Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **415,** 1220–1227 (2011) doi:10.1111/j.1365-2966.2011.18743.x

The pulsations of PG 1351+489

M. Redaelli,[1⋆] S. O. Kepler,[1] J. E. S. Costa,[1] D. E. Winget,[2] G. Handler,[3] B. G. Castanheira,[1,2,3] A. Kanaan,[4] L. Fraga,[5] P. Henrique,[4] O. Giovannini,[6] J. L. Provencal,[7,8] H. L. Shipman,[7] J. Dalessio,[7] S. E. Thompson,[8,9] F. Mullally,[9] M. M. Brewer,[10] D. Childers,[11] M. E. Oksala,[12] R. Rosen,[13] M. A. Wood,[14] M. D. Reed,[15] B. Walter,[16] W. Strickland,[16] D. Chandler,[16] T. K. Watson,[17] R. E. Nather,[2] M. H. Montgomery,[2] A. Bischoff-Kim,[18] C. J. Hansen,[19] A. Nitta,[20] S. J. Kleinman,[20] C. F. Claver,[21] T. M. Brown,[22] D. J. Sullivan,[23] S.-L. Kim,[24] W.-P. Chen,[25] M. Yang,[25] C.-Y. Shih,[25] X. Zhang,[26] X. Jiang,[26] J. N. Fu,[27] S. Seetha,[28] B. N. Ashoka,[28] T. M. K. Marar,[28] K. S. Baliyan,[29] H. O. Vats,[29] A. V. Chernyshev,[30] P. Ibbetson,[31] E. Leibowitz,[32] S. Hemar,[32] A. V. Sergeev,[33] M. V. Andreev,[33] R. Janulis,[34] E. G. Meištas,[34] P. Moskalik,[35] G. Pajdosz,[35] A. Baran,[36] M. Winiarski,[36] S. Zola,[36,37] W. Ogloza,[36] M. Siwak,[37] Zs. Bognár,[38] J.-E. Solheim,[39] R. Sefako,[40] D. Buckley,[40] D. O'Donoghue,[40] T. Nagel,[41] R. Silvotti,[42] I. Bruni,[42] J. R. Fremy,[43] G. Vauclair,[44] M. Chevreton,[43] N. Dolez,[44] B. Pfeiffer,[44] M. A. Barstow,[45] O. L. Creevey,[46] S. D. Kawaler[47] and J. C. Clemens[48]

[1]*Instituto de Física da Universidade Federal do Rio Grande do Sul, 91501-970 Porto Alegre, RS, Brazil*
[2]*Department of Astronomy and McDonald Observatory, University of Texas, Austin, TX 78712, USA*
[3]*Institut für Astronomie, Universität Wien, Türkenschanzstraβe 17, 1180 Wien, Austria*
[4]*Departamento de Física, Universidade Federal de Santa Catarina, 88040-900 Florianópolis, SC, Brazil*
[5]*Southern Observatory for Astrophysical Research, Casilla 603, La Serena, Chile*
[6]*Departamento de Física e Química, Universidade de Caxias do Sul, 95070-560 Caxias do Sul, RS, Brazil*
[7]*University of Delaware, Department of Physics and Astronomy Newark, DE 19716, USA*
[8]*Delaware Asteroseismic Research Center, Mt Cuba Observatory, Greenville, DE 19807, USA*
[9]*SETI Institute/NASA Ames Research Center, Moffett Field, CA 94035, USA*
[10]*William Jewell College, 500 College Hill Liberty, MO 64048, USA*
[11]*Department of Math and Science, Delaware County Community College, 901 S. Media Road, Media, USA*
[12]*Bartol Research Institute, University of Delaware, Newark, Delaware, USA*
[13]*National Radio Astronomy Observatory, PO Box 2, Green Bank, WV 24944, USA*
[14]*Florida Institute of Technology, Department of Physics and Space Sciences, Melbourne, FL 32901, USA*
[15]*Missouri State University and Baker Observatory, 901 S. National, Springfield, MO 65897, USA*
[16]*Meyer Observatory and Central Texas Astronomical Society, Waco, TX, USA*
[17]*Southwestern University, Georgetown, TX, USA*
[18]*Department of Chemistry, Physics and Astronomy, Georgia College & State University, Milledgeville, GA, USA*
[19]*JILA, University of Colorado, Boulder, CO, USA*
[20]*Gemini Observatory, 670 N A'ohoku PI., Hilo, HI 96720, USA*
[21]*Kitt Peak National Observatory, National Optical Astronomy Observatory, Tucson, AZ, USA*
[22]*Las Cumbres Observatory Global Telescope Network, Inc., 6740 Cortona Drive Suite 102, Santa Barbara, CA 93117, USA*
[23]*Victoria University of Wellington, Wellington, New Zealand*
[24]*Korea Astronomy and Space Science Institute, Daejeon 305-348, Korea*
[25]*Lulin Observatory, National Central University, Taiwan*
[26]*National Astronomical Observatories, Beijing 100012, China*
[27]*Department of Astronomy, Beijing Normal University, Beijing, China*
[28]*Indian Space Research Organization, Airport Road, Vimanapura PO, Bangalore 560017, India*
[29]*Physical Research Laboratory, Ahmedabad 380009, India*
[30]*Astronomical Institute, Astronomicheskaya 33, Tashkent, Uzbekistan*

