations.

The NOT data were taken using the 2.56 m Nordic Optical Telescope. The FIES (Fibre-fed Echelle Spectrograph) highest resolution fiber (the 1.3 arcsec fibre offering a spectral resolution of R = 67000) covered the entire spectral range 3700 - 7300 Å without gaps in a single fixed setting.

The final setup, HET, refers to data from the bench-mounted echelle fibre-fed High Resolution Spectrograph, mounted on the 9.2m Hobby-Eberly Telescope operated in its R = 15000 resolution mode. In the “2x3” on-chip binning mode that was used, the dispersion was about 6 km/s per binned output pixel. A 2-arcsecond optical fibre was used for the stellar target, and two additional fibers were used to record the sky spectrum. A cross-dispersing grating with 600 grooves per millimeter was used, centering $\lambda \approx 5822 \text{ Å}$ at the boundary between the “blue” and “red” CCDs. The useful wavelength coverage extended from 4810 Å to 6760 Å.

To reduce the spectra from the INT, WHT and SAAO, standard Starlink routines were used. Flatfields were taken to correct for the pixel to pixel variations in the CCD and the bias correction was carried out by using the overscan region in each CCD frame. The objects were extracted with the optimal extraction algorithm of Marsh (1989). CuAr+CuNe are spectra were taken before and after each target spectrum or after each set of two spectra at the target’s position to calibrate these in wavelength. Fourth order polynomials were computed to fit the lines in the arcs and the solutions were used for the calibration of the corresponding spectra. The NOT data were reduced with the automatic data reduction soft-
wab package FIEStool\textsuperscript{2}, which makes use of the IRAF and NumArray packages via a Python interface. After preprocessing, the raw frames were debiased and subsequently divided by a 2D normalized flatfield, correcting for the shape of each spectral order. Next the science spectra were extracted using the optimal extraction algorithm from Horne (1986) and corrected for the blaze shape. The wavelength calibration was done from a ThAr lamp spectrum within IRAF, using the “crreject” option in the task “imcombine” to reduce cosmic-ray contamination; additional rejection of cosmic-ray artifacts was done later by hand. As a result of this observational effort, we have a total of 125 spectra of PG 1018–047.

3 RESULTS

3.1 The optical spectrum of PG 1018–047

The normalised optical spectrum of PG 1018–047 is shown in Figure 1. It is obtained by averaging over a number of the ING/SAAO spectra taken at the same orbital phase, calculated using our best orbital solution from section 3.2. In order to normalise the spectra, we fitted third order polynomials to the regions free from absorption lines and divided the spectra by these fits. The mean spectrum shows several metal lines in the region between H\textalpha and H\textbeta. However, the He I line at 4472 Å, which is typical of sdB stars is absent. Instead the Si II triplet (4553, 4568, 4575 Å) is the strongest feature. Several lines in the region between 4600 and 4700 Å can be identified with O II lines and possibly also N II. We made a fit to the mean spectrum of PG 1018–047 using the LTE model grids of Heber et al. (2000), with explicit metals of solar composition and abundances depleted by 0.0, 0.5, 1.0, 1.5 and 2.0 dex relative to solar. A reasonable fit is achieved with $T_{\text{eff}} = 30500 \pm 200$ K, $\log g = 5.50 \pm 0.02$, and with the N and O abundance 1/10 of the solar value. In Figure 1, a synthetic spectrum with these parameters broadened to match the resolution of the observed spectrum is shown. The model spectrum contains helium at a fraction $\log N(\text{He})/N(H) = -3.0$, but even this is clearly too much. In order to make helium fit with the observed spectrum, the model must be depleted to $\log N(\text{He})/N(H) < -4$. It is also clear that the abundances of the various elements are quite far from solar composition relative to each other, which is not unusual for the sdBs (Heber et al. 2000). Note that the K-star contributes some light also in the blue part of the spectrum, but insufficient to make any lines clearly visible in the spectrum. However, the contribution to the continuum might still be sufficient to affect the fitting procedure. In the H\textalpha region, however, metal lines from the K-star are clearly seen. Our high S/N mean spectrum has too low resolution to reliably infer the abundances of the individual components, and our high resolution spectra have insufficient S/N.

3.2 The orbit of PG 1018–047

3.2.1 Radial velocity measurements

The radial velocities (RVs) of the INT, WHT, SAAO and NOT spectra were determined following the procedure described by Morales-Rueda et al. (2003), i.e. least squares fitting of a line profile model. This line profile model was built up from three Gaussians per Balmer line with different widths and depths, but with a common central wavelength position which varies between the observations. Observers: P. F. L. Maxted (P. M.), T. Augustijn (T. A.), T. R. Marsh (T. M.), Luisa Morales-Rueda (L. M.), G. Nelemans (G. N.), C. Copperwheat (C. C.), R. A. Wade (R. W.) and M. A. Stark (M. S.).

