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Research Note

Complex light variations of the "hybrid" PG 1159 star HS 2324+3944

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Abstract. We present 17.36 hours of new time-series photometric observations of the variable "hybrid" PG 1159 star HS 2324+3944. These data allow us to demonstrate the presence of four frequencies in the light variations with evidence for more. The dominating time scale of the variability (around 35 minutes) is much longer than that of GW Vir pulsators.

Binarity is not likely to cause the object's light variations. A pulsational origin of the variability seems more attractive. Recent theoretical investigations suggest that pre-white dwarf pulsations can be excited despite the presence of hydrogen in the model's driving region.

Key words: stars: oscillations – stars: individual: HS 2324+3944 – stars: white-dwarfs

1. Introduction

HS 2324+3944 is one of only four "hybrid" PG 1159 stars. The latter objects are a subgroup of DO white dwarfs, whose spectra are dominated by He II, C IV and O VI (Sion et al. 1985). On the other hand, the spectra of "hybrids" show an He II/C IV absorption trough similar to the "classical" PG 1159 stars, but also strong Balmer lines (Napiwotzki & Schönberner 1991).

About 30% of the PG 1159 stars are multiperiodic nonradial g-mode pulsators (the GW Vir stars). Driving of these pulsations is believed to be caused by the κ-γ-mechanism in the region of partial ionisation of carbon and oxygen (Starrfield et al. 1985).

Analyzing two weeks of almost continuous data gathered with the Whole Earth Telescope network, Winget et al. (1991) identified more than 100 pulsation modes in PG 1159-035. This allowed an unprecedented investigation of the object's inner structure by means of precision asteroseismology. Similar analyses of other GW Vir stars have been performed in the recent years (e. g. Kawaler et al. 1995).

However, according to model calculations, the efficiency of the above κ-γ-mechanism seems to be very sensitive to the chemical composition in the driving region, which is located very close to the stellar surface. In particular, the presence of hydrogen in the driving zone is believed to inhibit pulsations (Stanghellini et al. 1991). Regrettably, asteroseismological investigations were not helpful in constraining the structure of the driving regions, since the eigenfunctions of the observed modes have little weight in these parts of the models.

The spectral analysis by Dreizler et al. (1996) places HS 2324+3944 in the GW Vir instability strip. However, their analysis shows the presence of hydrogen as well. Dreizler et al. suggested that HS 2324+3944 should be observed photometrically to look for pulsational variability. This, they suggested, would provide a test for Stanghellini et al.'s (1991) models which predict no pulsations when the partial ionization zone is contaminated by hydrogen.

Silvotti (1995, 1996) obtained two nights of time-series photometric data of HS 2324+3944. He discovered the star to be variable with a period of about 35 minutes and suggested this is due to high-order g-mode pulsations. However, such a period is a factor of 3–4 larger than the periods of GW Vir pulsators.

There is a second possibility to explain the light variations of HS 2324+3944: binarity. The AM CVn stars (see Provencal (1994) and Warner (1995) for detailed discussions) are helium-transferring double-degenerate binaries with orbital periods of the same order as the time scale of the variations of HS 2324+3944 reported by Silvotti (1995, 1996). Hence, it should not be ruled out without further scrutiny that HS 2324+3944 be a related object, although spectroscopic observations (Dreizler et al. 1996) did not show evidence of mass transfer.

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Table 1. Journal of the observations

Telescope	Observer(s)	Detector	Date (UT)	Start (UT)	Length (hrs)
McD 2.1 m	GH	PMT	13 Dec 95	2:18:28	1.90
McD 2.1 m	GH	PMT	15 Dec 95	1:11:44	2.71
McD 0.9 m	GH, AK, MHM	CCD	16 Dec 95	2:29:02	3.60
McD 0.9 m	GH, AK, MHM	CCD	17 Dec 95	2:38:05	3.05
McD 0.9 m	GH	CCD	20 Dec 95	1:05:06	1.08
McD 0.9 m	GH	CCD	21 Dec 95	3:13:18	0.50
McD 0.9 m	GH	PMT	27 Dec 95	1:22:54	1.64
McD 0.9 m	GH	PMT	28 Dec 95	1:24:33	2.88
				Total	17.36

Earlier observations of ours (of a quality too low to publish) confirmed the unusual variability. Therefore, and because Silvotti's data set was too small to determine whether the variations are multiperiodic or not, we carried out a more extensive photometric study of HS 2324+3944.