⋆E-mail: maukeyboard@gmail.com

[31] *Wise Observatory, Tel Aviv University, Tel Aviv, Israel*
[32] *School of Physics and Astronomy and the Wise Observatory, Tel Aviv University, Tel Aviv, Israel*
[33] *Ukranian National Academy of Sciences, Main Astronomical Observatory, Golosiiv, Kiev 022 252650, Ukraine*
[34] *Institute of Theoretical Physics and Astronomy, Vilnius University, Vilnius, Lithuania*
[35] *Copernicus Astronomical Center, Warsaw, Poland*
[36] *Mt Suhora Observatory, Cracow Pedagogical University, Cracow, Poland*
[37] *Astronomical Observatory, Jagiellonian University, ul. Orla 171, 30-244 Cracow, Poland*
[38] *Konkoly Observatory, PO Box 67, H-1525 Budapest XII, Hungary*
[39] *Institute of Theoretical Astrophysics, University of Oslo, NO 0315 Oslo, Norway*
[40] *South African Astronomical Observatory, Observatory 7935, Cape Town, South Africa*
[41] *Institut für Astronomie und Astrophysik, Universitet Tübingen, Sand 1, 72076 Tübingen, Germany*
[42] *INAF Osservatorio Astronomico di Torino, strada dell Osservatorio 20, 10025 Pino Torinese, Italy*
[43] *LESIA, Observatoire de Paris-Meudon, Meudon, France*
[44] *Laboratoire d'Astrophysique de Toulouse-Tarbes CNRS-UMR5572, Université de Toulouse, France*
[45] *Astronomy Department, Leicester University, University Road, Leicester LE1 7RH*
[46] *Instituto de Astrofisica de Canarias, Tenerife, Spain*
[47] *Department of Physics and Astronomy, Iowa State University, Ames, IA 50211, USA*
[48] *Department of Physics and Astronomy, University of North Carolina, Philips Hall, CB 3255, Chapel Hill, NC 27599, USA*

Accepted 2011 March 18. Received 2011 March 15; in original form 2010 September 3

ABSTRACT

PG 1351+489 is one of the 20 DBVs – pulsating helium-atmosphere white dwarf stars – known and has the simplest power spectrum for this class of star, making it a good candidate to study cooling rates. We report accurate period determinations for the main peak at 489.334 48 s and two other normal modes using data from the Whole Earth Telescope (WET) observations of 1995 and 2009. In 2009, we detected a new pulsation mode and the main pulsation mode exhibited substantial change in its amplitude compared to all previous observations. We were able to estimate the star's rotation period, of 8.9 h, and discuss a possible determination of the rate of period change of $(2.0 \pm 0.9) \times 10^{-13}$ s s $^{-1}$, the first such estimate for a DBV.

Key words: stars: evolution – stars: individual: PG 1351+489 – stars: oscillations – white dwarfs.

1 INTRODUCTION

White dwarf stars with spectra dominated by He I lines pulsate when their effective temperatures are between about 30 000 and 22 000 K (see e.g. Beauchamp et al. 1999). These stars, collectively known as DBV, were the first variables to be correctly predicted before their discovery (Winget et al. 1982). There are only 20 DBVs known (Kilkenny et al. 2009; Nitta et al. 2009) and PG 1351+489 is one of them. This star has two determinations for the effective temperature, $T_{\rm eff} = 22\,600$ K, $\log g = 7.9$ using pure He atmosphere and $T_{\rm eff} = 26\,100$ K, $\log g = 7.89$ allowing for unseen H contamination (Beauchamp et al. 1999). Castanheira et al. (2006) estimated from *IUE* spectra the values $T_{\rm eff} = 22\,500 \pm 190$ K, $\log g = 7.60 \pm 0.15$ for pure He and $T_{\rm eff} = 22\,000 \pm 150$ K, $\log g = 7.00 \pm 0.07$ allowing for H contamination. The analysis of the time series photometric data shows one main mode and at least two other normal modes (Winget, Nather & Hill 1987). This is one of the simplest DBV periodogram known.

The study of white dwarfs can contribute to our knowledge about the Galaxy disc and halo (e.g. Winget & Kepler 2008). White dwarf pulsations provide important information about high-energy and high-pressure systems, because the pulsations observed in white dwarfs are their normal modes and depend on their global structure. Also, cooling rates may be measured by the rate of change of period (Winget et al. 1985), because the evolution of a white dwarf is dominated by cooling. As the temperature of a pulsating white dwarf decreases, the depth of the ionization zone increases and longer periods can be excited. Up to now, such a rate of change has been measured for the lukewarm DAVs (Kepler et al. 2005) and for the hot DOVs (Costa & Kepler 2008), but not for DBVs.

PG 1351+489 is a candidate for the first measurement of a DBV cooling rate because its power spectrum is dominated by one mode. The largest amplitude mode, at 489 s, has a peak-to-peak amplitude of 0.16 mag and several harmonics have also been detected (Winget et al. 1987). In addition, two smaller amplitude normal modes have been observed, along with several linear combination frequencies (Alves et al. 2003). In this work we confirm these previous results and provide more precise values for the periods; we also find a new small amplitude mode in the 2009 data and estimate the rotation period for this star. We report the observations of PG 1351+489 during two Whole Earth Telescope (WET) campaigns (Nather et al. 1990) from 1995 and 2009, and discuss a possible rate of change of the main period for this star. A rate of pulsation period change is an evolutionary time-scale, and offers a unique way to look inside a star to measure its internal composition. These rate of period changes constrain models used in cosmochronology, and can even be used to probe for exotic particles like neutrinos and axions.

2 OBSERVATIONS

We obtained ∼170 h of high-speed photometric data from seven different observatories in the WET campaign of 1995 (xcov12), spanning 38 d. There was a 20 d gap between April 5 and April 25, and the coverage was about 40 per cent in the two weeks of intense observation. From the WET campaign of 2009 (xcov27) we obtained only ∼20 h of observations from four observatories, since PG 1351+489 was a tertiary target. We also used four data sets from McDonald Observatory, obtained during the years 1984, 1985, 1986 and 2004. The time base used in this work is the Barycentric Dynamical Time (TDB), or Barycentric Julian Dynamical Date (BJDD), obtained after a conversion from UTC to the barycenter of the Solar system. Table 1 shows the Journal of Observations.

3 ANALYSIS

We began the analysis of PG 1351+489 data looking for pulsation modes in the individual light curves. The peaks in the Fourier transform whose amplitude were above the detection limit of 1/1000 false alarm probability were considered real. For the individual light curves, which consist of equally spaced data, the detection limit was three times the average amplitude, computed by $\langle A \rangle = \sqrt{\Sigma A_i^2}/N$. The main peak of 489 s was present in all the runs. The small amplitude modes were detected only in the longer runs.