### Table 1. Journal of observations

| Date          | Setup | $\lambda$ region | # Spectra | Mean dispersion (Å/pixel) | Observer(s) |
|---------------|-------|------------------|-----------|---------------------------|-------------|
| 11 - 19/04/00 | INT-R | $H_{\alpha}$     | 4         | 0.39                      | P. M.       |
| 08 - 13/03/01 | INT-R | $H_{\alpha}$     | 11        | 0.39                      | P. M.       |
| 01 - 07/05/01 | INT-R | $H_{\alpha}$     | 9         | 0.39                      | P. M.       |
| 26 - 30/03/02 | SAAO  | Blue             | 6         | 0.49                      | T. M.       |
| 25 - 27/04/02 | INT-B | Blue             | 6         | 0.48                      | T. A. & T. M. |
| 09 - 16/04/03 | INT-B | Blue             | 27        | 0.48                      | T. M.       |
| 30/03 - 05/04/04 | SAAO  | Blue             | 5         | 0.49                      | T. M.       |
| 23 - 24/06/05 | SAAO  | Blue             | 2         | 0.50                      | T. M.       |
| 06/02/06     | WHT-R | $H_{\alpha}$     | 2         | 0.22                      | G. N.       |
| 09/03/07     | WHT-B | Blue             | 2         | 0.44                      | G. N.       |
| 27/03 - 07/04/07 | INT-B | Blue             | 11        | 0.48                      | T. M.       |
| 29 - 31/03/07 | WHT-R | $H_{\alpha}$     | 5         | 0.25                      | G. N.       |
| 21 - 22/03/08 | INT-B | Blue             | 4         | 0.48                      | C. C.       |
| 01/05/08     | WHT-R | $H_{\alpha}$     | 2         | 0.49                      | P. M.       |
| 11/03/09     | WHT-B | Blue             | 2         | 0.44                      | P. M.       |
| 30/04/09     | WHT-R | $H_{\alpha}$     | 4         | 0.25                      | T. M.       |
| 03/04/10     | WHT-B | Blue             | 4         | 0.44                      | T. M.       |
| 06/12/07 - 23/03/10 | HET  | $H_{\alpha}$ + Blue | 7 | 0.12 | R. W & M. S. |

\textsuperscript{2} Developed by Eric Stempels (http://www.not.iac.es/instruments/fies/FIEStool/FIEStool.html)
Figure 1. The mean spectrum of PG 1018–047 for the region covering Hβ to Hι (left) and the region around Hα (right). Plotted below the mean spectrum (shifted down for clarity) is a model spectrum for an sdB star (see text for details). Lines from the K-dwarf are clearly seen in the red part, but the lines in the blue are from the sdB.

Table 2. Narrow absorption lines present in the optical spectrum (Figure 1). The identification was done using the mid- and high-resolution spectral library of Montes et al. (1997) and also Ralchenko et al. (2010). The lines with a * were included in the template to determine the radial velocities of the secondary (see section 3.2.3). For reference, we have added the wavelengths for the Balmer lines we adopted in our analysis as well.

| λ (Å) | Element | λ (Å) | Element | λ (Å) | Element |
|-------|---------|-------|---------|-------|---------|
| 4153.30 | O II | 4596.17 | O II | 6337.28* | 6609.05* |
| 4164.79 | Fe III, blend | 4630.54 | N I | 6359.45* | 6614.42* |
| 4189.80 | O II | 4639.70 | O II, blend | 6363.71* | 6637.09* |
| 4253.59 | S III + O II | 4642.26 | O II, N II | 6394.45* | 6644.39* |
| 4276.74 | O II, blend | 4649.14 | O II | 6400.43* | 6664.37* |
| 4414.91 | O II | 4664.01 | O II | 6408.96* | 6678.97* |
| 4416.58 | O II | 4676.23 | O II | 6412.37* |
| 4442.49 | O II | 4700.31 | O II, blend | 6422.05* | 4101.735 Hδ |
| 4552.65 | Si III | 4705.44 | O II | 6431.44* | 4340.465 Hγ |
| 4567.87 | Si III | 4710.04 | O II | 6439.70* | 4861.327 Hβ |
| 4574.78 | Si III | 4711.04 | O II | 6450.51* | 6562.800 Hα |
| 4590.57 | O II | 6335.83* | 6456.49* |

paring the model to the normalized average spectrum over all observations; see Maxted, Marsh & Morard (2003) for further details of this procedure. For the blue spectra we fit simultaneously for Hβ, Hγ and Hδ, whereas for the red spectra only the Hα line can be fitted. The RV of the NOT spectrum was determined using a model containing Hα, Hβ and Hγ (see also Table 2). The radial velocities from the 7 HET spectra are obtained from the Hβ absorption line using simple Gaussian fitting to the core of the line within the IRAF "splot" task. A list of the radial velocities and the uncertainties measured is given in Table 3.

3.2.2 Orbital parameters

Once the radial velocities for all spectra were known, we used the floating mean periodogram (Cumming, Marcy & Butler 1999), a generalization of the well-known Lomb-Scargle periodogram (Lomb 1976; Scargle 1982), to determine the most probable frequencies (periods) present in the data. The method consists in fitting the radial velocity data with a model composed of a sinusoidal plus a constant of the form:

\[ v = \gamma + K \sin[2\pi f(t - t_0)], \]

with \( f \) the frequency and \( t \) the time of observation. This means we assume the binary system to have a circular orbit with semi-amplitude \( K \) and a systemic velocity \( \gamma \). For each frequency (\( f=1/P \)) we perform least squares fitting of the data, solving for \( \gamma \) and \( K \) simultaneously using singular value decomposition (Press et al. 2002). In this way we can obtain the \( \chi^2 \) statistic of the model as a function of frequency, or in other words the periodogram.

In our initial period determination, the \( \chi^2 \) values turned out larger than expected given the number of data points, indicating that there must have been an extra unaccounted source of uncertainty, most likely due to systemic effects, intrinsic variability of the star or slit-filling errors (see also Morales-Rueda et al. 2003). Such errors are unlikely to be correlated with either the orbit or the statistical errors we have estimated. To allow for this we compute the level of systematic uncertainty (\( \sigma \)) per telescope that when added in quadrature to our error estimates gives a reduced \( \chi^2 \) ≈ 1 for each of the INT, WHT subsets, telescope by telescope, relat-
Table 3. The 125 radial velocity measurements for PG 1018–047 with their formal errors from the least squares fitting routine.