2. Data acquisition and reduction

In December 1995, we acquired eight time-series photometric runs of HS 2324+3944 during a time span of 15 days. Three different telescope/instrument combinations at McDonald Observatory were used: the 2.1 m telescope with a two-channel photoelectric photometer (no filter), the 0.9 m telescope with a CCD (B filter) and the 0.9 m telescope with the two-channel photometer (no filter). This choice of the filters ensures measurements at approximately the same effective wavelength for both the photoelectric and CCD data. An observing log is given in Table 1.

2.1. CCD observations

For our CCD observations we used a Tektronics 2048 $\times$ 2048 CCD with 27μm pixels binned 2×2. The full width at half maximum through most of the measurements was about $3''0$. Each observation consisted of a 60 second exposure; we attempted to observe as many comparison stars on the same frame together with HS 2324+3944. By reading out only part of the chip we decreased the readout time as far as possible. In this way, we acquired one observation each 70 seconds.

The frames were corrected for bias and flat field effects using the standard IRAF procedures. Photometric reductions were then accomplished using the IRAF APPHOT task. We extracted the magnitudes of HS 2324+3944 plus 7 or 8 comparison stars and selected the aperture size giving the lowest scatter for the comparison star data. We double-checked the constancy of the comparison stars by calculating amplitude spectra of their magnitudes relative to the brightest comparison star and relative to the mean of all comparison stars. No evidence for variability of any of these objects was found within the 4 nights of CCD observation. Final synthetic comparison star magnitudes were computed by adopting a weighted mean of the measurements of the individual objects.

These synthetic comparison star data were subtracted from the measurements of HS 2324+3944 on a point-by-point basis and a correction for differential extinction was applied (since HS 2324+3944 is much bluer than its comparison stars). Finally, all the times of measurement were converted into Heliocentric Julian Date (HJD) and the data were subjected to further analysis.

We also note that the nightly mean magnitudes of HS 2324+3944 relative to the comparison stars did not change during the observations.

2.2. Photoelectric observations

Since the variability of the target object happens on time scales at which slow variations in sky transparency can already occur, we checked the quality of the nights by means of the Channel 2 comparison star. The latter was assumed to be photometrically constant, since it was also one of the comparison stars used during the CCD measurements and not found to be variable in these data. Since we had only two channels available and could thus not check the stability of the sky background, we chose a Channel 2 star with star/sky count ratio similar to that of the variable. In this way, we could roughly test for possible sky background variations (and did not find any during our measurements).

We started the reductions with discarding bad data. Consequently, we performed sky subtraction by a piecewise linear or spline fit to our sky measurements (which were obtained by interrupting the target light curves each 20 – 30 minutes). Then we corrected the data for extinction. The mean magnitude of each run was set to zero. If some systematic trends in the data not attributable to intrinsic variations of HS 2324+3944 remained, we removed them by fitting a straight line to the data. Finally, we summed the photoelectric measurements in 70-second bins to give them equal weight to the CCD data, and we calculated the HJD of each observation. Fig. 1 shows our reduced light curves together with a four-frequency fit to be derived in Sect. 3, where we will further comment on this plot.

3. Frequency analysis

Our final time series was analysed with a period-finding package (Breger 1990), using single-frequency Fourier and multiple least-squares sine wave fitting methods. These programs allow us to search for promising peaks and prewhiten the data by calculating simultaneous n-frequency fits[1].

In this way three frequencies can easily be revealed in the light variations of the program star (Fig. 2). As can be seen in the third lowest panel of Fig. 2, there may still be more periodicities hidden in the data. However, special care must be taken

[1] During our prewhitening process we do not necessarily choose the highest peak in our successive power spectra as the next frequency to be included in our solution. Because of the aliasing present we rather select the frequency combination yielding the lowest residuals between the observed light curves and the calculated fit. We consider this approach to be more reliable.