Table 1. Journal of observations.

Run	Telescope	Δt (s)	Date (UT)	Begin (UT)	Length (h)
r2957	McDonald 2.1 m	10	1984 May 06	04:04:30	04:25:20
r2961	McDonald 2.1 m	10	1984 May 07	03:20:00	02:36:40
r2962	McDonald 2.1 m	10	1984 May 07	06:28:20	03:54:30
r3006	McDonald 2.1 m	10	1985 February 16	07:20:55	04:15:00
r3007	McDonald 2.1 m	10	1985 February 17	08:28:00	03:44:40
r3015	McDonald 2.1 m	10	1985 March 22	08:15:39	01:28:50
r3019	McDonald 2.1 m	10	1985 March 23	05:29:11	06:06:00
r3025	McDonald 2.1 m	10	1985 March 24	06:24:10	04:47:10
r3072	McDonald 2.1 m	10	1985 June 15	03:44:50	02:19:50
r3077	McDonald 2.1 m	10	1985 June 22	03:40:10	02:26:20
r3080	McDonald 2.1 m	10	1985 June 24	07:37:00	01:47:30
r3142	McDonald 2.1 m	10	1986 April 03	04:04:30	05:07:20
r3144	McDonald 2.1 m	10	1986 April 04	03:54:20	07:25:40
r3149	McDonald 2.1 m	10	1986 April 10	05:37:56	04:21:50
r3150	McDonald 2.1 m	03	1986 April 13	05:23:40	02:50:57
r3151	McDonald 2.1 m	10	1986 April 13	09:21:40	01:46:20
r3168	McDonald 2.1 m	10	1986 June 10	03:36:00	05:10:30
r3170	McDonald 2.1 m	10	1986 June 11	03:38:30	05:12:30
r3172	McDonald 2.1 m	10	1986 June 12	03:36:40	05:31:40
r3173	McDonald 2.1 m	10	1986 June 13	03:36:30	05:07:40
gv0502	Pic du Midi 2.0 m	10	1995 April 02	22:53:07	03:10:10
gv0504	Pic du Midi 2.0 m	10	1995 April 03	22:24:37	01:51:40
gv0506	Pic du Midi 2.0 m	10	1995 April 04	22:09:10	02:44:10
gv0508	Pic du Midi 2.0 m	10	1995 April 05	23:38:50	05:10:40
eml-0002	Wise 1.0 m	10	1995 April 25	18:43:10	05:07:20
eml-0003	Wise 1.0 m	10	1995 April 26	17:55:40	07:24:10
eml-0005	Wise 1.0 m	10	1995 April 27	21:56:40	03:43:10
eml-0006	Wise 1.0 m	10	1995 April 28	18:43:00	01:07:00
eml-0008	Wise 1.0 m	10	1995 April 28	21:06:00	03:55:20
eml-0009	Wise 1.0 m	10	1995 April 29	18:03:00	07:01:00
jebp01	Isaac Newton 2.5 m	10	1995 April 26	00:17:40	05:10:40
jebp02	Isaac Newton 2.5 m	10	1995 April 26	22:58:30	02:07:10
jebp03	Isaac Newton 2.5 m	10	1995 April 27	21:45:00	07:03:50
jebp04	Isaac Newton 2.5 m	10	1995 April 28	23:31:20	05:47:20
jebp05	Isaac Newton 2.5 m	10	1995 April 29	20:54:40	08:26:10
ra360	McDonald 2.1 m	10	1995 April 26	02:40:50	07:59:50
ra361	McDonald 2.1 m	10	1995 April 27	02:29:40	07:25:40
ra362	McDonald 2.1 m	10	1995 April 28	02:39:20	08:03:00
ra363	McDonald 2.1 m	10	1995 April 29	02:35:10	08:35:50
ra364	McDonald 2.1 m	10	1995 April 30	02:31:40	07:58:10
ra367	McDonald 2.1 m	10	1995 May 03	07:29:40	03:37:00
emac-002	Maidanak 1.0 m	10	1995 May 01	20:31:30	01:49:00
emac-003	Maidanak 1.0 m	10	1995 May 01	18:30:00	01:44:10
emac-004	Maidanak 1.0 m	10	1995 May 02	15:54:00	02:49:50
emac-006	Maidanak 1.0 m	10	1995 May 05	16:32:30	05:40:30
emac-008	Maidanak 1.0 m	10	1995 May 06	19:16:00	03:41:50
cfc-202	Mauna Kea 0.6 m	10	1995 May 01	07:47:00	04:24:50
cfc-208	Mauna Kea 0.6 m	10	1995 May 07	08:48:50	04:18:40
rk368	McDonald 2.1 m	10	1995 May 04	02:48:00	06:46:40

Table 1 – *continued*

Run	Telescope	Δt (s)	Date (UT)	Begin (UT)	Length (h)
rk369	McDonald 2.1 m	10	1995 May 06	08:52:40	01:55:30
sjk-0384	BAO 2.16 m	10	1995 May 02	14:22:30	05:10:10
sjk-0385	BAO 2.16 m	10	1995 May 03	14:06:50	05:19:00
sjk-0386	BAO 2.16 m	10	1995 May 04	12:45:00	07:17:00
sjk-0387	BAO 2.16 m	10	1995 May 05	13:24:40	06:00:40
sjk-0388	BAO 2.16 m	10	1995 May 06	16:32:40	03:54:10
an-0015	McDonald 2.1 m	10	1995 May 11	08:03:20	03:03:20
A0876	McDonald 2.1 m	05	2004 May 12	05:54:35	02:34:55
A0900	McDonald 2.1 m	05	2004 June 14	03:06:06	04:01:50
mole090525	Moletai 1.6 m	17	2009 May 25	20:17:08	02:54:32
mole090530	Moletai 1.6 m	17	2009 May 30	20:27:08	02:14:52
naoc090529	China 2.16 m	20	2009 May 29	12:48:11	03:49:00
naoc090530	China 2.16 m	20	2009 May 30	12:38:48	02:04:30
naoc090531	China 2.16 m	20	2009 May 31	12:41:48	01:40:20
pjmo090531	Meyer 0.6 m	30	2009 May 31	04:49:35	03:32:30
teub090524	Tuebingen 0.8 m	30	2009 May 24	21:26:01	04:12:30

