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An Additional Pulsating Mode (7.35 mHz) and Pulsations Timing Variations of PG 1613+426

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Research Article

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Abstract: We present the detection of an additional pulsation mode (7.35 mHz) of a subdwarf B star, PG 1613+426, and periodic Observed minus Calculated (O-C) variations for two existing pulsations. PG 1613+426 is near the hot end of the sdB instability strip. One pulsation mode (6.94 mHz) was detected so far by Bonanno *et al.* (2002) and another pulsation mode candidate (7.05 mHz) was proposed with a confidence level above 90% by Kuassivi and Ferlet (2005). To constrain sdB star evolutional scenarios, this star was monitored in 2010, 2011, 2015, and 2017 as a part of a project for finding companions to sdB stars using the pulsation timing method. The photometric analysis of those data shows an additional 7.35 mHz pulsation mode as well as the previously detected 6.93 mHz mode. However the 7.05 mHz mode was not detected. Nightly amplitude changes of 7.35 mHz mode were observed in the 2011 data, however the 2017 data did not show nightly amplitude shifts. O-C variations were detected in both 6.93 mHz and 7.35 mHz pulsations, indicating that PG 1613+426 may have a low mass companion star. However, more observations are needed to confirm it.

Keywords: pulsations, subdwarfs, binaries

1 Introduction

Sudwarf B (sdB) stars are low-mass (about 0.47 $M_\odot$) core helium burning objects on the Extreme Horizontal Branch, that are normally found in both the disk and halo of our Galaxy (Saffer *et al.* 1994; Heber 2009). Due to the very thin hydrogen-rich envelopes, sdB stars evolve to the white dwarf cooling sequence without experiencing the Asymptotic Giant Branch phases (Mengel et al. 1976).

The existence of sdB pulsators (sdBV) was predicted by Charpinet *et al.* (1996). Soon after, Kilkenny *et al.* (1997) discovered the first short period sdBV star, EC 14026-2647. These stars are p-mode pulsators, where pulsations are driven by the kappa mechanism, with pressure as restoring force (Charpinet *et al.* 2000). The first long period sdBV star, PG 1716+426, is a g-mode pulsator (Green *et al.* 2003), in which gravity provides the restoring force. Some sdB stars have been discovered to exhibit both p-mode pulsations and g-mode pulsations. These objects are called hybrid pulsators (Schuh *et al.* 2006; Oreiro *et al.* 2004). The

p-mode pulsation periods are typically two to five minutes, but the longest known period is nine minutes. The pulsation amplitudes are up to a few tens of mmag (0.01 mag). On the other hand, g-mode pulsation periods range from 30 to 90 min with amplitudes of a few mmag (0.001 mag).

The formation mechanism of sdB stars is a matter of current debate. The binary evolution scenario (Han *et al.* 2002, 2003) convincingly explains sdB star formation. According to Silvotti *et al.* (2011), companion stars have been detected in at least 50% of sdB stars, strongly supporting a binary origin. However, other formation channels are also proposed (Heber 2009; Fontaine *et al.* 2012). Orbital information of planets and companion stars and quantitative values of stellar structures will be able to confirm or re-model current evolutionary scenarios.

Most sdB pulsators have stable pulsation periods (Østensen *et al.* 2001; Kilkenny 2007; Silvotti *et al.* 2007), and therefore they are good chronometers for searching binaries. A star's position in space may wobble due to the gravitational perturbations of a companion. From the observer's point of view the light from the pulsating star is periodically delayed when it is on the far side of its orbit and advanced on the near side. Changes in the pulse arrival times are detected using the Observed minus Calculated (O-C) diagram. Several planets and substellar companions to sdB host stars have been detected by this

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method. Silvotti *et al.* (2007) were the first to detect a planet around the sdB star V391 Peg in this way.

PG 1613+426 is near the hot end of the sdB instability strip. Bonanno *et al.* (2003) determined T_{eff} = 34,400 ± 500 K, log g = 5.97 ± 0.02 and N(He)/N(H) = 0.022 ± 0.003. One pulsation mode (6.94 mHz) was detected so far by Bonanno *et al.* (2002), and another pulsation mode candidate (7.05 mHz) was proposed with a confidence level above 90% by Kuassivi and Ferlet (2005). PG 1613+426 was selected as part of an observational search for companions among known sdB pulsators using the O-C method (Otani 2015). It was observed during 2010-2011, however she did not find any convincing result. Since this star already had 7 nights of data during 2010-2011, it was chosen as a follow-up observation target to search planets and companion stars. In this paper, we present our PG 1613+426 photometric results, amplitude stabilities, and our primary O-C analysis to search for companions.

