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A photometric monitoring of bright high-amplitude δ Scuti stars

I. The double-mode pulsation of V567 Ophiuchi

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Abstract. We present the first results of an observational project, which addresses the period changing behaviour of a sample of high-amplitude δ Scuti stars. In this paper we discuss the double-mode nature of V567 Ophiuchi. It was observed on 15 nights in two consecutive years in order to resolve the long-standing ambiguity related to its secondary period. A frequency analysis of almost 5000 individual single-filtered CCD V measurements resulted in two independent frequencies (f_1 = 6.6879 d^{-1} and f_2 = 11.8266 d^{-1}) with a ratio of f_1/f_2 = 0.565. Earlier data taken from the literature were used to refine the dominant period, and the re-analysis supports the existence of the secondary period. Possible asteroseismological implications are briefly discussed.

Key words. stars: variables: general – stars: oscillations – δ Sct – stars: individual: V567 Oph

1. Introduction

High-amplitude δ Scuti stars (hereafter HADS) form an interesting subgroup of short-period pulsators located inside the classical instability strip near the main-sequence. Their light variation is characterized by relatively large amplitudes (a conventional limit is $A_{\rm V} \geq 0\overset{\rm m}{.}30$) which is associated with one or two stable frequencies. The variability of these stars has been interpreted as caused by radial pulsation in fundamental or low-order radial overtone pulsation (Rodríguez et al. 1996; Petersen & Christensen-Dalsgaard 1996), although some empirical evidence is present for microvariability due to weakly excited high-order radial or non-radial modes of pulsation (Garrido & Rodríguez 1996). It also appears that they exhibit a period-luminosity relation which has been studied by several authors (e.g. McNamara 1997; Petersen & Høg 1998). Previous studies based on bright field stars have recently been supplemented by analyses of tens of objects discovered by the MACHO and OGLE projects (Alcock et al. 2000; Poretti 2001).

Breger & Pamyatnykh (1998) tried to infer evolutionary conclusions from long-term observational records of selected HADS. Although they found evidence of period changes in a significant fraction of HADS, it was not possible to relate them to stellar evolution. The detected period changing behaviour ranges from continuous period decrease to continuous period increase, and period jumps might also be present in several stars. Furthermore, cyclic period variations due to a possible binary light-time effect were inferred in a few cases (see references in Breger & Pamyatnykh 1998). However, despite the large amplitudes, short periods and moderate brightnesses of the stars studied, many of them need period updates as the latest observations in the literature were obtained almost two decades ago. That is why we started a photometric monitoring of bright northern HADS. Our target stars include all HADS brighter than $V \sim 11^{\rm m}$ situated in favourable positions in the northern sky (our sample partially overlaps that of Breger & Pamyatnikh). The observations started in 1995 (Kiss & Szatmáry 1995), and since then we have obtained unfiltered (one star), Johnson (eight stars) and Strömgren (one star) photometric observations for ten stars in order to get an updated view of their period changes (some early results have already been published in Kiss & Szatmáry 1995 and Kiss & Derekas 2000). Here we report on results for V567 Ophiuchi, which is the only one that clearly shows double-mode pulsation. The period changes of the remaining stars will be discussed in a companion paper.

The light variations of V567 Oph (=BD+1°3547, $\langle V \rangle \approx 11\overset{\rm m}{.}2$, $A_{\rm V} = 0\overset{\rm m}{.}34$, P = 0.1495 d, spectral type A6–F1, Powell et al. 1990) were discovered by Hoffmeister (1943) giving a period (≈1/8 d) that was an alias of the true one (≈1/7 d). De Bruyn (1972) was the first who determined the period accurately. The observational record until 1990 is quite numerous and has been summarized in Powell et al. (1990). These authors carried out a detailed photometric and spectroscopic study of V567 Oph, which was based on Strömgren photometry and medium-resolution optical spectroscopy. Besides determining

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the fundamental physical parameters of the star, Powell et al. (1990) suspected the existence of a secondary period, although they could not draw a firm conclusion on it. In the same year, Poretti et al. (1990) presented Fourier decomposition of three HADS. The true period of 0.149 d was established for V567 Oph and they concluded that it was monoperiodic. This conclusion was based on four nights of observations distributed in two separate years (1984 and 1986). Rodríguez et al. (1996) studied the phase shifts and amplitude ratios for a large set of stars, including V567 Oph. The radial nature of its pulsation was deduced. Hintz & Joner (1997) and McNamara (1997), adopting the suggestion by Powell et al. (1990), mentioned the star in their studies as double-mode variable. Contrary to this, Petersen & Høg (1998) listed V567 Oph as oscillating in fundamental mode only. Musazzi et al. (1998) went farther, as they denied the secondary periodicity of the star. It was claimed that the stability of the light curve found by Poretti et al. (1990) clearly proves the monoperiodic nature. The final argument so far was presented by Schwendiman & Hintz (1999), who gave information on the existence of a second period of V567 Oph. Unfortunately, in their poster abstract they did not go into any further details (neither the period value nor its amplitude was specified).