The longest data set, acquired in 1995, has the best resolution and signal-to-noise ratio. The detection limit used for the whole 1995 data set was $n\ \langle A\rangle$, where $n = A_{\rm rand}^{\rm max}/\langle A_{\rm rand}\rangle$, and $A_{\rm rand}^{\rm max}$ are the maximum and $\langle A_{\rm rand}\rangle$ are the average amplitudes of the Fourier transform of the randomized light curve, which has no signal, only noise, but the same spacings as the real data. We found $n = 4.3$ using a Monte Carlo simulation method, and $n = 4.12$ using the analytical method described by Scargle (1982). Because the noise increases with decreasing frequency for $f \leq 6000\,\mu$Hz, the detection limit is a function of frequency.

Run 'emac-002', listed in Table 1 shows a very large phase deviation from the surrounding runs, inconsistent with the rest of the light curve. We assumed a timing mistake occurred and excluded that file from further analysis.

We computed a weighted Fourier transform for the whole 1995 data, shown in Fig. 1. The weights are the inverse of the dispersion in each light curve, (e.g. Handler 2003b; Costa & Kepler 2008). A list of frequencies from our analysis is shown in Table 2.

After pre-whitening the power spectrum of 1995 data by the main peak and its first harmonic, some energy remained around these frequencies (Handler 2003a). Some amount of this energy must be just mathematical artefact: amplitude modulation, real in the star or caused by different sensitivity in the detectors or possible problems in sky subtraction, causes side lobes in a Fourier transform. To search for nearby periodicities to the main pulsation mode in our combined data set, which includes data from different size telescopes, located at different sites, with non-uniform effective wavelength sensitivity, we attempted to minimize the effects of amplitude modulation. We re-normalized each run, from each observatory, by the amplitude average of the main mode estimated from the whole 1995 data set, assuming it remained intrinsically constant over the 38 d of observation.

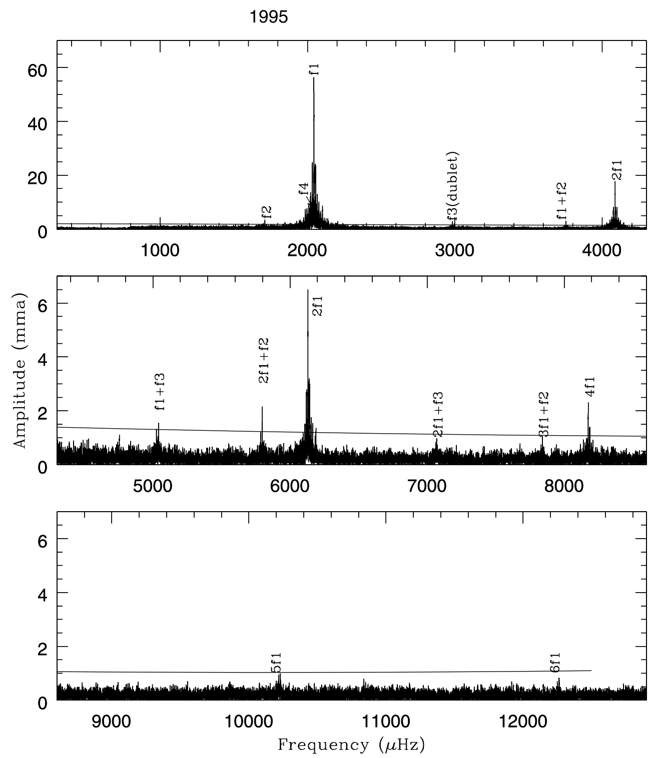

Figure 1. Weighted Fourier transform for 1995 data. The weights are the inverse square of the dispersion in each light curve. The line is the detection limit obtained from the Monte Carlo Simulation. Note the change in the *y*-axis for the lower panels.

4 ROTATION PERIOD

We found a new peak in the Fourier transform at 2027 μHz. Handler (2003a) analysed a subset of data of four consecutive nights at the 2.5 m Isaac Newton Telescope and pointed out this same interesting result. The original Fourier transform, pre-whitened by the main peak, and the one after re-normalization is shown in Fig. 2. Because this small amplitude mode beats with the main period, it is not easy to resolve it. As the difference of f_1 and this new peak is 16 μHz, the beating period is about 17 h. We need over 10 beating cycles (170 h) to separate these two close frequencies. Fortunately, we obtained more than 260 h in the last two weeks of the 1995 campaign. The doublet at $f_3 = 2982\,\mu$Hz has a splitting frequency of 15 μHz and is probably caused by rotation. The observed 16 μHz splitting of the main mode agrees with the splitting of the doublet mode f3, suggesting

Table 2. Frequencies detected in PG 1351+489 during 1995 data.

