SDSS J0349-0059 is a GW Virginis star

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ABSTRACT

High speed photometric observations of the spectroscopically-discovered PG 1159 star SDSS J034917.41-005917.9 in 2007 and 2009 reveal a suite of pulsation frequencies in the range of 1038 – 3323 µHz with amplitudes between 3.5 and 18.6 mmag. SDSS J034917.41-005917.9 is therefore a member of the GW Vir class of pulsating pre-white dwarfs. We have identified 10 independent pulsation frequencies that can be fitted by an asymptotic model with a constant period spacing of 23.61 ± 0.21 s, presumably associated with a sequence of ℓ = 1 modes. The highest amplitude peak in the suite of frequencies shows evidence for a triplet structure, with a frequency separation of 14.4 µHz. Five of the identified frequencies do not fit the ℓ = 1 sequence, but are, however, well-modeled by an independent asymptotic sequence with a constant period spacing of 11.66 ± 0.13 s. It is unclear to which ℓ mode these frequencies belong.

Key words: techniques: photometric – stars: oscillations – stars: individual: SDSS J034917.41-005919.2

1 INTRODUCTION

The GW Vir stars are a sub-group of variables in the spectroscopic PG 1159 class, which form a link between the (post-AGB) central stars of planetary nebulae and the H-deficient white dwarf cooling sequence. They pulsate non-radially and lie in an instability strip bounded by effective temperatures 200 000 > T_{eff} > 75 000 K, excited by the kappa mechanism working through partial ionization of carbon and oxygen. Studying these stars with asteroseismology has provided important knowledge on the interiors of the late stages of stellar evolution (Winget & Kepler 2008). There are 19 known GW Vir stars (Quirion, Fontaine & Brassard 2007; Quirion 2009), showing a wide variety of behaviour. The possible addition of more examples is therefore of significance. Here we show that the known spectroscopic PG 1159 star SDSS J034917.41-005917.9 is a non-radial pulsator, putting it in the GW Vir subclass. In Sect. 2 we describe what is already known about SDSS J0349-0059 and list our high speed photometric observations. Sect. 3 analyses these and presents comparisons with other GW Vir stars.

2 SDSS J0349-0059 AS A PG 1159 STAR

2.1 The PG 1159 Instability Strip

Hügelmeyer et al. (2006) used Sloan Digital Sky Survey spectra of five spectroscopically discovered PG 1159 stars, including SDSS J0349-0059, to interpret their spectra using non-LTE model atmospheres; these were added to the analyses of six previously analysed stars. Among these, SDSS J0349-0059 has an average position, with T_{eff} = 90.0 ± 0.9 kK and log g = 7.50 ± 0.01 (cgs).

Córscio et al. (2006) computed nonadiabatic pulsation models for stars in the GW Vir instability strip and found that their models agree with the observed strip. The parameters listed above for SDSS J0349-0059 place it within the observed instability strip (cf. figures 6 and 7 of Córscio et al.).

2.2 High speed photometry of SDSS J0349-0059

SDSS J0349-0059 was observed in January 2007, March 2009 and December 2009 with the University of Cape Town’s CCD photometer (O’Donoghue 1995) attached to the 40-in and 74-in reflectors at the Sutherland site of the South African Astronomical Observatory. The motivation for observing this star was inclusion as a UV-rich star included in a search for possible AM CVn stars.

The observing log is given in Tab. 1 and the individual light curves are shown in Fig. 1. Note that the short ob-

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Table 1. Observing log of photometric observations

