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MULTIPERIODIC VARIABILITY OF THE PULSATING STAR GSC 0476-1362

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The variability of GSC 0476-1362 was discovered by one of the authors (I. I.) on September 29, 2007, while studying a series of unfiltered 5-min exposures of the nearby 12-mag planetary nebula NGC 6781 (Gazeas & Iliopoulos 2014).

GSC 0476-1362 (TYC 476-1362-1) is located in the constellation of Aquila, and its equatorial coordinates are: RA = $19^{h}17^{m}27\overset{s}{.}2$ and Dec = $+06°29'49.9''$ (J2000). It is listed in the GSC and TYC2 catalogue as a non-variable star with VTmag=11.48 and color index $(B-V)_{\rm Tycho}$=0.63, based on TYC2 magnitudes (Tycho photometry, not corrected for interstellar reddening). This color index corresponds to the rough value of $B-V=0.57$ in Johnson's photometric system, i.e. to a spectral type of F9, however with quite large uncertainty. 2MASS color index gives a value of $J-H=0.22$ (Cutri et al. 2003), which corresponds to a spectral type of F3-F5. The photometric light curves show a multi-periodic pulsating variable, possibly of δ *Sct* type. Being unable to find any previously recorded variability for this star, we decided to undertake photometric observations in the optical R-band between 2007 and 2009.

Photometric observations were obtained from AKTIS Astronomical Observatory (private), located in Thessaloniki, Greece. The site of the observatory is typically suburban with mediocre seeing and transparency. The first observations in 2007 were obtained with a 102 mm f/9 apochromatic refractor, while for the observations in 2008 and 2009 a 127 mm f/7.5 apochromatic refractor was used. In all cases the detector was a SBIG-ST8XME CCD camera. The 2007 configuration resulted in a 34×51 arcmin non-vignetted field of view. A 20×25 arcmin sample of the entire FOV is presented in Fig. 1, where the variable (GSC 0476-1362, $V=11.48$ mag) and main comparison (GSC 0476-1816, $V=12.39$ mag) stars are shown. In order to compensate for the small diameter of the telescope, the R filter was used in all observations, taking advantage of the higher sensitivity of the CCD camera in this spectral region. The star GSC 0476-1816 served as the comparison star (C), while several other stars in the field were used in order to check and confirm its brightness stability.

In total 369 exposures were obtained in 11 nights, during the period of October-November 2007. The early photometric analysis of the data showed quite a confusing situation of pulsating frequencies, due to ±1 c/d alias and the small number of data.

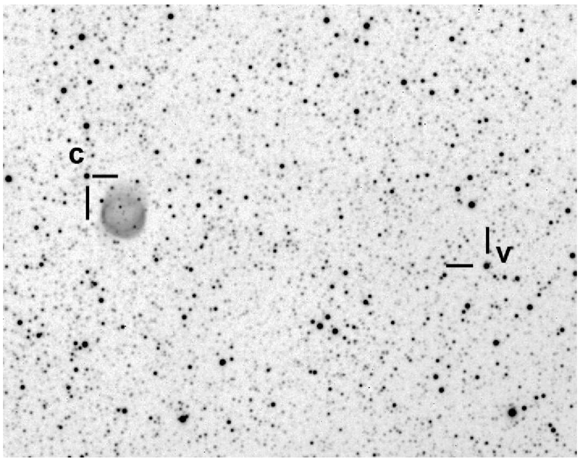

Figure 1. A cropped 20×25 arcmin sample of the original images, where variable (V) and comparison (C) stars are shown, together with the planetary nebula NGC 6781. North is up and East to the left.

Archival data from ASAS automated sky survey (Pojmański 2002) were added in our analysis without any significant improvement, since they were taken sporadically. The archival data set consists of a sum of 237 observations, which are randomly scattered along 8 years between 1998-2006, lacking any continuous time-series acquisition.

Follow up observations obtained in 2008, concluding with 530 exposures in 17 nights. This data set resulted in a stronger signal of the pulsation frequencies on the Fourier analysis and established a better determination of the pulsating behavior of GSC 0476-1362. However, signal-to-noise on the frequency spectrum was still low in the data and the multi-periodicity on top of the ±1 c/d alias was rendering the discrimination of the pulsation frequencies a complicated task. It was clear that longer duration observations were necessary in order to determine the exact pulsation frequencies of this star.