2 Photometry

PG 1613+426 (RA = 16 14 46.9, DEC = +42 27 35.90 (epoch = J2000)) was originally monitored during 2010-2011 with the 0.9 m SARA-KP telescope at the Kitt Peak National Observatory (KPNO)[1] and the 0.8 m Ortega telescope at Florida Institute of Technology in Melbourne, Florida. For the follow-up observation in 2015 and 2017, PG 1613+426 has been monitored using the SARA-KP 0.9 m telescope in Kitt Peak National Observatory (KPNO) in Kitt Peak, Arizona, and SARA-RM 1.0 m telescope in Canary Island, Spain[2]. The FLI-PL Charge Coupled Device (CCD) was used for the Ortega telescope, the ARC-E2V42-40 CCD Photometer was used for the SARA-KP telescope, and the Andor Ikon-L Charge CCD Photometer was used for the SARA-RM telescope. No filter was used for cameras. 1 by 1 prebinning was used for all images. The observation log is listed in Table 1. Due to the bad weather during the observations in 2017, only four nights of data were obtained. The observations were made in white light to maximize S/N. Exposure times of 25 s were used at the SARA-KP and SARA-RM telescope observation sites and 35 s were used at the Ortega telescope site.

Standard calibration and reduction process were performed by IRAF[3] to extract the raw intensity values for the target and comparison stars. All flat fields were exposed on a twilight sky. These values were then divided by similarly extracted intensity values of non-variable comparison stars. The data were reduced by removing the sky background. For each night, the raw light curves were then normalized to the mean magnitude for the night. Then, a second-order polynomial was used to remove mild curvature in the light curves caused by differential extinction between the target and comparison stars. All times were corrected to Barycentric Julian Date (BJD).

Table 1. Observation log

Date	Start of Run (BJD)	Length (hr)	Observatory
2010 Apr 4	2455290.78447	3.5	Ortega
2010 May 6	2455322.74430	2.1	Ortega
2010 May 8	2455324.76785	2.0	Ortega
2010 Sep 12	2455451.63293	2.2	SARA-KP
2011 May 8	2455689.69869	4.4	Ortega
2011 May 21	2455702.75902	4.4	SARA-KP
2011 May 22	2455703.75611	4.9	SARA-KP
2011 Jun 5	2455717.72259	3.5	Ortega
	2455717.82360	2.2	SARA-KP
2011 Jun 6	2455718.63897	4.9	Ortega
2011 Jun 7	2455719.81674	4.0	SARA-KP
2015 Jun 13	2457186.65057	5.9	SARA-KP
2017 May 4	2457877.48090	2.1	SARA-RM
2017 Jun 12	2457916.66687	5.9	SARA-KP
2017 Jun 15	2457919.66233	6.6	SARA-KP
2017 Jun 19	2457923.66591	7.3	SARA-KP

3 Result

3.1 Power spectra of 2010-2017 data

Previously, the power spectrum for PG 1613+426 in 2002 (Bonanno *et al.* 2003) showed a dominant peak at 6.936 ± 0.003 mHz (144.18 ± 0.06s) with an amplitude of about 5 mma in each observation night. No signal was observed at 7.35 mHz, with a noise level of 2 mma in these power spectra. Far Ultraviolet Spectroscopic Explorer (FUSE) observation results shows 7.048 ± 0.3 mHz frequency with a
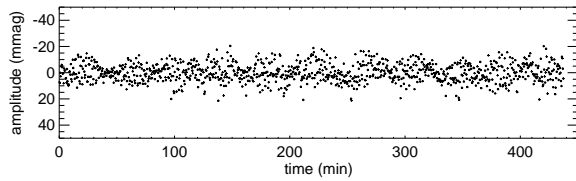
Figure 1. Light curve of PG 1613+426 for June 19th, 2017.
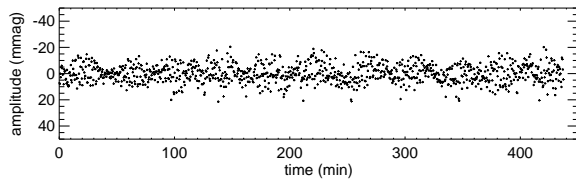
Figure 2. Power spectra for PG 1613+426 obtained from the data of year 2010-2017.