| Run   | Date of obs. (start of night) | HJD$^\dagger$ (+2450000.0) | Length $t_{in}$ (h) | Integration time $t_{in}$ (s) | V (mag) |
|-------|-------------------------------|-----------------------------|---------------------|-----------------------------|---------|
| S7699 | 20/01/2007                    | 4121.29287                  | 2.38                | 20                          | 17.7    |
| S7701 | 21/01/2007                    | 4122.27472                  | 3.39                | 20                          | 17.7    |
| S7703 | 22/01/2007                    | 4123.27466                  | 3.02                | 20                          | 17.7    |
| S7706 | 23/01/2007                    | 4124.27198                  | 3.06                | 20                          | 17.8    |
| S7846 | 20/03/2009                    | 4911.23629                  | 1.34                | 30                          | 17.9    |
| S7855 | 23/03/2009                    | 4914.23355                  | 1.19                | 30                          | 17.9    |
| S7859 | 24/03/2009                    | 4915.23460                  | 1.12                | 30                          | 17.9    |
| S7899 | 24/12/2009                    | 5190.35493                  | 1.27                | 30                          | 17.8    |
| S7901 | 25/12/2009                    | 5191.28264                  | 2.83                | 30                          | 17.8    |
| S7904 | 26/12/2009                    | 5192.28631                  | 2.63                | 30                          | 17.8    |
| S7906 | 27/12/2009                    | 5193.28308                  | 2.74                | 30                          | 17.9    |

$^\dagger$HJD of first observation; $t_{in}$ is the integration time.

Figure 1. Individual light curves of SDSS J0349-0059. The light curve of run S7699 is displayed at the correct brightness. Vertical offsets (indicated between brackets) have been applied to other light curves for display purposes only.

Figure 2. The Fourier transforms of SDSS J0349-0059 in January 2007 (upper panel), March 2009 (middle panel) and December 2009 (lower panel).

3 ANALYSIS

The Fourier transforms of the combined runs in January 2007 (upper panel of Fig. 2) and December 2009 (lower panel of Fig. 2) show a substantial amount of variation in the distribution of power in the FTs. The March 2009 data set is shown for completeness, but given the relatively few short observing runs, the signal-to-noise in the FT of the combined runs in March 2009 (middle panel of Fig. 2) is too low to identify many individual pulsation frequencies. However, the main peak in March 2009 at $\sim 2865 \mu$Hz is also seen in January 2007 and December 2009.

The Fourier transforms of the combined runs in January 2007 (upper two panels) and December 2009 (lower two panels) in the 1000 – 3500 $\mu$Hz frequency range. The windows functions for the two data sets are given in the rightmost panels of Fig. 3, scaled to the amplitude of the highest peak in the respective FTs. In each FT, the horizontal dashed line corresponds to $4\sigma$ amplitude detection limit; this limit is 3.5 mmag for January 2007 and 3.1 mmag for December 2009. The standard deviation ($\sigma$) has been determined over the 1000 – 4000 $\mu$Hz frequency range, after prewhitening the FT by the frequencies listed in Tab. 2 and randomizing the residual brightness variations for each observing run against the timing array.

In the January 2007 FT, 13 frequencies have been iden-
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Figure 3. The Fourier transforms of SDSS J0349-0059 in January 2007 (upper panels) and December 2009 (lower panels). For each data set three panels are displayed: the original Fourier transform of the combined observing run (top-left), the residual Fourier transform after prewhitening with the identified frequencies listed in Tab. 2 (lower-left) and the window function (top right). The $4\sigma$ amplitude limit is indicated by the horizontal dashed line, the identified frequencies are marked by the vertical dashed lines and frequencies associated with the two asymptotic models with a constant period spacing are marked by short vertical markers, see Sect. 3.2 for details.

Identified with amplitudes above the $4\sigma$ amplitude limit. They are marked by the vertical dash lines in Fig. 3. Successive prewhitening of the highest amplitude peak has resulted in the identification of the 13 pulsation frequencies listed in Tab. 2. Some of these frequencies could possibly be mis-identified as a one-day alias, although the coincidence of frequencies in the two independent data sets gives some reassurance of correct identification; in Tab. 2 we merely list the frequencies associated with the highest amplitude signals. The final FT prewhitened at these 13 frequencies is shown immediately below the original FT.

Similarly, ten independent frequencies have been identified in the December 2009 data. They are listed in Tab. 2 and marked by the vertical dashed lines in the third vertical panel (left) of Fig. 3. Again, the final FT prewhitened at the identified frequencies is displayed below the original FT.