| HJD  | RV  | HJD  | RV  | HJD  | RV  |
|------|-----|------|-----|------|-----|
| -2450000 | 31.3 ± 4.4 | -2450000 | 49.8 ± 3.0 | -2450000 | 52.1 ± 1.4 |
| 1646.47135 | 2741.52795 | 4189.54710 | 1646.47650 | 2741.53909 | 4189.54712 |
| 1654.46074 | 2741.54857 | 4190.40980 | 1654.46780 | 2741.55807 | 4190.40982 |
| 1977.48220 | 2743.42040 | 50.4 ± 4.5 | 1978.62533 | 2743.43451 | 60.3 ± 4.5 |
| 1979.54044 | 2743.52128 | 4190.42422 | 1979.59958 | 2744.35895 | 54.3 ± 3.5 |
| 1979.60655 | 2744.37308 | 4191.59767 | 51.4 ± 2.7 | 1982.51489 | 2744.39186 |
| 1982.52185 | 54.6 ± 4.1 | 1985.6118 | 53.9 ± 2.6 | 1985.62457 |
| 1982.55421 | 75.7 ± 4.0 | 1986.6059 | 52.6 ± 2.6 | 38.1 ± 4.5 |
| 1982.60755 | 75.7 ± 4.0 | 1986.6118 | 52.6 ± 2.6 | 38.1 ± 4.5 |
| 2031.36769 | 62.1 ± 8.3 | 2034.4097 | 51.4 ± 2.8 | 4441.00811 |
| 2031.37466 | 41.4 ± 8.4 | 2034.4097 | 51.4 ± 2.8 | 39.7 ± 2.0 |
| 2031.38641 | 49.5 ± 4.4 | 2034.44131 | 54.6 ± 2.5 | 4502.85094 |
| 2032.48243 | 54.9 ± 3.0 | 2034.45544 | 51.0 ± 2.5 | 33.5 ± 2.0 |
| 2032.49633 | 53.6 ± 3.5 | 2034.47412 | 55.4 ± 2.2 | 4547.37872 |
| 2033.39672 | 53.8 ± 4.1 | 2034.48824 | 44.8 ± 2.3 | 33.0 ± 1.7 |
| 2033.40369 | 53.8 ± 4.3 | 2035.38227 | 26.8 ± 6.7 | 4547.62144 |
| 2037.45584 | 54.1 ± 3.8 | 2035.40366 | 19.0 ± 6.6 | 29.6 ± 2.0 |
| 2037.46282 | 50.9 ± 3.5 | 2035.45840 | 12.9 ± 9.8 | 26.7 ± 2.0 |
| 2360.56683 | -33.8 ± 25.0 | 2361.31890 | 18.8 ± 9.2 | 29.7 ± 2.5 |
| 2360.77459 | -4.6 ± 22.9 | 2361.31890 | 19.7 ± 8.7 | 4588.35125 |
| 2362.66641 | 17.5 ± 19.3 | 2364.21953 | 51.4 ± 7.2 | 22.8 ± 2.6 |
| 2362.38049 | 5.4 ± 20.3 | 2364.21953 | 51.4 ± 7.2 | 4588.35646 |
| 2364.39275 | 23.1 ± 6.0 | 2364.28768 | 52.6 ± 5.8 | 29.5 ± 2.5 |
| 2364.40338 | 17.9 ± 6.7 | 2364.55466 | 35.6 ± 0.8 | 4902.42320 |
| 2390.51113 | 34.6 ± 17.1 | 2392.68564 | 15.3 ± 0.9 | 34.8 ± 4.5 |
| 2390.52179 | 32.8 ± 9.0 | 2392.68565 | 34.6 ± 1.4 | 4592.38359 |
| 2391.37270 | 30.1 ± 4.3 | 2392.68565 | 34.6 ± 1.4 | 54.3 ± 5.1 |
| 2391.38337 | 32.7 ± 3.6 | 2392.43214 | 43.8 ± 1.2 | 4592.39761 |
| 2392.36580 | 28.3 ± 2.1 | 2392.43214 | 43.8 ± 1.2 | 53.6 ± 3.9 |
| 2392.37993 | 24.5 ± 2.0 | 2392.46774 | 52.6 ± 6.1 | 4592.39762 |
| 2379.51074 | 45.0 ± 3.6 | 2392.46774 | 52.6 ± 6.1 | 49.6 ± 2.2 |
| 2379.52029 | 46.7 ± 3.8 | 2392.46774 | 52.6 ± 6.1 | 54.3 ± 2.9 |
| 2379.54514 | 49.3 ± 3.2 | 2394.43726 | 39.9 ± 3.0 | 4592.41400 |
| 2379.54566 | 51.9 ± 3.0 | 2394.43726 | 39.9 ± 3.0 | 58.4 ± 1.8 |
| 2474.50896 | 49.7 ± 3.1 | 2489.53608 | 49.9 ± 1.5 | 5295.96094 |
| 2474.51846 | 49.4 ± 3.1 | 2489.53609 | 49.9 ± 1.5 | 35.0 ± 1.6 |

* The SAAO science frames belonging to these 4 radial velocities were made with very marginal observing conditions. The resulting unreliable RVs are therefore not considered in the remaining analysis.
** This is a discrepant WHT data point, taken during service observations in 2006. It is not in line with the other data taken at the same night and therefore given no weight in the remaining analysis.
♦ For the blue WHT science frames belonging to these two RVs, only a single arc frame was available, taken before the first of the two subsequent observations.
♣ These two WHT observations in the $H_\beta - H_\delta$ region had no flat fields or bias frames available.

\[ \sigma_{\text{INT}} = 2.15 \text{ km s}^{-1} \] and \[ \sigma_{\text{WHT}} = 3.4 \text{ km s}^{-1} \] for respectively the INT and WHT data. The formal NOT and HET errors were left unchanged since these are fibre-fed instruments which do not suffer from normal slit-guiding errors. Also the 9 SAAO RVs were left as they were. Second we used the average residual from each data set to our best orbital fit at that point to apply offsets to the INT, WHT and SAAO data set\(^a\) (respectively 0.85, -2.00 and 4.63 km s\(^{-1}\), predicted minus observed). Finally, we scale the errors of the entire data set multiplicatively by a factor 1.244 to obtain a $\chi^2$ value equal to the degrees of freedom (dof).