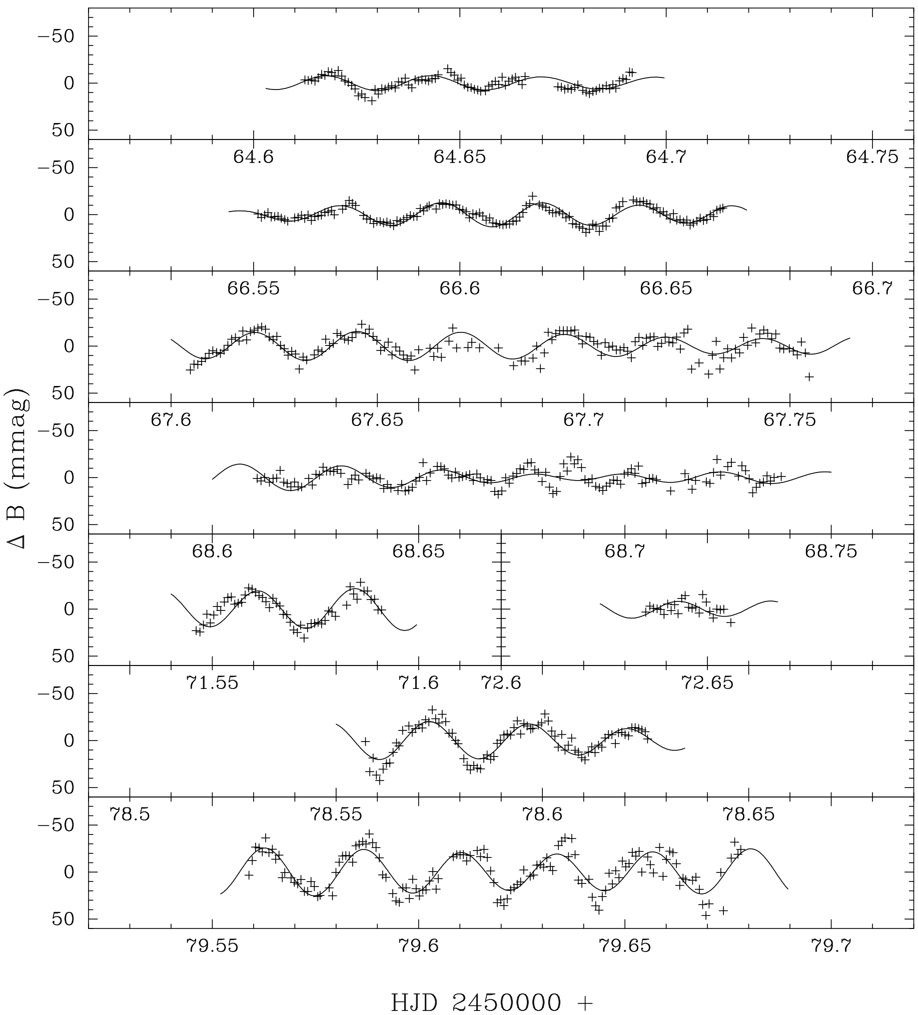

Fig. 1. B-light curves and the corresponding 4-frequency fit (derived in Sect. 3) for our data of HS 2324+3944

when trying to identify them. Therefore, we estimated a detection threshold for intrinsic variations by analysing high-speed photometric observations of constant stars, reduced and sampled in the same way as our data of HS 2324+3944. The nightly scatter was scaled to the same level as the residuals between the program star's light curve and our fit. Using this method we concluded that we may detect signals with an amplitude of about 3 mmag at frequencies around 200 μHz, and 2.5 mmag signals around 1000 μHz. We note that in the presence of strong aliasing like in our data the adoption of signal-to-noise criteria or false alarm tests is less safe.

The next promising frequency to consider is near 408.8 μHz. Its amplitude is almost 4 mmag, and by dividing our data in different subsets (e.g. using the three different telescope/detector combinations), we found out that this signal has constant amplitude and phase throughout the whole data set. On the other hand, adopting the daily alias of this frequency (which is stable throughout the data set as well) at 420.4 μHz for a four-frequency fit, the residual scatter of the light curve is only 0.03% larger. Hence, we cannot decide which of the two peaks is real, and we must consider both as a possible solution.