Frequency (μHz)	Period (s)	Amplitude (mma)	Identification
2043.5919 ± 0.0020	489.334 48 ± 0.000 48	56.36 ± 0.20	f_1
4087.1727 ± 0.0066	244.667 90 ± 0.000 39	17.19 ± 0.20	$2f_1$
6130.744 ± 0.017	163.112 32 ± 0.000 47	6.31 ± 0.20	$3f_1$
8174.315 ± 0.048	122.334 40 ± 0.000 72	2.34 ± 0.20	$4f_1$
10215.05 ± 0.13	97.8947 ± 0.000 13	0.40 ± 0.24	$5f_1$
12298.59 ± 0.46	81.3101 ± 0.0030	0.27 ± 0.27	$6f_1$
1710.337 ± 0.030	584.679 ± 0.010	3.68 ± 0.20	f_2
2982.771 ± 0.041	335.2586 ± 0.0046	2.81 ± 0.20	f_3[1]
3752.14 ± 0.35	266.514 ± 0.025	0.32 ± 0.21	$f_1 + f_2$
5040.885 ± 0.079	198.3778 ± 0.0031	1.44 ± 0.20	$f_1 + f_3$
5797.493 ± 0.050	172.4883 ± 0.0015	2.23 ± 0.20	$2f_1 + f_2$
2027.082 ± 0.023	493.3199 ± 0.0057	4.84 ± 0.20	$f^a{}_1$
1563.390 ± 0.25	639.63 ± 0.10	11.5 ± 1.1	f_4[2]

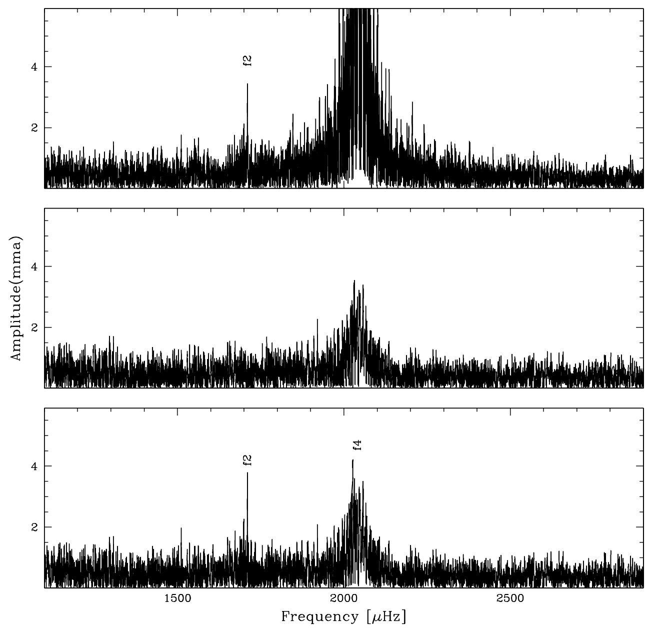

Figure 2. Fourier transforms of 1995 data. The top box shows the whole data FT in a crop of the main peak vicinity. The middle box shows an FT without f_1 and f_2. Some peaks remained nearby the main peak after the pre-whitening of f_1 and f_2. Bottom box shows an FT without the main peak for the re-normalized data. We used the main peak amplitude to re-normalize each run, assuming it is constant over the 38 d of observation. A peak at 2027 μHz and $A = 4.43$ mma remained.

that both modes are being rotationally split. The relation between the splitting frequency and the rotation period of the white dwarf depends on the pulsation index ℓ and k (see e.g. Kepler et al. 1995), and is given in the first order by

$$\delta\sigma_{\ell k m} = \delta m \Omega_{\rm rot}(1 - C_{\ell {\rm km}}),$$

where $C_{\ell km}$ is the first-order splitting coefficient, $\delta\sigma_{\ell km}$ is the frequency splitting, δm is the m difference between the components and has a modulus of unity for $\ell = 1$ modes. $\Omega_{\rm rot}$ is the rotation frequency. Using *Hubble Space Telescope* time-resolved spectroscopy, Kepler et al. (2000) found $\ell = 1$ for the main mode. Montgomery (2005) found the same result using a convection model to fit the observed light curve. Even though the asymptotic value for $C_{\ell km}$ is valid only for large k, its value from the models is close to the asymptotic value of $[\ell(\ell+1)]^{-1}$. Using $\delta\sigma_{\ell km} = 15.5 \pm 0.5$ μHz and $C_{\ell km} = 0.5$, we find a rotation period of 8.9 ± 0.3 h for PG 1351+489. As we have approximately the same splitting at f_1 and f_3, both modes should have the same $\ell = 1$.

The data of 1985 March show a slightly different value for the main peak period, of 489.11 s. The best value found in 1995 data is 489.33 s, which leaves us to speculate that the star became unstable in 1985. The total length of the 1995 March data is ~50 h giving a resolution of 0.6 μHz, much smaller than the difference in the main mode for 1985 March and 1995, of 10 μHz. Before and after 1985 March the star seems stable, although it changed again in 2009.

The 2009 data surprised us with a different pulsation spectrum (Fig. 3). The main mode shows a small change in period from previous data and its amplitude is reduced by half. At this stage we cannot identify the reason for these changes and need to keep observing PG 1351+489 to determine whether the star reverts to the original set of pulsation modes or maintains this new pulsation spectrum. Another star has shown changes in its periodicities: GD 358, the first DBV detected, showed a remarkable change in its pulsation spectrum in 1996 (Kepler et al. 2003; Castanheira et al. 2005). During that year, the amplitude of all modes changed, the

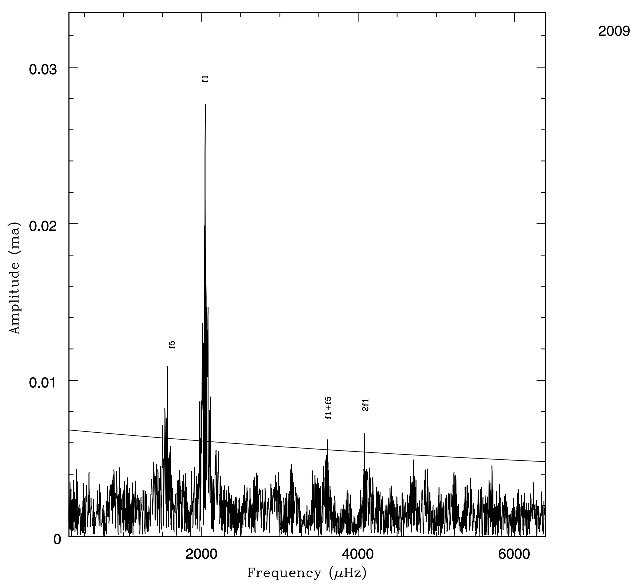

Figure 3. Power spectrum of 2009 data. We got only 20 h of data, but it was enough to see the changes in the star. PG 1351+489 shows a new mode and a decrease to the half of main mode amplitude.