Figure\(^b\) shows the resulting radial velocity periodogram for PG 1018–047 in the region where we find the lowest $\chi^2$ values. The best solution is found around 760 days, followed by a group of 1 day aliases and the yearly aliases of the long period around 250 days. An overview of the best aliases with their corresponding $\chi^2$ values is given in Table\(^c\). Given the large inhomogeneity of the data sets, we realize that the treatment of the errors described above might not be perfect in all details. Therefore we have con-

\(^3\) Table\(^a\) presents the RVs at this stage.
given the properties of the secondary.

star and vice versa to show that our orbital solution is plausible
numbers will be used later to constrain the nature of the companion
of

The minimum mass of the companion, assuming a typical sdB mass
calculated using
determined the radial velocities of the secondary by means of cross
so we focussed on the HET, NOT and red WHT/INT spectra. We
did not contain enough signal from the companion to be useful,
radial velocity variations for the secondary star. The bluespectra
the Balmer absorption lines from the sdB star, allowing us toobtain
Narrow metal lines of a cool companion were present in addition to

3.2.3 The secondary orbit

Figure 2. The radial velocity periodogram for PG 1018–047, showing
the most probable orbital periods present in the data.

Table 4. The best orbital periods found from the radial velocity period-
ogram for PG 1018–047. The $\chi^2$ value, mass function of the companion
and the minimum mass of the companion obtained by assuming an sdB
mass of 0.5 $M_\odot$ are also given.

| Alias | Period (d) | $\chi^2$ | $f_m (M_\odot)$ | $M_{2\min} (M_\odot)$ |
|-------|-----------|---------|----------------|------------------|
| 1     | 759.80    | 117     | 0.17245        | 0.58927          |
| 2     | 0.9987    | 188     | 0.00018        | 0.03704          |
| 3     | 241.35    | 238     | 0.02602        | 0.24313          |
| 4     | 267.93    | 258     | 0.05582        | 0.34031          |
| 5     | 1.0184    | 259     | 0.00013        | 0.03332          |

considered alternative methods to weight the data and errors as well,
but the essential result, the long period, was unchanged throughout.

In Table 4 we also quote the mass functions of the companion,
calculated using

$$f_m = \frac{M_{\text{MS}}^3 \sin^3 i}{(M_{\text{sdB}} + M_{\text{MS}})^2} = \frac{PK_{\text{sdB}}^2}{2\pi G}.$$  \hspace{1cm} (2)

The minimum mass of the companion, assuming a typical sdB mass
of 0.5 $M_\odot$ (Heber et al. 1984), is also given in each case. These
numbers will be used later to constrain the nature of the companion
star and vice versa to show that our orbital solution is plausible
given the properties of the secondary.

Table 5 lists the orbital parameters for our best orbital solution
found for PG 1018–047 and in Figure 3 the radial velocity curve
folded on the period is shown.

3.2.3 The secondary orbit

Figure 3. The radial velocity curve for PG 1018–047, showing the
most probable orbital periods present in the data.

Table 5. The best orbital solution for PG 1018–047 assuming a circular
and eccentric orbit.

| Circular | Eccentric |
|----------|-----------|
| $P_{\text{orb}}$ (d) | 759.8±5.8 | 755.9±5.1 |
| $\gamma$ (km/s) | 38.2±0.5 | 38.0±0.9 |
| $e$ | 0 | 0.246±0.052 |
| $\omega$ (°) | 0±24 | |
| HJD$_0$ (d) | 2453335.0±10.5 | 2453343.0±14.7 |
| $K_{\text{sdB}}$ (km/s) | 13.0±0.8 | 12.6±0.8 |
| $K_{\text{MS}}$ (km/s) | 8.1±1.0 | |

Narrow metal lines of a cool companion were present in addition to
the Balmer absorption lines from the sdB star, allowing us to obtain
radial velocity variations for the secondary star. The blue spectra
did not contain enough signal from the companion to be useful,
so we focussed on the HET, NOT and red WHT/INT spectra. We
determined the radial velocities of the secondary by means of cross
correlation with a template spectrum (Tonry & Davis 1979).

Table 6. The radial velocities of the cool companion.

| Bin | # spectra in bin | Average RV |
|-----|-----------------|------------|
|     |                 | (km/s)     |
| 0.100 - 0.125 | 2 | 0.1247 | 35.7 ± 1.9 |
| 0.125 - 0.150 | 7 | 0.1277 | 32.9 ± 1.3 |
| 0.200 - 0.225 | 11 | 0.2176 | 29.2 ± 3.3 |
| 0.250 - 0.275 | 9 | 0.2867 | 29.0 ± 4.3 |
| 0.4556 | HET | 36.7 ± 2.8 |
| 0.4585 | HET | 34.8 ± 0.9 |
| 0.4937 | HET | 39.0 ± 1.5 |
| 0.5370 | HET | 41.3 ± 1.1 |
| 0.5583 | HET | 41.9 ± 0.7 |
| 0.575 - 0.600 | 2 | 0.5759 | 43.5 ± 2.2 |
| 0.5810 | NOT | 40.2 ± 0.6 |
| 0.6000 | HET | 44.5 ± 1.1 |
| 0.6158 | HET | 43.6 ± 0.6 |
| 0.625 - 0.650 | 2 | 0.6496 | 39.4 ± 4.9 |
| 0.775 - 0.800 | 4 | 0.7826 | 44.8 ± 4.9 |

For the HET data we cross-correlated with 61 Cyg B (K7V),
which was obtained as part of a different program on April
15, 2010, using HRS in its R = 30,000 mode with a 316
groove/mm millimeter cross disperser centred at 6948 Å. As a result
only seven orders from the red CCD (six, on one night) were avail-
able for cross correlation, covering 6000 - 6760 Å (orders contain-
ing least squares fitting we estimated the projected semi-amplitude
$K_{\text{sdB}}$ of the secondary was fitted with a Gaussian profile, similar to the method
described in section 3.2.1. All features possibly originating in the
primary or of telluric origin were masked out, leaving a total of 19
lines from the cool companion in the template (see also Table 2).