Other studies dealing at least partly with V567 Oph include Kinman (1998), who presented an analysis of local space densities of HADS. He noted that for four stars (DY Her, V567 Oph, ZZ Mic and EH Lib) it is likely that they are old disk members instead of belonging to the young galactic disk or the halo, as other HADS do. Balona & Evers (1999) discussed the mode identification of well-observed δ Scuti stars with the use of multicolour photometry. The applied procedure failed to infer plausible mode identification in three HADS (DY Her, RS Gru, V567 Oph). The single frequency in each case was identified with an $l = 1$ g-mode. Balona & Evers (1999) concluded that the most likely explanation of their result is that these stars are evolved radially-pulsating stars outside the range of the models applied. Although the models show unstable g-modes for main-sequence stars, these are unlikely to attain the high amplitudes which are observed.

In this paper, we present new Johnson V photometry of V567 Oph which revealed the secondary period unambiguously. The observations are described in Sect. 2, while the period analysis is discussed in Sect. 3. An interpretation and possible implications are given in Sect. 4.

2. Observations

Single-filtered Johnson V observations were carried out at Szeged Observatory on 15 nights during 2001 and 2002. We used the 0.4m Cassegrain-telescope equipped with an ST–9E CCD camera (512×512 pixels). In order to attain better time resolution we used the CCD in 2×2 binned mode thus giving an angular resolution of 1.4″/pixel (the field of view is $6' \times 6'$). The exposure time was between 20 and 40 s depending on the weather conditions and the frames were obtained almost uninterruptedly enabling a very good light curve coverage during every cycle. The full log of observations is given in Table 1.

Table 1. Journal of observations.

Date (yyyy-mm-dd)	No. of points	Length (hours)
2001-07-07	329	5.3
2001-07-08	349	5.6
2001-07-14	242	4.5
2001-07-15	205	3.4
2001-07-20	46	0.7
2001-08-03	209	3.6
2001-08-04	266	4.7
2001-08-12	359	4.6
2001-08-15	176	2.7
2001-08-16	112	2.2
2002-06-18	516	5.8
2002-06-19	507	5.9
2002-06-22	563	6.1
2002-06-26	497	5.9
2002-06-27	594	6.3
Total:	4970	67.3

The data were reduced with standard tasks in IRAF[1]. The flat-field correction utilized sky-flat images taken during the evening or morning twillight. Differential magnitudes[2] were calculated with aperture photometry using two comparison stars of similar brightnesses (C_1 and C_4 in Powell et al. 1990, who gave the following magnitudes: C_1 — $y_{\rm mag} = 11\overset{\rm m}{.}261$, $b-y = 0\overset{\rm m}{.}489$; C_4 — $y_{\rm mag} = 11\overset{\rm m}{.}412$, $b-y = 0\overset{\rm m}{.}431$). Since V567 Oph has very similar colour to the comparison stars used (Table 5 in Powell et al. gives a $\langle b-y \rangle = 0\overset{\rm m}{.}44$), the standard transformations are negligible corrections, therefore, the use of only one filter is not expected to introduce large systematic differences.

The estimated photometric accuracy varied between $\pm 0\overset{\rm m}{.}007$ and $\pm 0\overset{\rm m}{.}020$ as judged from the rms scatter of the comparison *minus* check data. Although we have tried to reduce the data as carefully as possible, some instrumental drifts of order of a few millimags cannot be excluded. Due to the small field of view, the variable and comparison stars were located at the edge of the frames which may introduce some additional photometric uncertainty. The nightly mean values of the comp–check magnitudes were stable to $\pm 0\overset{\rm m}{.}004$ with a mean value of $\Delta V = -0\overset{\rm m}{.}193$, with a slight tendency for the 2002 data to be fainter by $\approx 0\overset{\rm m}{.}002$ in average. This is below the range in which we are interested but might be important when a much larger and longer dataset becomes available. We also noted the $0\overset{\rm m}{.}04$ difference between the ΔV and $\Delta y_{\rm mag}$ values of the comparisons (the latter difference is $-0\overset{\rm m}{.}15$, taking the magnitudes

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[2] Corresponding data files can be found at CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/394/943`

Table 2. New times of maximum for V567 Oph (MJD = HJD − 2 400 000). The uncertainties are about ±0.0003 d.