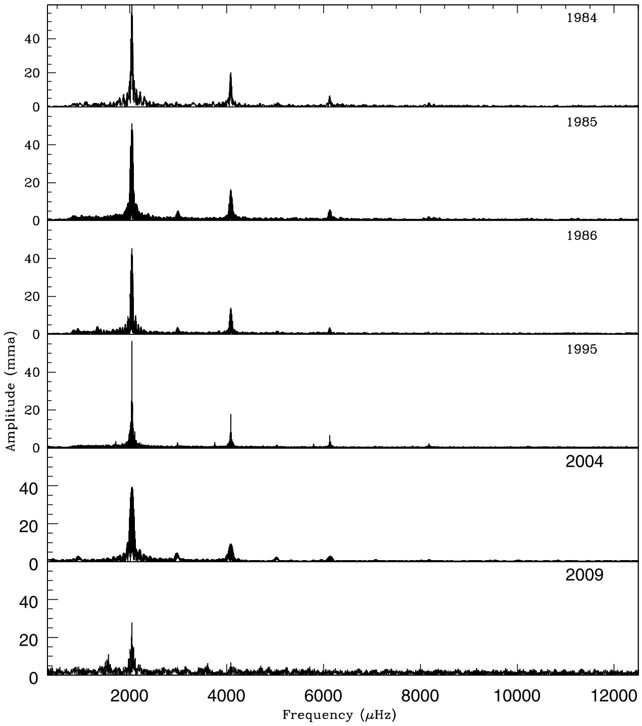

Figure 4. PG 1351+489 yearly Fourier transform on the same scale. Note the changes, especially in 2009.

dominant mode changed and even the shape of its light curve went from non-sinusoidal to sinusoidal. After 1996 their amplitudes returned basically to those of 1994, although the amplitude of all modes still show small changes from year to year (Provencal et al. 2009). Montgomery et al. (2010) show there was a significant change in the convection zone; when the observed amplitude of pulsation of GD 358 is high, the temperature in the heated area increases sufficiently to practically extinguish the convection layer. Robinson, Kepler & Nather (1982) show g-mode pulsations in white dwarf stars are mainly due to temperature changes across the surface of the star. Now we have knowledge of another DBV white dwarf – PG 1351+489 – which changed its pulsation spectrum over a time-scale of years. The fact that we detect at least six harmonics of the main pulsation implies that the intrinsic pulsation amplitude is high, as harmonics represent non-linear effects (Jevtić et al. 2005; Montgomery 2008). The high intrinsic pulsation amplitude possibly affects significantly the convection layers in PG 1351+489, as it does in GD 358.

Detecting as many modes as possible is important to apply seismology to the star, as each mode detected yields an independent constraint on its structure (e.g. Kepler et al. 2003). PG 1351+489 has four pulsation modes known up to now, including the new one detected in 2009. Fig. 4 shows the six amplitude spectra of the yearly data sets.

5 A POSSIBLE ESTIMATE OF $\dot{P}$

The rate of change of a period ($\dot{P} = \mathrm{d}P/\mathrm{d}t$) can be measured directly or indirectly (Costa & Kepler 2008). To do it directly, we must have high rates of change and small uncertainties. Supposing $\mathrm{d}P/\mathrm{d}t \sim 10^{-6}\,\mathrm{s\,yr^{-1}}$, then in 20 yr the period must change $\sim 2 \times 10^{-5}$ s. To measure this small change, the uncertainty in the measured periods must be smaller than $\sim 10^{-5}$ s. To measure $\mathrm{d}P/\mathrm{d}t$ indirectly, we can use the O − C method, which is quadratic in the time-span (e.g. Kepler et al. 1991). This method uses the difference between the times of maxima measured in the light curves and the computed values assuming no significant changes in period, over the number of cycles.

Table 3. Times of maxima for the main mode of PG 1351+489. The 2009 time of maximum was not considered in our analysis of $\mathrm{d}P/\mathrm{d}t$.

Year	$T_{\max}$(BJDD ± s)	P (s)
1984	244 5826.677 079 ± 0.6	489.292 91 ± 0.000 65
1985	244 6112.813 247 ± 0.7	489.316 24 ± 0.000 58
1986 April	244 6523.678 718 ± 0.6	489.302 81 ± 0.000 60
1986 June	244 6591.653 173 ± 0.5	489.2837 ± 0.0026
1995 April	244 9810.461 595 ± 0.9	489.3260 ± 0.0049
1995 May	244 9833.625 895 ± 0.2	489.3345 50 ± 0.000 18
2004	245 3137.751 014 ± 1.4	489.3359 ± 0.000 19
2009	245 6982.358 127 ± 3.2	489.3122 ± 0.025

As discussed, for example, in Kepler et al. (1991), a parabola is fitted to the values of O − C and the quadratic parameter is proportional to the rate of change of period. We assume the periods are changing smoothly in time and short perturbations to the periods do not affect significantly the phase of the pulsations.

Table 3 shows the values for the times of maxima and main period for each chunk of data. To increase the number of independent measurements, we separated the 1986 and 1995 light curves in two chunks each. The phase of the main pulsation for the 2009 data was not used because the star clearly changed in that year.

To apply this method, we assume we do not know the precise value of the period. The cycle count changes significantly when the period changes a little, but we are working with the hypothesis of an unknown period to estimate the secular $\mathrm{d}P/\mathrm{d}t$ for this star. Thus, we must test many different O − C diagrams for many different values of period, following O'Donoghue & Warner (1987). We tested periods from 489.33 to 489.34 s, in steps of 0.000 01 s. For each possible period we found a different O − C set. We chose the smallest S^2 (the normalized sum of the phase differences squared) computed for the O − C values and the fitted parabola. The diagram is shown in Fig. 5. The best values for S^2 are shown in Table 4. The smallest S^2 gives $P = (489.334\,645 \pm 0.000\,023)$ s and $\dot{P} = (2.0 \pm 0.9) \times 10^{-13}\,\mathrm{s\,s^{-1}}$.