The highest amplitude peak in both the 2007 and 2009 observations is located at $\sim 2386$ $\mu$Hz (peak amplitude of 18.6 and 15.2 mmag in 2007 and 2009, respectively). Other pulsation frequencies in common between the two data sets are around 2865 $\mu$Hz – peak amplitudes of 12.1 mmag (2007) and 9.6 mmag (2009) – and 2383 $\mu$Hz – peak amplitudes of 5.5 mmag (2007) and 4.3 mmag (2009).

3.1 Rotational splitting of the 2387-$\mu$Hz (419 s) oscillation

The highest peak in the 2007 data shows clear evidence for three closely spaced frequencies. This is illustrated in Fig. 4 where we show the January 2007 FT in the frequency range of 2000 – 3000 $\mu$Hz (original, top panel). After prewhitening by the main peak at 2387.2 $\mu$Hz, a clear window function remains (middle panel) at 2401.4 $\mu$Hz. Prewhitening at 2401.4 $\mu$Hz leaves a distinct signal at 2372.6 $\mu$Hz (lower panel). All frequencies are marked by vertical dashed lines. This suggests that the strongest peak is in fact a triplet, with a frequency separation of $14.4 \pm 0.2$ $\mu$Hz.

The 2009 data reveal two components of the triplet; a strong peak at 2385.6 $\mu$Hz and a low amplitude peak at 2383.5 $\mu$Hz which is probably the 1-day alias of the 2372.6 $\mu$Hz peak seen in 2007.

We draw again on the similarity with PG 1707+427, where evidence was found for a 9 $\mu$Hz split of the main mode, interpreted as a rotational frequency splitting, corresponding to a rotation period of 0.65 days (Kawaler et al. 2004). In SDSS J0349-0059 this would imply a rotation period of $0.40 \pm 0.01$ days if the pulsation mode is $\ell = 1$.

3.2 Period spacing

Given the strong similarity with PG 1707+427, we suspected that the frequencies identified in SDSS J0349-0059 and listed...
Table 2. Frequency identifications

| Frequency (µHz) | Period (s) | Amplitude (mmag) | Rank |
|-----------------|------------|------------------|------|
| **January 2007** |            |                  |      |
| 1037.9 ± 0.4    | 963.48 ± 0.37 | 3.7 ± 0.9       | 12   |
| 1103.3 ± 0.4    | 906.37 ± 0.33 | 3.9 ± 0.9       | 11   |
| 1931.1 ± 0.1    | 517.84 ± 0.03 | 11.3 ± 1.0      | 4    |
| 1983.4 ± 0.2    | 504.18 ± 0.05 | 6.8 ± 0.9       | 6    |
| 2055.9 ± 0.4    | 486.49 ± 0.09 | 4.2 ± 0.9       | 10   |
| 2072.2 ± 0.2    | 482.58 ± 0.05 | 6.6 ± 0.9       | 8    |
| 2150.3 ± 0.4    | 465.05 ± 0.09 | 3.5 ± 0.9       | 13   |
| 2372.6 ± 0.2    | 421.48 ± 0.04 | 6.7 ± 0.9       | 7    |
| 2387.2 ± 0.1    | 418.90 ± 0.02 | 18.6 ± 1.1      | 1    |
| 2401.4 ± 0.1    | 416.42 ± 0.02 | 15.2 ± 1.0      | 2    |
| 2826.5 ± 0.2    | 353.79 ± 0.03 | 7.2 ± 0.9       | 5    |
| 2865.2 ± 0.1    | 349.02 ± 0.01 | 12.1 ± 1.0      | 3    |
| 3323.0 ± 0.3    | 300.93 ± 0.03 | 5.5 ± 0.9       | 9    |