Longer time-series observations were obtained in 2009. In total, 401 exposures were obtained during 6 nights in 2009. This time the Fourier analysis gave a clear picture of the existing pulsation frequencies, as the data were better in quality and longer in duration with no interruptions. In our study, the effort to add all data together (1537 data points) and perform a combined analysis resulted in more accurate values. The complete log for all observations between 1998 and 2009 is given in Table 1.

All images were processed and analyzed with the MIRA AP package (Mirametrics, Inc. 1990-2005). The overall range of light variation is about 0.2 mag, while the amplitude of pulsation during the observing runs was of the order of 0.08 mag. The error in magnitude estimation is typically of the order of 0.02 mag in each individual night. Our observations were not transformed to a standard photometric system.

We performed the standard Fourier analysis with Period04 software package (Lenz & Breger 2005), applying a multi-frequency sine-wave fitting. The frequency search was performed on the original data, in the interval from 0 to 50 c/d, with a frequency step smaller than 10^{-3} c/d. After each successful detection, the most dominant frequency was prewhitened from the original data. The results of the frequency analysis are presented in Table 2. In this table we give the identification number of each frequency with their values, as well as the amplitude, phase shift and signal-to-noise ratio (S/N) of each one of them. Errors on these values were calculated following Breger et al. (1999) and Montgomery & O'Donoghue (1999). The errors in the table are expressed in units of

Table 1: Observational log.

Date	HJD 2450000+	Number of data points	Filter	Obs.
1998 - 2006	1286-3896	237	*V*	ASAS
2007-10-03	4377	29	*R*	AKTIS
2007-10-14	4388	26	*R*	AKTIS
2007-10-15	4389	29	*R*	AKTIS
2007-10-16	4390	52	*R*	AKTIS
2007-10-17	4391	49	*R*	AKTIS
2007-10-25	4399	18	*R*	AKTIS
2007-10-29	4403	43	*R*	AKTIS
2007-11-06	4411	26	*R*	AKTIS
2007-11-11	4416	40	*R*	AKTIS
2007-11-13	4418	28	*R*	AKTIS
2007-11-21	4426	29	*R*	AKTIS
Total in 2007	4377-4426	369	*R*	AKTIS
2008-10-01	4741	24	*R*	AKTIS
2008-10-06	4746	11	*R*	AKTIS
2008-10-07	4747	23	*R*	AKTIS
2008-10-13	4753	50	*R*	AKTIS
2008-10-16	4756	40	*R*	AKTIS
2008-10-20	4760	41	*R*	AKTIS
2008-10-22	4762	5	*R*	AKTIS
2008-10-23	4763	53	*R*	AKTIS
2008-10-28	4768	20	*R*	AKTIS
2008-11-02	4773	48	*R*	AKTIS
2008-11-03	4774	32	*R*	AKTIS
2008-11-04	4775	43	*R*	AKTIS
2008-11-11	4782	20	*R*	AKTIS
2008-11-12	4783	45	*R*	AKTIS
2008-11-13	4784	12	*R*	AKTIS
2008-11-20	4791	35	*R*	AKTIS
2008-11-27	4798	28	*R*	AKTIS
Total in 2008	4741-4798	530	*R*	AKTIS
2009-06-16	4999	42	*R*	AKTIS
2009-07-01	5014	23	*R*	AKTIS
2009-07-13	5026	84	*R*	AKTIS
2009-07-14	5027	96	*R*	AKTIS
2009-07-20	5033	90	*R*	AKTIS
2009-08-18	5062	66	*R*	AKTIS
Total in 2009	4999-5062	401	*R*	AKTIS

last decimal places quoted, given in parentheses after each value. In our analysis we adopt a significance criterion of amplitude S/N of 4.0, following Breger et al. (1993). We calculated amplitudes and phases up to a certain order, since the amplitudes of the higher order frequencies went below the significance level. We repeated the same procedure using the data sets obtained in 2007, 2008 and 2009 individually, as well as using ASAS data alone.

The significance (S/N) of the first four detected frequencies seem to remain at the same level in the data sets obtained in 2007 and 2008.

As expected, the better quality data were obtained with the larger telescope in 2008 and 2009 and therefore we trust more the results obtained from the combined analysis. Especially the long-duration time series obtained in 2009 reduced significantly the ±1 c/d alias from the early data, resulting in accurate and definite determination of the three main pulsation frequencies with high S/N values. Searching for frequencies using all data together results in low S/N values, as the ASAS data add noise to the overall data set. Therefore, the solution from the combined data set are not presented, since they add no

Table 2: Results derived from the Fourier analysis of all the observed data.