6 DISCUSSION

The measurement of the cooling rate of a hot DBV star can be used to estimate the plasmon-neutrino emission rates (Winget et al. 2004). Using the optical spectra determination of effective temperature with pure helium atmospheres, PG 1351+489 is not on the blue edge of the DBV instability strip, hence the plasmon-neutrino emission should not dominate the cooling, except if the star has low mass. Compared to the values calculated by Winget et al. (2004) for such low temperature, but normal mass, the estimate of $\mathrm{d}P/\mathrm{d}t$ we obtain is higher than predicted by the cooling by photon and plasmon-neutrino emission. We call our $\mathrm{d}P/\mathrm{d}t$ an estimate, not a measurement, because the 1985 value is not included; we will discuss these glitches in the next section. Córsico & Althaus (2004) estimate for a $0.5\,\mathrm{M}_{\odot}$ DB white dwarf model at $T_{\rm eff} = 22\,100$ K a rate of period change of $\dot{P} = 8.6 \times 10^{-14}\,\mathrm{s\,s^{-1}}$, for their $P = 485$ s mode, with cooling dominated by photon emission. The theoretical value is a factor of 2.3 smaller than that estimated from the observations in this paper.

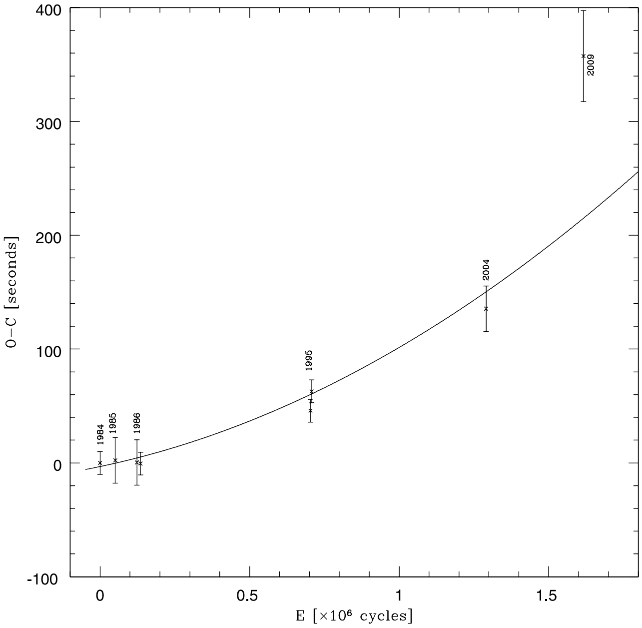

Figure 5. O − C diagram for PG 1351+489. The fitted parabola gives $\dot{P} = (2.0 \pm 0.9) \times 10^{-13}\,\mathrm{s\,s^{-1}}$ and $P = 489.334\,645 \pm 0.000\,023$ s. The 2009 value was not included in this analysis because the pulsations changed in that year; its value is shown only as a guide. Note we do not include the 489.11 s period and its time of maxima, obtained in 1985.

Table 4. Some values for P and $\dot{P}$ for different O − C diagrams.

S^2 (s ^{2})	P_i(s)	P (s)	$\dot{P}(10^{-13}\,\mathrm{s\,s^{-1}})$
43.383 7290	489.334 59	489.334 645 ± 0.000 023	2.0 ± 0.9
43.383 7292	489.334 87	489.334 645 ± 0.000 023	2.0 ± 0.9
190.750 3123	489.333 68	489.334 472 ± 0.000 048	−29.2 ± 1.9
190.750 3125	489.333 75	489.334 472 ± 0.000 048	−29.2 ± 1.9
321.933 2478	489.335 67	489.334 818 ± 0.000 063	33.2 ± 2.4

Some pulsation modes have higher amplitude in the core than in the surface layers, while others have the opposite. The core of white dwarf stars represents around 99 per cent of their mass. For those modes with larger amplitudes in the core, the fractional rate of change of their pulsation periods, $\dot{P}/P$, decreases very approximately at the same rate as the star cools, $\dot{T}_{\rm core}/T_{\rm core}$, considering the fractional radius change, $\dot{R}/R$, is around one to two orders of magnitude smaller. For those modes where the surface layer amplitudes dominate, the pulsation periods can change on a much faster time-scale, representative of avoided crossings or changes in the transition layers causing mode trapping. As the masses involved in the surface layers are small, these relatively rapid changes will revert to evolutionary (cooling) time-scales, which are not affected by the surface layer changes. In pulsars, for example, even in the Hulse & Taylor PSR B1913+16, glitches occur, and their rotation behaviour over long time-scales are significantly affected by small-scale irregularities not explicitly accounted for in a deterministic model. Nevertheless, the physically important astrometric, spin and orbital parameters are well determined and well decoupled from the timing noise (Weisberg, Nice & Taylor 2010).

If the estimated $\dot{P}$ value is representative of the stellar cooling and the star has a relatively low temperature, but normal mass, the rate of period change could be used to constrain the axion emissivity. At the low effective temperature determined from pure He models, the energy lost by axion emission is expected to be larger than the energy lost by neutrinos (Kim 2007, fig. 1.2). For an effective temperature of PG 1351+489 as high as $T_{\rm eff} = 26\,000$ K, estimated by Montgomery et al. (2010, fig. 6) non-linear curve fitting, or Beauchamp et al. (1999) if some H contamination is allowed, Córsico & Althaus (2004) estimate $\dot{P} = 1.7 \times 10^{-14}\,\mathrm{s\,s^{-1}}$; thus the estimated rate of period change could be reflecting the white dwarf cooling for such a high effective temperature.