| December 2009 |            |                  |      |
| 1097.1 ± 0.1   | 911.49 ± 0.08 | 9.1 ± 0.7       | 4    |
| 1468.8 ± 0.3   | 680.83 ± 0.14 | 3.6 ± 0.7       | 8    |
| 1779.9 ± 0.3   | 561.80 ± 0.09 | 4.0 ± 0.7       | 1    |
| 1935.3 ± 0.4   | 516.72 ± 0.11 | 3.3 ± 0.7       | 10   |
| 1955.3 ± 0.3   | 511.43 ± 0.08 | 4.2 ± 0.7       | 6    |
| 2383.5 ± 0.4   | 419.55 ± 0.07 | 3.4 ± 0.7       | 9    |
| 2385.6 ± 0.1   | 419.18 ± 0.02 | 15.2 ± 0.9      | 1    |
| 2425.6 ± 0.2   | 412.72 ± 0.03 | 10.0 ± 0.8      | 2    |
| 2864.8 ± 0.1   | 349.06 ± 0.01 | 9.6 ± 0.8       | 3    |
| 3323.0 ± 0.3   | 300.93 ± 0.03 | 4.3 ± 0.7       | 5    |

Figure 4. The Fourier transform of SDSS J0349-0059 in January 2007 (upper panel). The middle panel displays the Fourier transform after prewhitening of the strongest signal in the original data at 2387.2 µHz. The lower panel displays the residual Fourier transform after subsequently prewhitening the data at a frequency of 2401.4 µHz. Peak frequencies of the resolved triplet at 419 s are marked by the dashed vertical lines.

Table 3. Periods compared to an asymptotic model with a period spacing of 23.61 s and a constant period of 300.54 s.

| ∆n | P<sub>mod</sub> (s) | P<sub>obs</sub> (s) | ∆P (s) | ∆P/23.61 | Remarks |
|-----|---------------------|-------------------|--------|----------|---------|
| 0   | 300.53              | 300.93            | 0.40   | 0.02     | 2007[5.5]/2009[4.3]‡ |
| 2   | 347.76              | 349.02            | 1.26   | 0.05     | 2007[12.1]† |
| 5*  | 418.59              | 418.90            | 0.31   | 0.01     | 2007[18.6]† |
| 7   | 465.81              | 465.05            | 0.76   | 0.03     | 2007[3.5] |
| 9   | 489.42              | 486.40            | -3.02  | -0.13    | 2007[4.2] |
| 11  | 513.03              | 511.43            | -1.60  | -0.07    | 2009[4.2] |
| 16  | 678.30              | 680.83            | 2.53   | 0.11     | 2009[3.6] |
| 26  | 914.40              | 911.49            | -2.91  | -0.12    | 2009[9.1] |
| 28  | 961.62              | 963.48            | 1.86   | 0.08     | 2007[3.7] |

The year in which the pulsation is detected; the amplitude of the pulsation in list in square brackets (in units of mmag).

* The m = ±1 modes of this triplet are not listed here.
† The one-day alias of the ∆n = 8 mode is at 489.2 s, which gives ∆P = -0.2 s and δP/23.61 = -0.01.
‡ The one-day alias of the ∆n = 26 mode (2007) is at 916.2 s, which gives ∆P = 1.8 s and δP/23.61 = 0.07.

To search the suite of periods for a constant period spacing, we used the inverse variance method as outlined by O’Donoghue (1994). By letting ∆P vary between 10 and 40 s (in steps of 0.005 s), we compared the measured periods with the model periods and plotted the inverse variance of the timing residual (divided by ∆P) as a function of ∆P. The results are shown in the upper panel of Fig. 5 for all the 10 periods identified in December 2009. A low amplitude peak around ∆P = 23.5 is evident. The significance of this peak improves substantially when two periods are removed from the sequence (412.3 and 516.7 s), where the remaining 7 independent periods (we have also removed the lower sideband component of the 419-s triplet) form a well-defined sequence with ∆P = 23.52 ± 0.19 s and C = 301.70 s. This is shown in the bottom panel of Fig. 5. In comparison, Kawaler et al. (2004) find ∆P = 23.0 s and C = 332.9 s for PG 1707+427.