Dataset	Frequency	f [c/d]	A [mag]	ϕ [deg]	S/N
ASAS	f_1	7.28146 (2)	0.0451 (48)	29 (6)	7.4
	f_2	7.43831 (3)	0.0312 (48)	30 (8)	5.1
	f_3	8.08597 (3)	0.0324 (48)	168 (8)	5.4
	$2f_1$	14.56291 (3)	0.0271 (48)	154 (9)	4.3
2007	f_1	7.28010 (42)	0.0330 (12)	224 (2)	16.5
	f_2	7.43723 (46)	0.0299 (12)	181 (2)	15.1
	f_3	8.08675 (42)	0.0331 (12)	79 (2)	16.2
	$2f_1$	14.56020 (52)	0.0268 (12)	195 (2)	9.7
2008	f_1	7.28058 (23)	0.0412 (9)	45 (1)	15.8
	f_2	7.43776 (34)	0.0281 (9)	243 (2)	10.8
	f_3	8.08669 (30)	0.0324 (9)	204 (1)	12.9
	$2f_1$	14.56115 (37)	0.0258 (9)	188 (2)	11.1
	$3f_1$	21.84173 (96)	0.0065 (9)	1 (8)	3.4
2009	f_1	7.28104 (15)	0.0462 (7)	354 (1)	32.0
	f_2	7.43879 (18)	0.0375 (7)	221 (1)	25.4
	f_3	8.08514 (31)	0.0220 (7)	2 (2)	13.1
	$2f_1$	14.56208 (28)	0.0242 (7)	111 (1)	9.5
	$3f_1$	21.84399 (11)	0.0056 (7)	79 (7)	4.7

The errors in all values are expressed in units of last decimal places quoted, given in parentheses after each value.

useful information.

In Figures 2-5 we present samples of the time-series of the original data, over-plotted with the predicted light curve, as calculated with the recovered frequencies, listed in Table 2.

Figure 6 presents the Fourier (amplitude) spectra of all available data, showing the dominant frequency and its harmonics (f_1, $2f_1$ and $3f_1$). Two more detected frequencies are shown in the same plots (f_2 and f_3), and the effect of a possible alias on f_3.

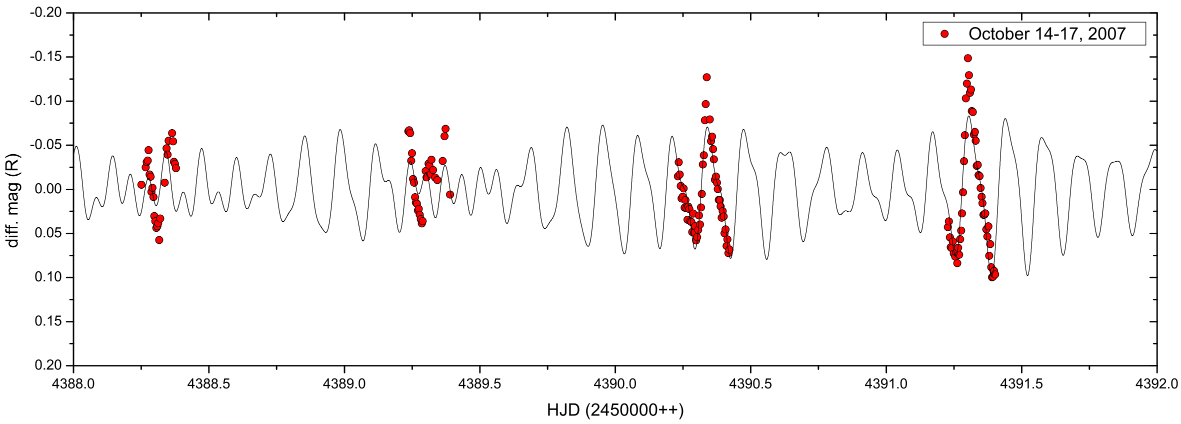

Figure 2. Observed and predicted light curve, according to the data taken on October 14-17, 2007.

The light curves of the pulsating star GSC 0476-1362 displays multi-periodic behaviour, which cannot be described by a single frequency. At least three frequencies (f_1, f_2 and f_3) seem to be real, as they are prominent with high S/N ratio, according to the results given in Table 2. The main frequency f_1 is so strong that the first and second harmonics

($2f_1$ and $3f_1$) were apparent in the Fourier spectrum. Higher order frequencies have low S/N ratio and they are subject to be either unrealistic or aliases of the main frequencies.

Following the detection criteria as established by Loumos & Deeming (1978), we find that the difference between all detected frequencies is larger than the value of $1.5/T$ (where T corresponds to the time interval in each data set). This is an extra proof or at least strong evidence that all detected frequencies are real.