Including this fourth frequency in our fit and removing the improved fit from our data, a further signal at 368.6 μHz (or 379.3 μHz, when the 420.4 μHz frequency is assumed) becomes conspicuous (second lowest panel of Fig. 2). This signal is present in the whole data set with constant amplitude and phase as well, but its low amplitude of about 2.5 mmag prevents us from suggesting it is intrinsic to the star.

There is further power between 750 and 950 μHz (lowest panel of Fig. 2), which exceeds our detection threshold as estimated above. However, when testing these variations for amplitude and phase stability, they are very prominent in only a few of the nights (mostly December 17 and 27, see below for more). Moreover, the dominating peaks in this frequency region do not correspond to linear combinations or harmonics of the already detected frequencies (Fig. 3). Hence we cannot reliably include them in our frequency solution and we are left with four secure frequencies in the light curves of HS 2324+3944. These are summarized in Table 2. The errors in frequencies, amplitudes and phases as listed in Table 2 are formal errors determined following Kovacs (1981) and should be taken only as estimates.

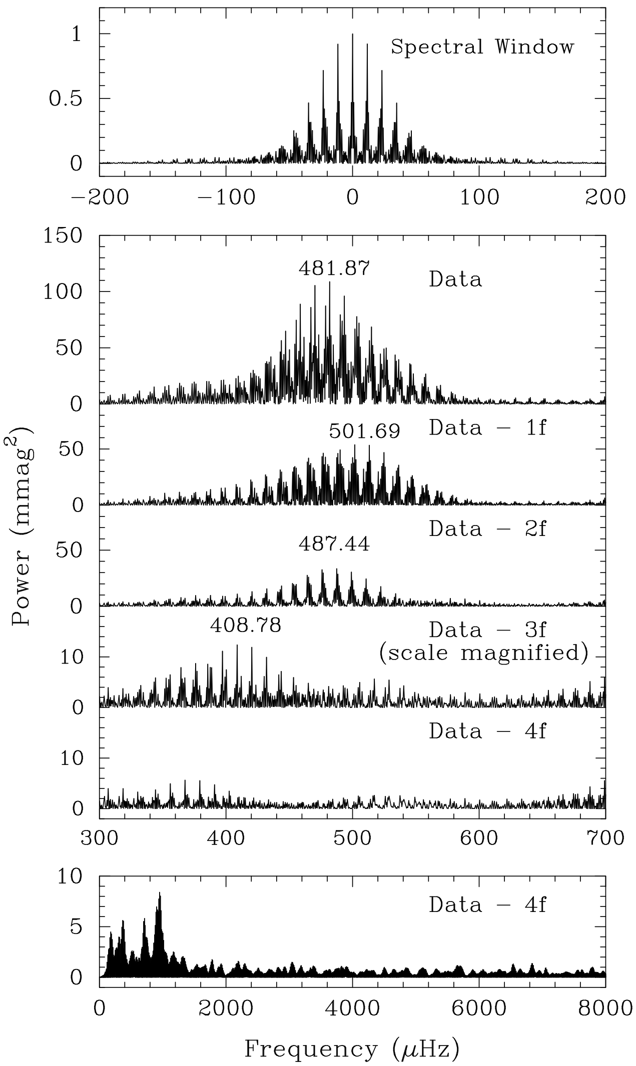

Fig. 2. Power spectra of HS 2324+3944. Four frequencies are detected in the star's light variations

Of course, due to the aliasing present and despite our great care, the frequency values are not definite. They may differ from the values in Table 2 by their daily aliases. It may be suspected that f_2 and f_4 (f_{4a}, respectively) are aliases of each other. However, when calculating residual power spectra of our light curves after removing the variations due to f_1 and f_3, both f_2 and f_4 (f_{4a}) are present, and no alias of either of these frequencies can account for the presence of both maxima in our power spectra.

Our synthetic light curves calculated with the parameters in Table 2 fit the light curves well, except the second half of the run obtained on HJD 2450068. It seems that in this night the variability of the star suddenly switched to a faster time scale. We do not think that this is a sign of inaccurate measurements, since our comparison star data for that night did not show any suspicious behavior. It rather seems likely that further presently undetected frequencies are active in HS 2324+3944.