MJD_{max}	MJD_{max}	MJD_{max}	MJD_{max}
52098.4246	52125.3480	52444.4262	52453.5453
52099.4703	52126.3818	52444.5680	
52105.4578	52134.3087	52452.3432	
52106.4952	52138.3497	52452.4945	

in Powell et al. 1990), which we attribute to the difference between the Strömgren y and Johnson V filters.

3. Period analysis

3.1. The O–C diagram

First, we wanted to refine the period of V567 Oph by the traditional method of the O−C diagram. For this, we have collected all times of maximum from the literature. The data sources were the following: early data were taken from the compilation of Powell et al. (1990); since then, Agerer & Hübscher (1996, 1997, 1998) and Agerer et al. (2001) published times of maximum quite regularly. We have determined 13 new epochs from our own light curves with the best phase coverages around maximum (see Table 2). This was done by fitting low-order (3–5) polynomials to the parts of the light curves around maximum light. The whole collection consists of 46 times of maximum between JD 2 429 785 (1940) and JD 2 452 453 (2002). We have calculated the O−C values plotted in the top panel of Fig. 1 with the following ephemeris (GCVS):

$$\mathrm{Hel.JD_{max}} = 2\,438\,592.4048 + 0.1495230 \cdot E.$$

As can be seen in Fig. 1, the global trend is linear, and can easily be subtracted. The bottom panel shows the residuals, which were calculated with the improved period of $P = 0.149523644 \pm 0.000000024$ days. This agrees very well with the period in Powell et al. (1990), as they gave $P = 0.149523641 \pm 0.000000043$ days. We conclude, that the global picture of the period constancy is not changed when another 15 years are added to the previous O−C diagram by Powell et al. (1990). This means that any relative change of the main period (expressed as $(1/P)\mathrm{d}P/\mathrm{d}t$, Breger & Pamyatnykh 1998) is smaller than 2.6×10^{-9} year^{-1}.

However, as has been already discussed by Powell et al. (1990), the O−C diagram shows a large scatter (about ±0.01 days, i.e. ±15 min!) which cannot be observational noise. Furthermore, our light curves alone showed considerable cycle-to-cycle variations which enforced us to reject the assumption of monoperiodicity. Fortunately, the amount of data enabled a more detailed analysis with the Fourier method.

3.2. Frequency analysis

The frequency analysis was performed by means of standard Fourier-analysis with subsequent prewhitening steps. For this we have used Period98 of Sperl (1998) which also includes

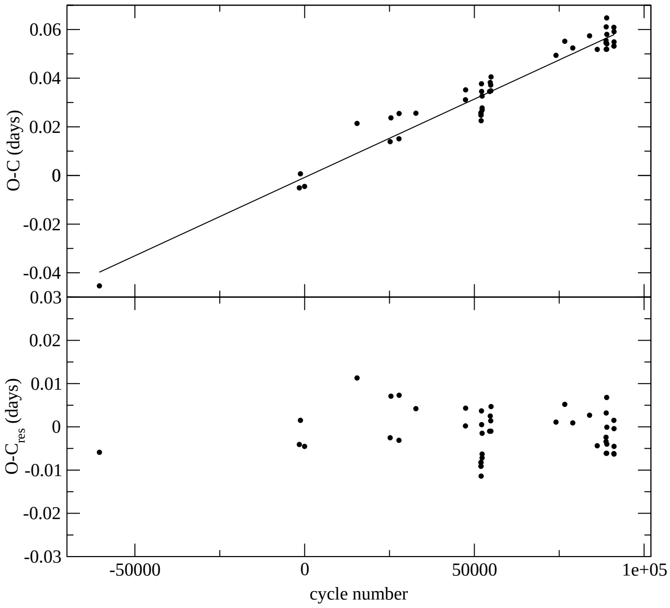

Fig. 1. The O−C diagram of V567 Oph.

multifrequency least squares fitting of the parameters. To test our results, we have also re-analysed other datasets in the literature (Poretti el al. 1990; Powell et al. 1990 and Hipparcos Epoch Photometry, ESA 1997).