Castanheira et al. (2006) determined from *IUE* spectra a surface gravity of $\log g = 7.0 \pm 0.07$, allowing for the presence of unseen atmospheric H, but the external uncertainty in $\log g$ is much larger, because of the weak dependency of DB models on surface gravity. Such a low surface gravity would imply a stellar mass for PG 1351+489 markedly lower than $0.5\,\mathrm{M_\odot}$. For such low mass, the neutrino emission could be important even at $T_{\rm eff} = 22\,000$ K (Winget et al. 2004, fig. 1, $0.45\,\mathrm{M_\odot}$ white dwarf model).

Unfortunately, we do not have yet a measurement of the cooling rate, because the uncertainty in $\dot{P}$ is relatively high and because our assumption of a stable period cannot be proven. We must continue to observe the star to get a $\dot{P}$ measurement.

The study of the pulsating DB stars can provide new information about their progenitors, possible very late thermal pulse (VLTP) remnants (Althaus et al. 2009). New DB stars have been observed and now we can make good advances to unveil the DB instability strip. It is important to continue observing known DB stars in order to check their pulsation profiles and understand their instabilities while searching for new ones is potentially useful to test theories and improve models.

PG 1351+489 is a very important star to study the cooling rate for DBVs. However, its relatively cool temperature drops it to a secondary choice to measure the plasmon-neutrino emission rate for white dwarfs (e.g. Kim, Winget & Montgomery 2006). We estimate the rotation period of 8.9 ±0.3 h using the splitting frequency of 15.5 ±0.5 μHz we found in the main peak; using this rotation period we deduce the $1.46f_1$ mode has $\ell = 1$ too. We estimate a possible rate of change of period using the O − C method; we found $\mathrm{d}P/\mathrm{d}t = (2.0 \pm 0.9) \times 10^{-13}\,\mathrm{s\,s^{-1}}$. The high uncertainty in this result is due to the low number of points in the O − C diagram (Fig. 5). Low numbers of points can lead to low confidence statistics, e.g. a negative secular change of PG 1159−035, estimated by Winget et al. (1985), had the best S^2 at that time. Costa, Kepler & Winget (1999) showed the second solution in 1985, a positive $\mathrm{d}P/\mathrm{d}t$ was in fact the correct one when more data were added. As we have no proof of period stability for PG 1351+489, we cannot conclude that the $\dot{P}$ we found represents the evolution of the star. New observations of PG 1351+489 are required in order to improve our chances of estimating the secular changes in the star.

ACKNOWLEDGMENTS

We sincerely thank the referee, Dr Leandro Althaus, for his insightful comments that made this a better paper.

REFERENCES

Althaus L. G., Panei J. A., Miller Bertolami M. M., García-Berro E., Córsico A. H., Romero A. D., Kepler S. O., Rohrmann R. D., 2009, ApJ, 704, 1605

Alves V. M. et al., 2003, Baltic Astron., 12, 33

Beauchamp A., Wesemael F., Bergeron P., Fontaine G., Saffer R. A., Liebert J., Brassard P., 1999, ApJ, 516, 887

Castanheira B. G., Nitta A., Kepler S. O., Winget D. E., Koester D., 2005, A&A, 432, 175
Castanheira B. G., Kepler S. O., Handler G., Koester D., 2006, A&A, 450, 331
Córsico A. H., Althaus L. G., 2004, A&A, 428, 159
Costa J. E. S., Kepler S. O., 2008, A&A, 489, 1
Costa J. E. E., Kepler S. O., Winget D. E., 1999, ApJ, 522, 973
Handler G., 2003a, Baltic Astron., 12, 11
Handler G., 2003b, Baltic Astron., 12, 253
Jevtić N., Zelechoski S., Feldman H., Peterson C., Schweitzer J. S., 2005, ApJ, 635, 527
Kepler S. O. et al., 1991, ApJ, 378, L45
Kepler S. O. et al., 1995, ApJ, 447, 874
Kepler S. O., Robinson E. L., Koester D., Clemens J. C., Nather R. E., Jiang X. J., 2000, ApJ, 539, 379
Kepler S. O. et al., 2003, A&A, 401, 639
Kepler S. O. et al., 2005, ApJ, 634, 1311
Kilkenny D., O'Donoghue D., Crause L. A., Hambly N., MacGillivray H., 2009, MNRAS, 397, 453
Kim A., 2007, PhD thesis, University of Texas at Austin, http://whitedwarf.org/theses/kim.pdf
Kim A., Winget D. E., Montgomery M. H., 2006, Mem. Soc. Astron. Ital., 77, 460
Montgomery M. H., 2005, ApJ, 633, 1142
Montgomery M. H., 2008, Comm. Asteroseismol., 154, 38
Montgomery M. H. et al., 2010, ApJ, 716, 84
Nather R. E., Winget D. E., Clemens J. C., Hansen C. J., Hine B. P., 1990, ApJ, 361, 309
Nitta A. et al., 2009, ApJ, 690, 560
O'Donoghue D., Warner B., 1987, MNRAS, 228, 949
Provencal J. L. et al., 2009, ApJ, 693, 564
Robinson E. L., Kepler S. O., Nather R. E., 1982, ApJ, 259, 219
Scargle J. D., 1982, ApJ, 263, 835
Weisberg J. M., Nice D. J., Taylor J. H., 2010, ApJ, 722, 1030
Winget D. E., Kepler S. O., 2008, ARA&A, 46, 157
Winget D. E., Robinson E. L., Nather R. D., Fontaine G., 1982, ApJ, 262, L11
Winget D. E., Robinson E. L., Nather R. E., Kepler S. O., O'Donoghue D., 1985, ApJ, 292, 606
Winget D. E., Nather R. E., Hill J. A., 1987, ApJ, 316, 305
Winget D. E., Sullivan D. J., Metcalfe T. S., Kawaler S. D., Montgomery M. H., 2004, ApJ, 602, L109

This paper has been typeset from a TEX/LATEX file prepared by the author.