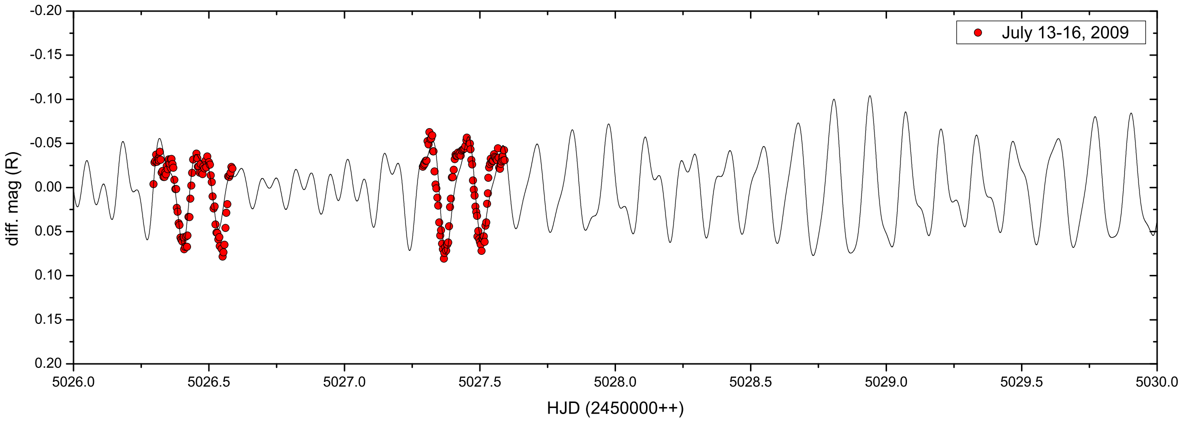

Figure 3. Observed and predicted light curve, according to the data taken on July 13-16, 2009.

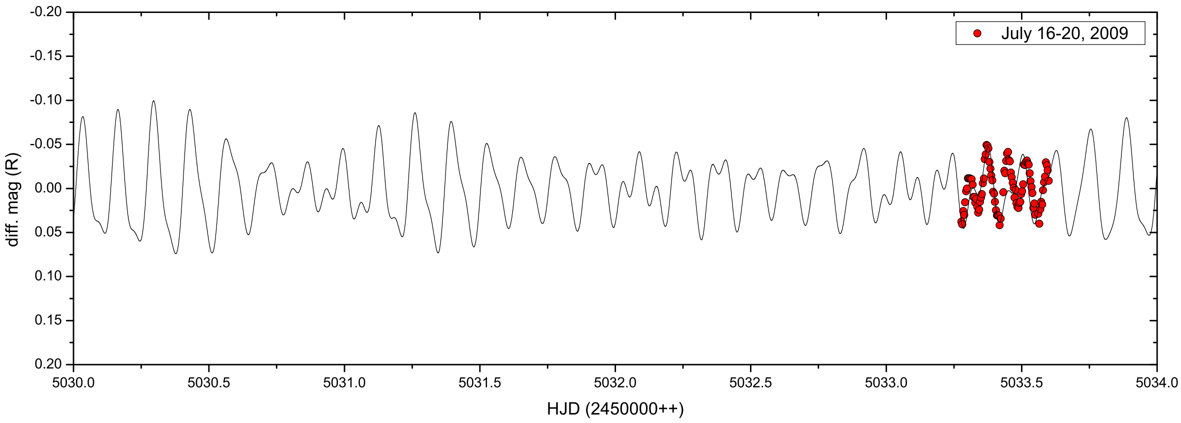

Figure 4. Observed and predicted light curve, according to the data taken on July 13-16, 2009.

Since our data sets consist of single-band photometry, we cannot conclude about the nature of the frequencies (radial or non-radial), as this information requires multi-band photometry. However, we notice that the frequency ratios which are found in this study do not follow the same pattern as the typical radial pulsators. The detected frequencies