The calculated amplitude spectra are shown in Fig. 2. The primary peak at $f_1 = 6.687901$ d^{-1} is in very good agreement with the period determined from the O−C analysis (6.6879055 d^{-1}). In every step of the prewhitening procedure we allowed all parameters to vary to get the optimal Fourier-fit of the light curve. The first four prewhitening steps resulted in peaks in the subsequent frequency spectra with S/N ratios (Breger et al. 1993) larger than 10. The fifth step yielded a low-frequency component at 3.008 d^{-1} with S/N of 5. However, we did not accept it because this frequency range is especially sensitive to instrumental effects. This has been tested by a Fourier-analysis of the magnitude differences between the comparison stars. As expected, besides a very low-frequency component (approximately equal to $1/2\Delta T$, our time span) we could detect another component at 2.8 d^{-1} with an amplitude of 3.5 mmag. Therefore, we stopped the analysis of V567 Oph at the fourth prewhitening step.

As expected from the asymmetric light curve shape, some of the frequencies are integer harmonics of the primary one. In fact, we have detected f_1, $2f_1$ and $3f_1$ with amplitudes of $0\overset{m}{.}154$, $0\overset{m}{.}035$ and $0\overset{m}{.}011$. The third frequency was the only one independent of f_1 at 11.82658 d^{-1} with an amplitude of $0\overset{m}{.}014$. Therefore, we decided to repeat the whole analysis by fixing $f_1 = 6.6879055$ d^{-1} and its two integer harmonics. After fitting their amplitudes and phases only one prewhitening step yielded the secondary frequency of V567 Oph, hereafter referred to as f_2. The parameters of the adopted frequencies are summarized in Table 3, while the Fourier-fit of the individual light curves are presented in Fig. 3.

We have separately re-analysed previous data in the literature to put some constraints on the stability of the secondary period. The dataset of Poretti et al. (1990) allowed

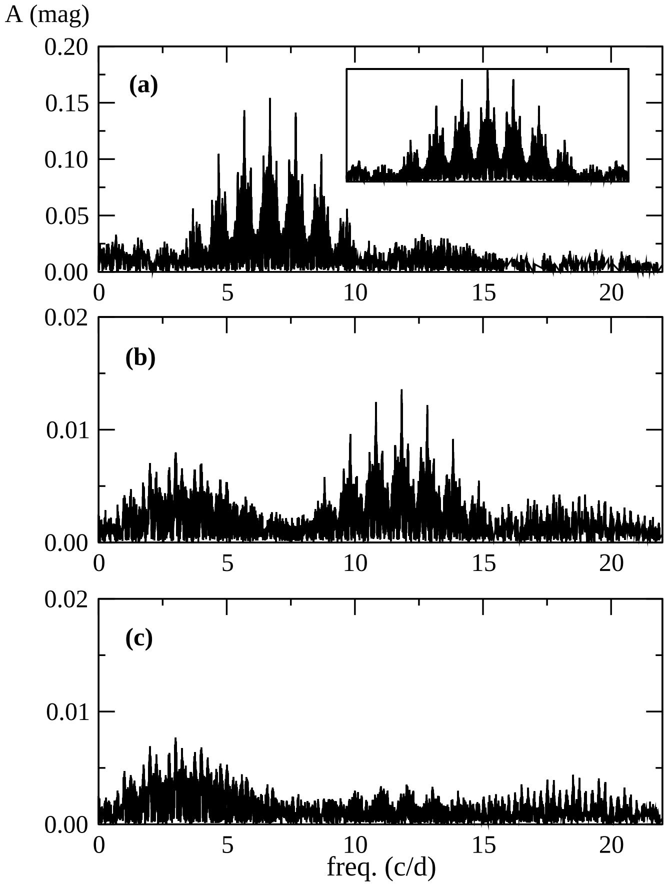

Fig. 2. Amplitude spectrum of the complete dataset. The insert shows the window function **a**). After removal of the main period and harmonics the secondary period is clearly seen **b**). After removal of the secondary period **c**).

Table 3. The result of the period analysis.

No.	Freq. (d^{-1})	Ampl. (mmag)	S/N
f_1	6.6879055	153.1	109
$2f_1$	13.375811	34.8	31
$3f_1$	20.063717	10.5	11
f_2	11.82660	13.5	12.2

the detection of f_1 and $2f_1$ and some low-frequency noise between 3 and 4 d^{-1} (it has been already noted in that paper that zero-point shifts affected the data). The Hipparcos Epoch Photometry, consisting of 190 data points, yielded only f_1, though quite accurately (6.687967 d^{-1}). The strongest pieces of evidence came from the re-analysis of the Powell et al. (1990) dataset. Besides f_1, $2f_1$ and $\sim 3f_1$, the subsequent prewhitening steps resulted in f_2 = 11.77 d^{-1} with an amplitude of $0\overset{\mathrm{m}}{.}014$. Although $\sim 3f_1$ and f_2 have low S/N ratio in that dataset, their values strongly support our results (note, that the amplitude of the secondary frequency is very close to ours). Therefore, we conclude that the light curve of of V567 Oph is doubly periodic and consequently, the star is a double-mode pulsator.