Unfortunately the quality of the secondary radial velocities
obtained from the red INT and WHT spectra were not sufficient
to derive any trustworthy orbital period from a periodogram or to
estimate the orbital semi-amplitude $K_{\text{MS}}$ for the secondary. We
therefore used our best orbital period obtained from the primary
RVs (Table 5) to phase-bin the 37 medium-resolution red spectra
before the cross-correlation routine. In total 7 out of 40 bins are
filled. The HET and NOT spectra were left unbinned.

In Figure 4 we have plotted phase versus radial velocity. Us-
ing least squares fitting we estimated the projected semi-amplitude
of the secondary to be $K_{\text{MS}} = 8.1 ± 1.0$ km/s, which con-
strains the mass ratio of the secondary to the primary star to be
$q = M_{\text{MS}}/M_{\text{sdB}} = 1.6 ± 0.2$. The $\chi^2$ value of the fit was 13.29,
given 15 data points minus 2 fitting parameters.
3.2.4 Eccentricity of the orbit

In sections 3.2.2 and 3.2.3 the analysis was based upon the assumption that PG1018-047 has a circular orbit. However, we also tried fitting eccentric orbits using the Markov chain Monte Carlo (MCMC; Gilks, Richardson & Spiegelhalter 1995) method obtaining an eccentricity of $0.246 \pm 0.052$; the favoured period for these fits decreased from $759.8 \pm 5.7$ days to $755.9 \pm 5.1$ days and had $\chi^2 = 152$, starting from the radial velocities in Table A1. To obtain $\chi^2$/dof = 1 we needed to scale the errors by a factor 1.153. Table 5 presents the orbital parameters. The argument of periapsis ($\omega$) is defined as the angle in the orbital plane between the ascending node and the line of apsides. 0 degrees indicates that the major axis of the ellipse is in the plane of sky. Note as well that HJD$_0$ is given as the ascending node passage minus $P_{\text{orb}}/4$ to be consistent with our definition for the circular orbit (see eq. 1).

Computing the F-statistic we tested whether eccentricity was needed in our model. Assuming a locally linear model, the variable $X = \chi^2_{\text{circ}} - \chi^2_{\text{ecc}}$ should itself have a $\chi^2$ distribution with 2 dof (the eccentricity fit parameters), independent of the $\chi^2$ of the 114 degrees of freedom of the eccentric orbit.

$$F = \frac{(\chi^2_{\text{circ}} - \chi^2_{\text{ecc}})/2}{\chi^2_{\text{ecc}}/114} = 11.24$$

should then be distributed as F(2;114) under the null hypothesis that the orbit is circular. The chances of such a large value are very small, meaning we reject the null hypothesis at the 99.9% significance level in favour of an eccentric orbit. Although formally significant the heterogeneous nature of our data and the limited phase coverage lead us to be wary of claiming a definitive detection of eccentricity. However, it is equally true that the orbit could be significantly non-circular.

3.3 The nature of the companion

We determined the spectral type of the companion star by minimizing the residuals after subtracting different template star spectra from the mean red PG 1018–047 spectrum in the wavelength region between 6390 Å and 6700 Å. We masked out $H\alpha$, because the line contains a large contribution from the sdB. This optimal subtraction routine (Marsh, Robinson & Wood 1994) is sensitive to both the rotational broadening $v_{\text{rot}} \sin \ i$ and the fractional contribution $f$ of the companion star to the total flux. We used template stars from two different origins in the spectral range F0 to M9: Kurucz models (Munari et al. 2005, solar composition) and 43 real star templates (Montes et al. 1997). All templates were prepared so that they had the same wavelength coverage and resolution as our normalised PG 1018–047 spectrum in the $H\alpha$ region.

Figure 5 clearly shows the difference in $\chi^2$ between the dwarf and (sub)giant templates. The main sequence models, which have the lowest $\chi^2$-values, show a distinct minimum at spectral type K4 - K6, whereas the (sub)giant models seem to converge to a spectral type G5. This is consistent with the set of template spectra from Montes et al. (1997) as well, where we find the best $\chi^2$ for the K5V star HD 201091 (61 Cyg A), followed by a K7V and K3V star. For M stars the worst values are found. The best non-dwarf templates were both G5 stars.
Figure 4. The orbital fit for the secondary star. The red triangles are the radial velocities from the cool companion, obtained from the intermediate resolution spectroscopy. The NOT measurement is plotted with a blue dot and the HET data with black squares. The radial velocity curve (dashed green) is also shown.

Figure 5. Results of the optimal subtraction routine for the Kurucz templates. The circle curve are the results for dwarf stars, whereas the triangles and squares plot the reduced $\chi^2$ versus spectral type for respectively subgiant and giant stars.

Since PG 1018–047 was observed by 2MASS, we adopt a similar approach as Stark and Wade (2003) as a complementary way to identify the spectral type of the companion star. We choose to focus on $J - K_S$ versus $B - V$ and $J - K_S$ versus $V - K_S$ and converted the Strömgren magnitudes to the Johnson system following the approach of Turner (1990). The calculated colours are given in the lower part of Table 7.