Figure 3. Day to day amplitude variation of PG 1613+426 (May-June, 2011) for F1 (top) and F2 (bottom) pulsations. Except days 717-719 in F2, both F1 and F2 amplitudes look stable. Days 717-719 in F2 show that the amplitude is decreasing.

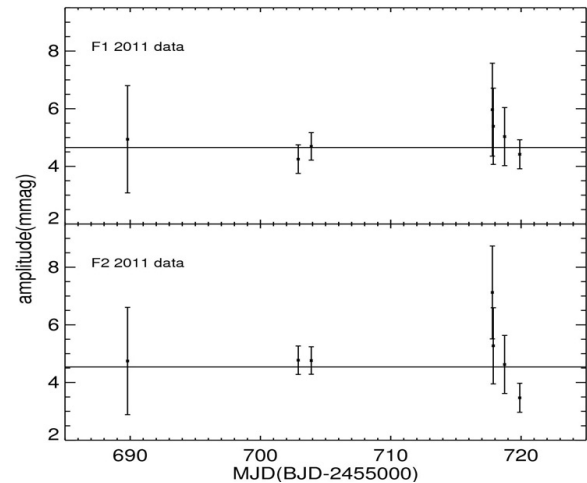confidence level above 90%, as well as the 6.936 mHz frequency (Kuassivi and Ferlet 2005).

Figure 1 shows a light curve of PG 1613+426 for June 19th, 2017 observation night. Figure 2 shows power spectra of PG 1613+426 during 2010-2017. These plots show not only the previously detected 6.936 mHz pulsation peak with an amplitude around 5 mmag, but also a 7.35 mHz pulsation peak with an amplitude almost the same as the 6.936 mHz pulsation (5 mmag). The previously observed 7.048 mHz frequency was not detected in any of the observation nights. No other power spectrum peaks are detectable. The detected pulsation frequencies are listed in Table 2.

Table 2. Pulsation peak frequencies of PG 1613+426. All data was used to obtain the frequencies.

Mode	Freq (mHz)	Freq σ (mHz)	Period (s)	Amp (mmag)	Amp σ (mmag)
F1 (p)	6.9363	0.0017	144.17	5.5	0.4
F2 (p)	7.3505	0.0020	136.05	4.5	0.4

3.2 Day to day amplitude variation

The pulsation frequencies shown in Table 2 are detectable for all observing nights. However, day to day pulsation amplitude variations were also observed for both pulsations in 2011 June data (See Figure 3). In this figure, Days 717-719 (June 5th-7th, 2011) shows that the amplitude is decreasing for both F1 and F2. That may be a consequence of un-

resolved closely spaced pulsation frequencies, like rotational splitting (Lynas-Gray 2013). Kawaler (2010) detected pulsation amplitude variation of KIC 010139564 due to the rotational splitting. Randall *et al.* (2009) also successfully resolved rotational splitting of V541 Hya using a ground-based telescope. We originally wanted to search this daily amplitude variation in observation runs of year 2017, however the weather did not cooperate and only four days of data were obtained in summer 2017. The amplitude variations were not observed in these four nights. More continuous observation is needed to investigate the day to day amplitude variations.

3.3 Seasonal amplitude variation and O-C analysis of 2010-2017 dataset

To obtain a reliable O-C diagram, the star pulsations must have stable periods and amplitudes. Figure 4 shows seasonal amplitude variations for PG 1613+426 for F1 (6.94 mHz) and F2 (7.35 mHz) pulsations from 2010 to 2017. The amplitudes of both F1 and F2 are stable during this period except F2 amplitude of 2015 data.