On the other hand, we are unable to fit these variations when including some promising frequencies near 900 μHz. We are careful to note that the excess power near 900 μHz is present (but it is less strong) when we exclude the Dec 17 run from the analysis; hence it cannot originate from this night only. Its cause remains unexplained.

Table 2. The 4-parameter fit calculated for our light curves of HS 2324+3944

	Frequency (μHz)	Amplitude (mmag)	Epoch (HJD 2450000 +)
f_1	481.87 ± 0.01	11.6 ± 0.5	64.5726 ± 0.0002
f_2	501.69 ± 0.02	6.8 ± 0.5	64.5911 ± 0.0003
f_3	487.44 ± 0.03	6.9 ± 0.5	64.5822 ± 0.0004
f_4	408.78 ± 0.04	3.8 ± 0.5	64.5855 ± 0.0008
(f_{4a})	(420.41 ± 0.04)	(3.8 ± 0.5)	(64.5873 ± 0.0008)

Since we used three different telescope/detector combinations during our observations, it is interesting to compare the accuracy of these measurements. We find that the photoelectric observations with the 2.1 m telescope show a residual scatter between light curve and fit of less than 5 mmag per 70-second integration, while the 0.9 m CCD measurements are accurate to about 8 mmag per integration and the 0.9 m photoelectric observations have an rms error of about 10 mmag. This may suggest that CCD observations are to be preferred for a star of a magnitude and time scale of light variation similar to HS 2324+3944 (V = 14.8). We note, however, that the 0.9 m photoelectric data had a large contribution of moonlight, and thus their quality suffered from this influence.

4. Discussion

Our analysis shows that HS 2324+3944 is very likely a multiperiodic variable. In principle, this can be explained by both a pulsation and a binary hypothesis. Before we start discussing these two possibilities, let us note that Ciardullo & Bond (1996) - during their survey for variability among O VI central stars of Planetary Nebulae - observed the three other "hybrid" PG 1159 stars and reported suspected variations of two of those objects (A 43 and NGC 7094) with periods near 40 minutes and 2 hours, respectively. For the fourth, much fainter "hybrid" (Sh 2-68), their data was not conclusive.

Considering a binary hypothesis, it has to be pointed out that AM CVn stars may show complicated power spectra. These usually contain two independent frequencies (believed to be the orbital frequency and the rotational period of the accretor), which are different by only a few percent. Furthermore, linear combinations and harmonics of these frequencies may be present, as well as sidebands to the fundamental and harmonic periods (the frequency difference of these sidebands to the central frequency is believed to be the inverse precession period of the necessarily elliptical accretion disc). Comparing these features to our frequency solution, it is easy to see that the three close frequencies near 500 μHz we found in our data of HS 2324+3944 can be explained by such a binary hypothesis. However, the presence of the fourth frequency near 410 μHz

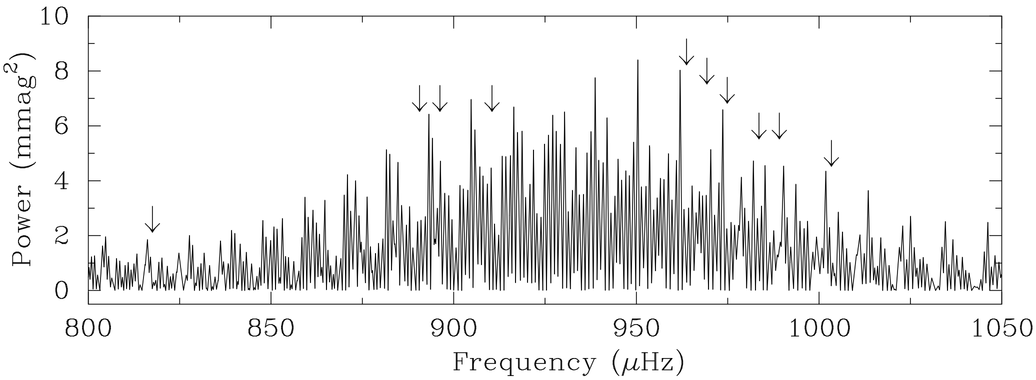

Fig. 3. Power spectra of HS 2324+3944 in the range where linear combinations or harmonics of the four detected frequencies may be present. The ten possible combinations are indicated with arrows. No agreements with the dominating peaks are visible.

does not fit into this scheme and argues against a binary origin of all the different periodicities.