The next step is to compare the PG 1018–047 colours to a theoretical grid of colours for sdB-MS binaries while varying the fraction of light at $V$ that arises from the companion. Defining this fraction as

$$f = \frac{F_{V_{\text{MS}}}}{F_V} = \frac{F_{V_{\text{sdB}}} + F_{V_{\text{MS}}}}{F_V}$$

we find the combined colour (e.g. for $B-V$) from the expression

$$\langle B - V \rangle_{\text{sdB+MS}} = -2.5 \log [(1 - f) \cdot 10^{-(B-V)_{\text{sdB}}/2.5} + f \cdot 10^{-(B-V)_{\text{MS}}/2.5}].$$

Colour indices for late-type stars are taken from Johnson (1966). The typical colours for a single sdB we take from Stark and Wade (2003).

Figure 6 shows that as the fractional contribution $f$ at $V$ from the secondary increases, the $B - V$ index shifts to redder values. On the other hand, the cooler the companion becomes, the more the $K_S$-band dominates the $J - K_S$ index. Swapping the $B - V$ index for the $V - K_S$ colour shows a similar trend. Zooming in on

Table 7. Magnitudes and colours for PG 1018–047. The $B - V$ colour is calculated using the transformation formula from Turner (1990).

| 2MASS (infrared) (Skrutskie et al. 2006) | Strömgren (visual) (Wesemael et al 1992) |
|------------------------------------------|------------------------------------------|
| $J = 13.298 \pm (.026)$                  | $y = 13.320 \pm (.005)$                 |
| $H = 12.980 \pm (.027)$                  | $b-y = -0.086 \pm (.004)$              |
| $K_S = 12.928 \pm (.033)$                | $u-b = -0.073 \pm (.006)$              |

Calculated colours

| $B-V$     | $-0.20 \pm (.007)$ |
|-----------|---------------------|
| $J-K_S$   | $0.370 \pm (.042)$  |
| $V-K_S$   | $0.392 \pm (.038)$  |
Figure 6. Grid of composite colours in \( B - V \) versus \( J - K_S \) space by combining the light from a typical hot subdwarf with that of a population I main-sequence star assuming various fractional contributions to the total light in the \( V \) band by the late-type star. The blue dot marks the values for PG 1018–047. A close-up is shown in the small inset figure. The diagonal cyan line indicates the location of the population I main sequence.

PG 1018–047, we find a spectral classification \( K3 - K6 \), which is consistent with the results from the optimal subtraction routine. We estimate the contribution of the secondary to be \( 6.1 \pm 1.0 \% \) in the \( V \)-band.

4 DISCUSSION

The role of the long period binary system PG 1018–047 in refining our understanding of the origin and evolution of hot subdwarf stars depends on whether its present orbit is circular or eccentric.

4.1 Evolution assuming a circular orbit

If PG 1018–047 indeed has a circular orbit, one can assume that tidal interaction has occurred between the sdB and the dK5 star. This means that from a theoretical point of view PG 1018–047 might be an important system, as it becomes a good candidate for formation through the first stable Roche lobe overflow channel described by Han et al. (2003). From Figure 15 in Han et al. (2003) we deduce that an sdB binary with a mid-K companion is feasible. However these systems are all subgiants and giants evolved from B stars (i.e. more massive stars at a later evolutionary state). Also, to have stable RLOF on the first giant branch onto a companion that is only 0.6-0.7 \( M_\odot \) and still to end up with such a long period, mass transfer would have to be close to conservative to avoid excessive angular momentum loss. If we want the mass donor to evolve in a Hubble time, it must have started with an initial mass of 0.8 \( M_\odot \) or greater, meaning that the initial mass of the present K star must have been no more than \( \sim 0.3-0.4 \ M_\odot \). But then the initial mass ratio \( q_0 \gtrsim 2 \) is not compatible with conservative mass transfer on the red giant branch, leading to a contradiction.

Second we can consider the alternative common-envelope prescription from Nelemans et al. (2000). In Nelemans (2010), a population of sdB stars is simulated in which the first phase of mass transfer can be described by this alternative common-envelope prescription (Nelemans et al. 2001a). Interestingly, in that model a substantial fraction of the sdB stars with low and intermediate mass main sequence companions have rather large orbital periods (100-1000 days, see their Figure 2) and the parameters of PG 1018–047 actually fall right in a densely populated area of the model. Thus a sample of these long-period sdB binaries will give another way of testing the outcome of the common-envelope phase.

4.2 Evolution assuming an eccentric orbit

Clausen & Wade (2011) propose that binaries similar to PG 1018–047 can be the remnants of original hierarchical triple systems, in which the inner binary has merged and evolved into the sdB star, and the outer (current sdB+MS) binary was never tidally interacting and is thus irrelevant to the production of the sdB. In the Han et al. (2002, 2003) merger scenario, two helium white dwarfs merge to make an object capable of core helium burning, and the resulting range of masses for the sdB star is 0.3-0.8 \( M_\odot \). In the new formation channel proposed by Clausen & Wade (2011), a helium white...
dwarf merges with a low-mass hydrogen-burning star whose resultant total mass is \( \sim 0.6 \, M_\odot \). Depending on the mixing history, this object has either a pre-formed helium core or is helium-enriched throughout, and the star experiences a greatly accelerated evolution to the tip of the red giant branch. Only minimal loss is required to remove the residual hydrogen envelope from this object at the time of normal degenerate helium ignition, so the expected mass range for the sdB star in this channel is narrow and at the “canonical” value \( \sim 0.5 \, M_\odot \). There is ample room inside the \( \sim 760 \) day orbit of the present-day PG 1018–047 binary system to accommodate an inner binary which underwent such evolution, and there is no cause for the outer orbit to have been circularised. The [Clausen & Wade (2011)] scenario could account for stars like PG 1018–047 with long (and possibly eccentric) binary orbits. Stable RLOF on the other hand predicts perfectly circular orbits.