Table 4. Q values from various physical parameter determinations.

Ref.	$\log g$	$M_{\rm bol}$	$\log T_{\rm eff}$	Q_1	Q_2
(1)	3.74	$1\overset{\mathrm{m}}{.}1$	3.87	0.037	0.021
(2)	3.76	$0\overset{\mathrm{m}}{.}85$	3.87	0.035	0.020
(3)	3.88	$1\overset{\mathrm{m}}{.}40$	3.87	0.047	0.027
(3)	3.26	$1\overset{\mathrm{m}}{.}34$	3.90	0.024	0.013

References: (1) Powell et al. (1990), (2) McNamara (1997), (3) Balona & Evers (1999).

4. Discussion

What can be said about the nature of this double-mode pulsation? To put some constraints on mode identification, we have inspected the period ratio and Q values.

The frequency ratio has an intriguing value of f_1/f_2 = 0.565 which is far from the usually found 0.75–0.79 associated with radial fundamental and first overtone pulsation (see Petersen & Christensen-Dalsgaard 1996 for a parameter study, while Alcock et al. 2000 for a larger sample of double-mode HADS). As pointed out by McNamara (2000), several candidates for higher overtone pulsation can be found in ω Cen, for which recent linear nonadiabatic models (Gilliland et al. 1998) predict f_0/f_2 = 0.63 and f_0/f_3 = 0.53. However, neither of these two values fits the observed one which is fairly accurate (its error is less than ±0.001). From the observational point of view, it is interesting that there is no other double-mode HADS with similar frequency ratio. Therefore, we searched the literature to find similar stars among the lower amplitude δ Scuti stars. Close resemblance was found for AN Lyn (0.565, Rodríguez et al. 1997; Zhou 2002), V663 Cas (0.591, Mantegazza & Poretti 1990) and 63 Her (0.564, Breger et al. 1994). In all cases the authors arrived at the conclusion that a mixture of radial and non-radial modes is needed to explain the "non-standard" frequency ratios. Adopting their argumentations, it is reasonable to accept this consideration in the case of V567 Oph, too. Recent theoretical models also support this idea (Bono et al. 1997; Gilliland et al. 1998).

We have calculated the pulsation constant Q for both frequencies with the formula

$$\log Q = -6.456 + \log P + 0.5 \log g + 0.1 M_{\rm bol} + \log T_{\rm eff}$$

in terms of four observables (Breger et al. 1993). The physical parameters of V567 Oph were determined by Powell et al. (1990), McNamara (1997) and Balona & Evers (1999). We list the corresponding Q values in Table 4.

While the first two sets of parameters are in good agreement, the last two are fairly contradictory. Balona & Evers (1999) used different calibrations. For V567 Oph, they applied calibrations by Balona (1994) and Moon & Dworetsky (1985) – the latter one produced that deviant $\log g$ = 3.26 resulting in hardly acceptable Q values. If we keep the first set of parameters of Balona & Evers, it still results in uncomfortably high Q_1. However, this is likely caused by a systematic error in their Strömgren calibrations, an error that was pointed out by Rodríguez & Breger (2001). From a comparison of photometric and geometric parallaxes they found that for slowly rotating