All but five periods identified in 2007 and 2009 fit the asymptotic model with a constant period spacing around ~23.5 s. They are listed in Tab. 3 against the identified mode difference (∆n), the period difference (δP = P<sub>obs</sub> - P<sub>mod</sub>) and presumably belong to ℓ = 1 modes. The best fit model based on the periods listed in Tab. 3 gives ∆P = 23.61±0.21 s and C = 300.54 s. The upper panel of Fig. 6 shows the inverse variance as a function of ∆P for this set of periods. Had we only selected frequencies with amplitudes above a 5σ limit (as opposed to our current 4σ selection), the inverse variance analysis would have given a similar result (∆P = 23.47±0.13 s and C = 301.67 s). The sequence of frequencies associated with the best fit model (∆P = 23.61 s) is shown in Fig. 3 by the lower lower sequence of short vertical markers (starting at 3327 µHz).

The remaining five periods not matched by this model in Tab. 2 are predominantly part of a sequence of ℓ = 1 g-modes with constant period spacing; this is an asymptotic model of the form P<sub>mod</sub> = n∆P + C, where P<sub>mod</sub> is the model period, n is an integer, ∆P is a constant period spacing and C is a constant period.

Guided by the analysis of Kawaler et al. (2004), we first looked at the pulsation frequencies in the December 2009 data. In the December 2009 observations, a large-amplitude low frequency pulsation was detected at 1097 µHz, assumed to be a high order (n) mode similar to the ∆n = 25 mode identified by Kawaler et al. in PG 1707+427 around 1100 µHz.
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Figure 5. The inverse variance versus $\Delta P$ for all periods identified in December 2009 (upper panel), and for seven independent periods (all except 412.3, 419.6 and 516.7 s; lower panel).

Table 4. Periods compared to an asymptotic model with a period spacing of 11.66 s and a constant period of 353.91 s.

| $\Delta n$ | $P_{\text{model}}$ (s) | $P_{\text{obs}}$ (s) | $\delta P$ | $\delta P/\Delta P$ | Remarks |
|------------|------------------------|----------------------|------------|---------------------|---------|
| 0          | 353.91                 | 353.79               | -0.12      | -0.01               | 2007[7.2] |
| 5          | 412.21                 | 412.27               | 0.06       | 0.01                | 2009[10.0]|
| 11         | 482.17                 | 482.58               | 0.41       | 0.04                | 2007[6.6] |
| 13         | 505.49                 | 504.18               | -1.31      | -0.11               | 2007[6.8] |
| 14         | 517.15                 | 517.84               | 0.69       | 0.06                | 2007[11.3]|
|            | 516.72                 | -0.43                | -0.04      |                     | 2009[3.3] |

$^5$ The year in which the pulsation is detected; the amplitude of the pulsation in listed in square brackets (in units of mmag).

are part of a sequence themselves with a fixed period spacing of $\Delta P = 11.66 \pm 0.13$ s and $C = 353.91$ s. They are listed in Tab. 4 and the result of the inverse variance test is shown in the lower panel of Fig. 6. Within the formal error, this period spacing is consistent with being equal to half the period spacing of the $\ell = 1$ model. The sequence of frequencies associated with this model ($\Delta P = 11.66$ s) is also shown in Fig. 3 by the upper sequence of short vertical markers (starting at 2826 $\mu$Hz) and can be compared with the asymptotic model for the $\ell = 1$ modes.

The $\delta P/\Delta P$ residuals we obtain for the two models are similar to those found in studies of other GW Vir stars (e.g., Kawaler et al. 2004).

4 DISCUSSION

Our photometric observations show that SDSS J0349-0059 is a non-radial pulsator in the GW Vir class of variable stars. Frequency splitting of the principal oscillation mode at 419 s reveals a rotation period of 0.40 d, if the oscillation mode is $\ell = 1$. As with many other GW Vir stars, it is possible to represent most of the modes with a linear relationship in period, similar to what has been seen in PG 1707+427, but with parameters that put SDSS J0349 slightly redward of the latter star, which now defines the red edge of the GW Vir instability strip.

The five oscillation modes not included in the above group can be fitted by another linear relationship in which the spacing is a harmonic of the first sequence. However, there is no currently known physical model which explains this behaviour. This is unlike PG 1707+427 where the discrepant oscillation modes appear to have an $\ell = 2$ origin.

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