5 CONCLUSIONS

With an orbital period of \( 760 \pm 4.7 \) days, PG 1018–047 is the first long period sdB+MS system for which a period has been determined. The spectral type of the companion was found to be a K5 dwarf star, consistent with the mass ratio \( M_{\text{MS}}/M_{\text{sdB}} = 1.6 \pm 0.2 \) derived from the radial velocity amplitudes of both stars. However, one has to note that the stated numbers are only indicative of the true orbital parameters, since they are sensitive to the exact uncertainties assigned to the RV data and the assumption of a circular versus eccentric orbit.

At first sight PG 1018–047 is a good candidate for formation through stable Roche lobe overflow if the orbit can be demonstrated to be circular. The predicted number of sdB binaries formed through this channel amounts to the largest contribution of sdB binaries according to binary population synthesis calculations [Han et al. (2002, 2003)]. At the same time, the number of known binaries that have been confirmed as having formed through this channel is small/nil compared to those formed through the common envelope channels. Alternatively, if the common envelope is governed by the gamma-formalism for the common envelope, as used in Nelemans (2010), there is a population of long period post-common envelope binaries with low-mass secondaries. Thus observing more of these binaries can constrain the first phase of mass transfer.

If the orbit turns out to be eccentric, the present binary may instead be the remnant of a hierarchical triple-star progenitor system, as outlined by Clausen & Wade (2011). Further observations are needed to better establish the orbit of PG 1018–047.

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References

Allard F., Wesemael F., Fontaine G., Bergeron P., Lamontagne R., 1994, AJ, 107, 1565
Bixel J. V., Bowyer S., Laget M., 1991, A&A, 250, 370
Brassard P., Fontaine G., Billères M., Charpinet S., Liebert J., Saffer R.A., 2001, ApJ, 563, 1013
Brown T. M., Ferguson H. C., Davidsen A.F., Dorman B., 1997, ApJ, 482, 685
Brown T. M., Bowers C. W., Kimble R. A., Sweigart A. V., Ferguson H. C., 2000, ApJ, 532, 308
Carroll B. W., Ostlie D. A., An introduction to modern astrophysics, 2007, Pearson Addison-Wesley
Casares J., Charles P. A., Naylor T., Pavlenko E. P., 1993, MNRAS, 265, 834
Charpinet S., Fontaine G., Brassard P., Dorman P., 1996, ApJ Letters, 471, L103
Charpinet S., Fontaine G., Brassard P., Green E. M., Chayer P., 2005, A&A, 437, 575
Clausen D., Wade R. A., 2011, ApJ, 733, L42
Copperwheat C. M., Morales-Rueda L., Marsh T. R., Maxted P. F. L., Heber U., 2011, MNRAS, 410, 1113
Cumming A., Marcy G. W., Butler R. P., 1999, ApJ, 526, 890
Ferguson D. H., Green R. F., Liebert J., 1984, ApJ, 287, 320
Ferguson H. C. et al., 1991, ApJ, 382, 575
Fontaine G., Brassard P., Charpinet S., Green E. M., Chayer P., Randall S. K., van Grootel V., 2008, ASP Conf. Ser., 392, 231
Geier S. et al., 2011, A&A, 530, A28
Gilks W. R., Richardson S., Spiegelhalter D., Markov Chain Monte Carlo in Practice, 1995, Chapman & Hall
Green R. F., Schmidt M., Liebert J., 1986, ApJ Sup. Ser., 61, 305
Green E. M. et al., 2003, ApJ, 583, L31
Han Z., Podsiadlowski Ph., Maxted P. F. L., Marsh T. R., Ivanova N., 2002, MNRAS, 336, 449
Han Z., Podsiadlowski Ph., Maxted P. F. L., Marshall T. R., 2003, MNRAS, 341, 669
Han Z., Podsiadlowski Ph., Lysaght A. E., 2008, MNRAS, 380, 1098
Heber U., Hunger K., Jonas G., Kudritzki R. P., 1993, A&A, 130, 119
Heber U., 1986, A&A, 155, 33
Heber U., Reid I. N., Werner K., 2000, A&A, 363, 198
Heber U., 2009, ARA&A, 47, 211
Home K., 1986, PASP, 98, 609
Johnson H. L., 1966, A&A, 4, 193
Kilkenny D., Koen C., O’Donoghue D., Stobie R. S., 1997, MNRAS, 285, 640
Kilkenny D., O’Donoghue D., Koen C., Lysaght A. E., van Wyk F., 1998, MNRAS, 296, 329
In table A1 we report the radial velocity values for PG 1018–047 with error and offset correction, as used for the final orbital fit results.

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Table A1. Radial velocity measurements for PG 1018–047 with error and offset correction, as used for the final orbital fit results.