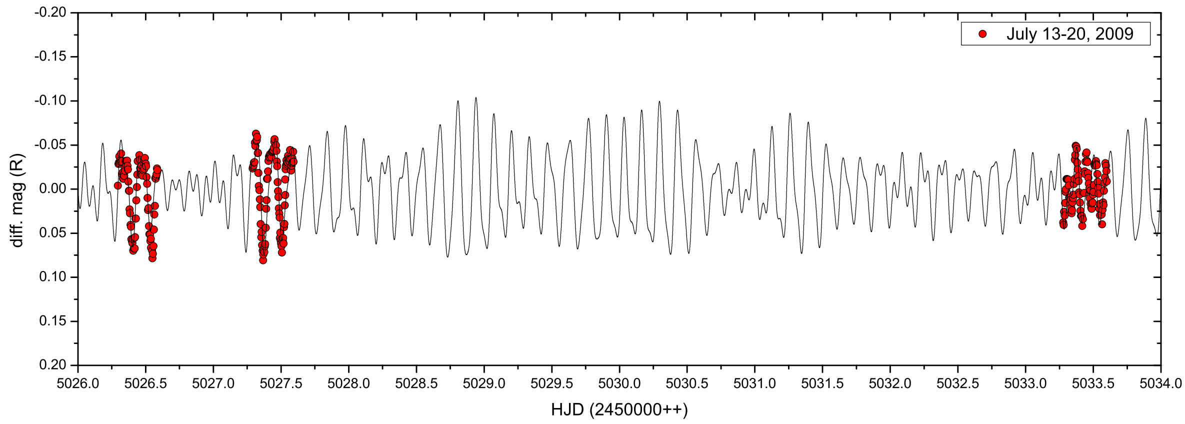

Figure 5. Observed and predicted light curve, according to the data taken on July 13-20, 2009.

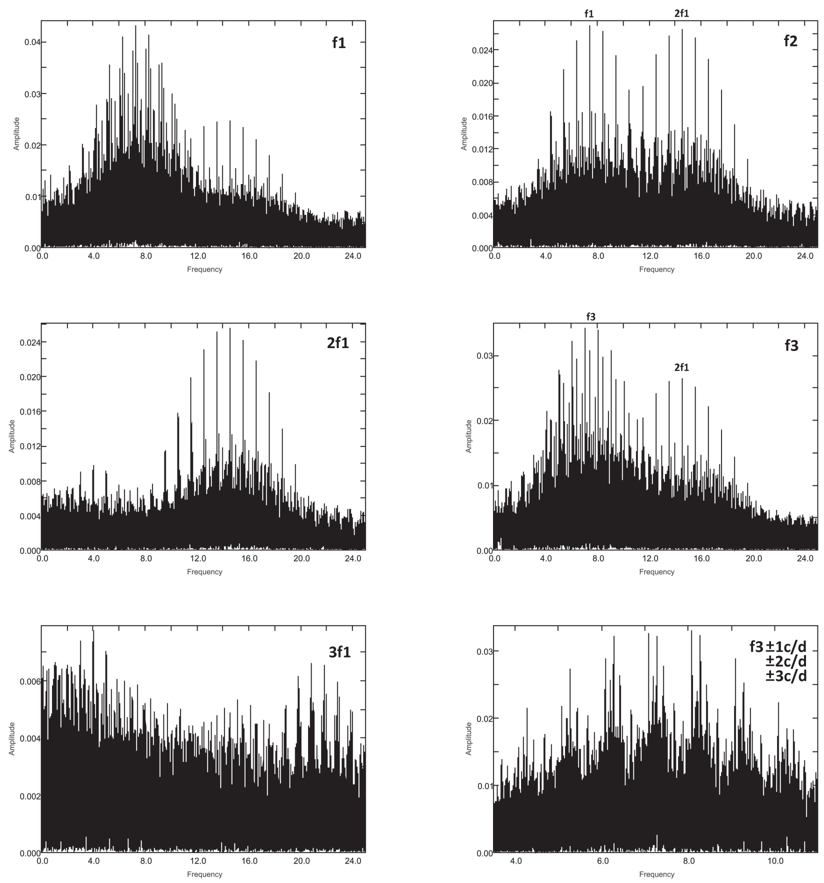

Figure 6. Fourier (amplitude) spectra of all available data, showing the dominant frequency and its harmonics, as well as two more detected frequencies and the effect of a possible alias. Units in x-axis are in cycles/day (c/d) while in y-axis are in magnitudes (mag).

give the ratios: $f_1/f_2 = 0.98$, $f_1/f_3 = 0.90$ and $f_2/f_3 = 0.92$, which are significantly higher than the value of 0.76-0.78, which is typical of radial pulsation modes (Jurcsik et al. 2006, Pigulski et al. 2006 and Poretti et al. 2005). This suggests that at least two of the detected frequencies are not radial pulsation modes. Although it is expected that high-order radial modes in multi-periodic pulsators can produce similar ratios (Breger 2000), they are usually not strong enough to be detected, as they are strongly damped in these stars.

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