Moreover, there is no spectroscopic correspondence between AM CVn stars and "hybrid" PG 1159-type stars. AM CVn stars have no hydrogen in their spectra; those of HS 2324+3944 show no evidence for mass transfer.

Consequently, the explanation of the variability of HS 2324+3944 in terms of high-order g-mode pulsations becomes attractive. The (nearly) sinusoidal light curves, the photometric amplitudes of the variations and the multiperiodicity point towards the excitation of pulsations.

Another interesting speculation can be made on the possible presence of two "magic numbers" in our frequencies. Firstly, the pulsating PG 1159 central star of NGC 1501 (Bond et al. 1996) shows frequency ratios very close to $\sqrt{3}/2$. These are interpreted in terms of trapped modes (see the paper cited above for more information). Interestingly, the ratio of our frequency f_{4a} to f_2 is within 1% of $\sqrt{3}/2$ as well as the ratio of the suspected signal at 368.6 μHz and f_{4a}. Secondly, mean period spacings of 20– 23 seconds (used to determine the masses) are present in the $\ell = 1$ modes of several GW Vir pulsators. The period difference of the two closest frequencies we determined for HS 2324+3944 is 23.7 seconds.

As mentioned in the Introduction, the efficiency of the driving mechanism for GW Vir pulsators has originally been found to be very sensitive to the chemical composition of the driving region of the models used. However, recent theoretical investigations provided several clues to resolve this difficulty:

In their detailed investigation of pulsation driving in GW Vir models, Bradley & Dziembowski (1996) could only duplicate the observed frequency range with oxygen-rich compositions in the driving region. Furthermore, the surface abundances of some pulsating and nonpulsating PG 1159 stars are so identical, that they are sometimes called "spectroscopic twins". Consequently, Bradley & Dziembowski (1996) suggested that no GW Vir star has a driving region with photospheric abundances. This can of course also be taken as a reason why a "hybrid" PG 1159 star may pulsate.

The periods we found for HS 2324+3944 are between 1990 and 2450 seconds. Bradley & Dziembowski (1996) could only match the maximum unstable periods for the hotter GW Vir stars (e.g. about 1000 seconds for PG 1159-035 itself[2]) by using models with a combination of oxygen-rich driving regions and artificially increased radii. This implies that Bradley & Dziembowski models used to fit the periods of HS 2324+3944 would require even larger radii.

Saio (1996) presented model calculations for pulsations of hydrogen-deficient stars by using new OPAL opacities. These models suggested that the sensitivity of the driving mechanism to the chemical composition in the driving region of pre-white dwarfs is not as strong as previously assumed.

Gautschy (1997) computed envelope models for GW Vir stars and HS 2324+3944. His results disagreed with those of Bradley & Dziembowski (1996). Gautschy's instability domains matched the observed frequency distributions of GW Vir stars well, except for the short period modes. He did not need to postulate chemical compositions in the driving region differing from the photospheric compositions and he did not require artificially increased radii for a good match to the observed frequency ranges.

Another result of Gautschy's (1997) explorations is that the existence of hydrogen in the driving zone does not necessarily influence the pulsational instability of HS 2324-like envelope models. He obtained unstable modes even with a hydrogen admixture of 20% in mass and he suggested that the differences between his results and those of Bradley & Dziembowski (1996) may simply be a consequence of differences in the numerical treatment of the nonadiabatic oscillations.

Anyway, theoretical approaches to possible pulsations of HS 2324+3944 still need refinement. A larger observational database to improve our knowledge of the variability of "hybrid" PG 1159 stars is also required. To this end, a multisite campaign of HS 2324+3944 is being planned.

[2] This may be an observational long-period cutoff because of the observing and analysis techniques used by Winget et al. (1991).

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