| HJD   | RV (km/s) | HJD   | RV (km/s) | HJD   | RV (km/s) |
|-------|-----------|-------|-----------|-------|-----------|
| -245000 |           | -245000 |           | -245000 |           |
| INT-B      |           | WHT-B      |           | σ = 2.15 km s^{-1}, off = +0.85 km s^{-1} | σ = 3.40 km s^{-1}, off = -2.01 km s^{-1} |
| 2390.51113 | 4179.52585 | 44.4 ± 2.9 | 2390.51279 | 4547.37872 | 33.9 ± 2.7 | 3772.55466 | 33.5 ± 3.5 |
| 2391.37270 | 536.3 ± 2.0 | 11.3 ± 2.9 | 2391.38337 | 4902.42320 | 35.7 ± 4.9 | 4169.44290 | 45.2 ± 3.7 |
| 2392.36580 | 1634.4 ± 3.0 | 37.5 ± 5.4 | 2392.37993 | 4902.44418 | 37.5 ± 5.4 | 4169.45704 | 45.4 ± 4.0 |
| 2393.51074 | 45.9 ± 4.2 | 37.5 ± 4.2 | 2394.45614 | 1646.47135 | 32.1 ± 4.9 | 4189.53609 | 40.5 ± 3.6 |
| 2394.50986 | 50.6 ± 3.9 | 21.3 ± 4.8 | 2395.50789 | 1646.46760 | 21.3 ± 4.8 | 4190.42422 | 48.7 ± 3.5 |
| 2395.51846 | 52.7 ± 3.7 | 25.6 ± 4.3 | 2395.52795 | 1977.48220 | 50.4 ± 5.7 | 4588.35123 | 27.7 ± 4.3 |
| 2395.53909 | 54.2 ± 3.7 | 32.9 ± 4.3 | 2396.54857 | 1979.54044 | 50.8 ± 3.9 | 4952.38360 | 53.1 ± 4.4 |
| 2396.55807 | 49.7 ± 4.0 | 66.3 ± 4.0 | 2397.42040 | 1982.51489 | 53.0 ± 4.4 | 4952.42802 | 56.4 ± 3.8 |
| 2397.43451 | 61.1 ± 5.0 | 55.5 ± 4.6 | 2398.42128 | 1982.52185 | 55.5 ± 4.6 | 4952.42802 | 56.4 ± 3.8 |
| 2398.54598 | 50.5 ± 3.6 | 58.7 ± 4.5 | 2399.53895 | 1982.56118 | 53.4 ± 4.4 | 3772.55467 | 24.7 ± 3.6 |
| 2399.53916 | 52.3 ± 3.5 | 58.4 ± 4.4 | 2400.45465 | 1982.60599 | 50.4 ± 4.5 | 4189.53609 | 47.9 ± 3.8 |
| 2400.45929 | 54.7 ± 3.3 | 62.9 ± 8.6 | 2401.36769 | 1982.67555 | 54.0 ± 4.9 | 4190.40980 | 49.9 ± 3.6 |
| 2401.43491 | 51.3 ± 3.3 | 25.8 ± 4.3 | 2402.43547 | 1982.50404 | 53.0 ± 4.9 | 4191.59677 | 50.1 ± 3.7 |
| 2402.43798 | 49.6 ± 4.1 | 32.8 ± 4.9 | 2403.43963 | 1982.48243 | 55.7 ± 3.7 | 4588.35123 | 32.2 ± 4.4 |
| 2403.43999 | 46.1 ± 3.7 | 54.5 ± 4.1 | 2404.43963 | 1982.48243 | 55.7 ± 3.7 | 4588.35646 | 20.7 ± 4.3 |
| 2404.45087 | 52.2 ± 3.5 | 54.7 ± 4.6 | 2405.49087 | 1982.39672 | 54.7 ± 4.6 | 4952.38359 | 52.3 ± 6.2 |
| 2405.45399 | 52.7 ± 3.4 | 54.6 ± 4.8 | 2406.43069 | 1982.43069 | 54.6 ± 4.8 | 4952.39761 | 51.6 ± 5.2 |
| 2406.44131 | 55.4 ± 3.3 | 49.4 ± 4.4 | 2407.45584 | 1982.43069 | 54.9 ± 4.4 | 4952.41340 | 49.8 ± 4.5 |
| 2407.45544 | 51.8 ± 3.3 | 41.8 ± 4.1 | 2408.46282 | 1982.43069 | 51.8 ± 4.1 | 4952.42802 | 49.1 ± 4.1 |
| 2408.47412 | 56.2 ± 3.1 |         | 2409.48284 | 1982.55421 | 58.7 ± 4.5 | 4952.42802 | 49.1 ± 4.1 |
| 2409.48573 | 45.7 ± 3.2 |         | 2410.49579 | 1982.55421 | 58.7 ± 4.5 | 4952.42802 | 49.1 ± 4.1 |
| 2410.49701 | 38.8 ± 4.2 |         | 2411.50581 | 1982.55421 | 58.7 ± 4.5 | 4952.42802 | 49.1 ± 4.1 |
| 2411.40925 | 40.9 ± 12.0 |         | 2412.41925 | 1982.55421 | 58.7 ± 4.5 | 4952.42802 | 49.1 ± 4.1 |
| 2412.43328 | 42.9 ± 3.6 |         | 2413.43328 | 1982.55421 | 58.7 ± 4.5 | 4952.42802 | 49.1 ± 4.1 |
| 2413.43719 | 52.2 ± 8.1 |         | 2414.43719 | 1982.55421 | 58.7 ± 4.5 | 4952.42802 | 49.1 ± 4.1 |
| 2414.43719 | 42.4 ± 2.9 |         | 2415.43719 | 1982.55421 | 58.7 ± 4.5 | 4952.42802 | 49.1 ± 4.1 |
| 2415.43719 | 37.2 ± 2.7 |         | 2416.43719 | 1982.55421 | 58.7 ± 4.5 | 4952.42802 | 49.1 ± 4.1 |
| 2416.43719 | 36.3 ± 3.3 |         | 2417.43719 | 1982.55421 | 58.7 ± 4.5 | 4952.42802 | 49.1 ± 4.1 |
| 2417.43719 | 39.0 ± 4.9 |         | 2418.43719 | 1982.55421 | 58.7 ± 4.5 | 4952.42802 | 49.1 ± 4.1 |
| 2418.43719 | 44.6 ± 2.8 |         | 2419.43719 | 1982.55421 | 58.7 ± 4.5 | 4952.42802 | 49.1 ± 4.1 |

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