Since both pulsation periods and amplitudes are stable, an O-C analysis was performed using the timings of light curve maxima. Figure 5 shows a primary PG 1613+426 O-C results using F1 and F2 pulsations. Even though there are not enough data points to confirm it, both diagrams shows periodical variations. The curves represent the best sinusoidal curve fits. The period of both sinusoidal curve fitting are 814.0 ± 1.6 days and 817.6 ± 2.6 days. These are the
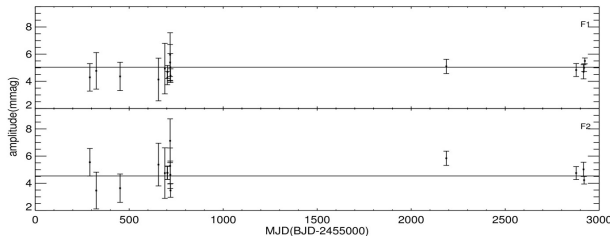
Figure 4. Seasonal amplitude variation and O-C analysis of 2010-2017 dataset for F1 (top) and F2 (bottom) pulsations.
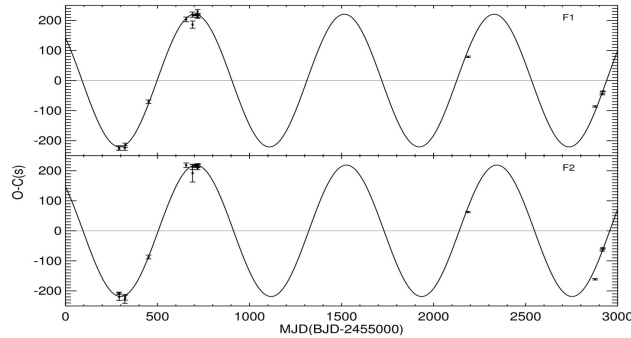

Figure 5. PG 1613+426 O-C results for F1 (top) and F2 (bottom). The curves represent the best sinusoidal curve fits. Each dot represents one night of observation.

same within the uncertainty levels of measurements. The χ^2 values are 5.59 (F1) and 6.7 (F2), respectively. The corresponding confidence levels are both higher than 99% and 98%. The resulting period of a sinusoidal curves do not match pulsation amplitude variabilities of F1 and F2 pulsations, so these are not due to the beating of two closely spaced pulsation frequencies. These O-C variations may be due to the light-travel effects caused by a companion. The frequencies and amplitudes of the sinusoidal fits used for both O-C diagrams, and the corresponding orbital information of the unseen binary are listed in Table 3. To calculate the orbital information, an average sdB mass $M_{sdB} = 0.47 M_\odot$ was assumed for PG 1613+426 mass.

Since the sinusoidal curve fits well to O-C diagrams, the eccentricity of the orbit is close to zero. According to Vos *et al.* (2015), there is a clear correlation between the period of wide sdB binary and the orbital eccentricity, and

Table 3. O-C diagrams best fit results for F1 and F2 pulsations

	F1	F2
O-C Amplitude (s)	220.8 ± 2.5	218.7 ± 4.0
Orbital Period (days)	814.0 ± 1.6	817.6 ± 2.6
Orbital distance (AU)	1.327 ± 0.002	1.330 ± 0.003
Mass $M \sin i$ ($M_\odot$)	0.157 ± 0.002	0.155 ± 0.003

the eccentricity of an orbit which has a period of 800 days is less than 0.1. Therefore, our result probably supports the period-eccentricity relationship. However, more data are needed to fit the O-C diagrams to an eccentric orbit and obtain full orbital solutions.

4 Conclusion

This paper presents PG 1613+426 photometric results, the detection of a new stable pulsation frequency, amplitude stabilities, and our primary O-C analysis to search for companions. Our 2010, 2011, 2015, and 2017 photometric data show a new stable pulsation frequency 7.3505 mHz. The day to day amplitude decrease was observed in 2011 data, and it may be due to the rotational splitting. One to two weeks continuous observation will be needed to investigate the day-to-day amplitude variations. Our primary O-C analysis shows possible periodic variations for both F1 and F2 results, indicating that PG 1613+426 may have a low mass ($M \sin i$ = 0.16 $M_\odot$) companion star with an orbital period of P = 814 days and an orbital distance of r = 1.32 AU. More data points are needed to obtain full orbital solutions, including eccentricities, as well as confirming the companion.

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