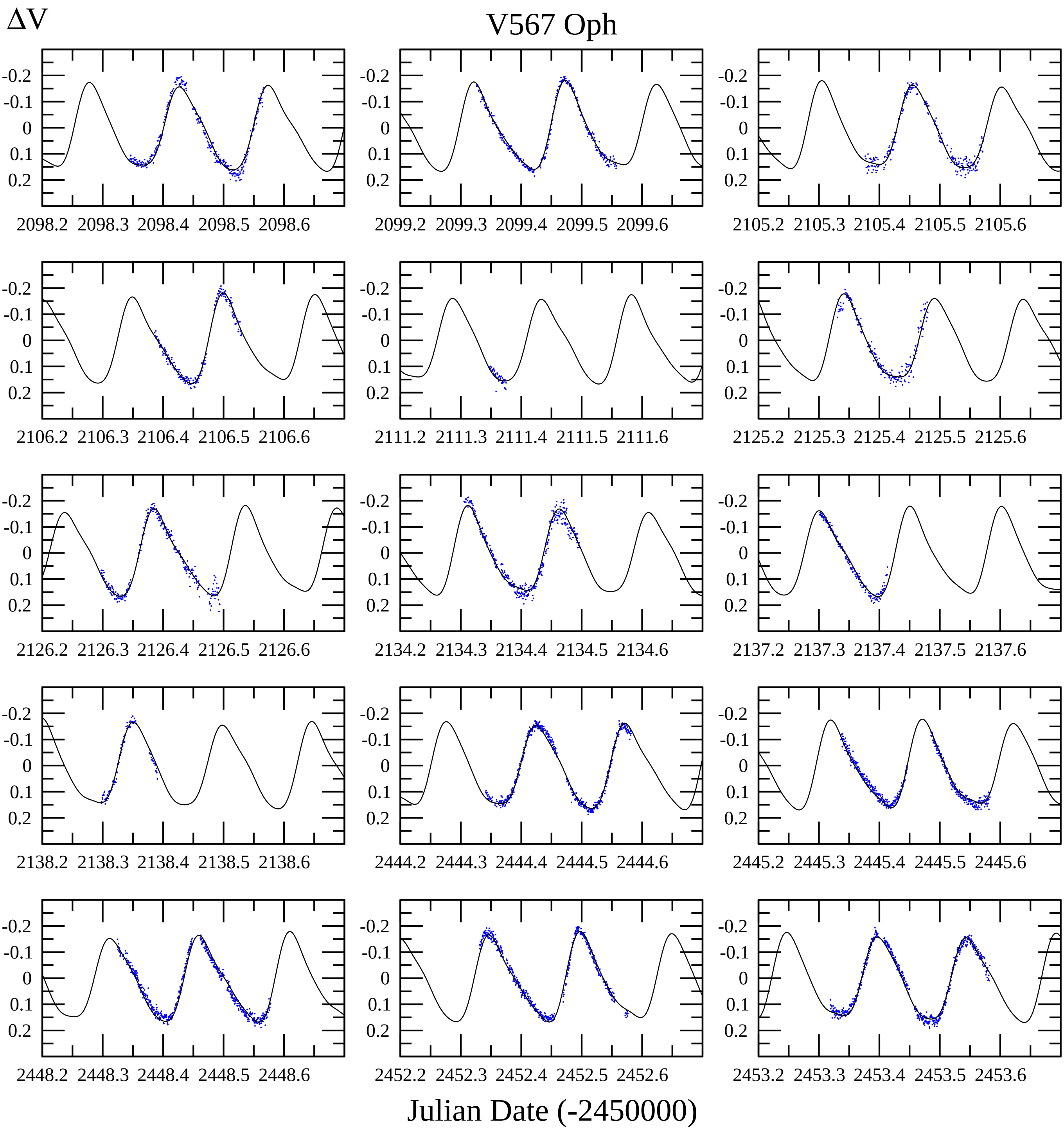

Fig. 3. The observed individual light curves (small dots) with the four-component harmonic fit.

stars Strömgren calibrations underestimate the absolute magnitude by $0\overset{m}{.}5$ on average. Since V567 Oph is a typical slowly rotating HADS ($v \sin i < 18$ km s^{-1}, McNamara 1985), its absolute magnitude is likely to be affected by this systematic error. A correction by $\Delta M_V = 0\overset{m}{.}5$ shifts Q_1 to 0.036 and Q_2 to 0.020, being in good agreement with the other two calibrations.

Assuming 20% uncertainty in Q values (that is ±0.007 and ±0.004 for Q_1 and Q_2, respectively) we conclude that the dominant period indeed corresponds to the radial fundamental mode, as assumed for the overwhelming majority of HADS. On the other hand, the secondary period can be identified with a non-radial mode of radial order $n = 2$ or 3 (Bono et al. 1997; Gilliland et al. 1998). At present nothing can be specified unambiguously about the non-radial degree l, for which the simpliest assumption is 1 or 2.

In order to perform more secure mode identification, accurate multicolour photometry would be of great importance. Unfortunately, the relative faintness of the star does not make it favourable target object for photoelectric photometry. Therefore, CCD observers with proper instrumentation are expected to gain more insights into the peculiar pulsation pattern of V567 Oph by taking follow-up observations of this interesting HADS.

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