A&A 432, 219–224 (2005)
DOI: 10.1051/0004-6361:20041125

Astronomy & Astrophysics

Whole Earth Telescope observations of BPM 37093: A seismological test of crystallization theory in white dwarfs⋆

A. Kanaan[1], A. Nitta[2], D. E. Winget[3], S. O. Kepler[4], M. H. Montgomery[5,3], T. S. Metcalfe[6,3], H. Oliveira[1], L. Fraga[1], A. F. M. da Costa[4], J. E. S. Costa[4], B. G. Castanheira[4], O. Giovannini[7], R. E. Nather[3], A. Mukadam[3], S. D. Kawaler[8], M. S. O'Brien[8], M. D. Reed[8,9], S. J. Kleinman[2], J. L. Provencal[10], T. K. Watson[11], D. Kilkenny[12], D. J. Sullivan[13], T. Sullivan[13], B. Shobbrook[14], X. J. Jiang[15], B. N. Ashoka[16], S. Seetha[16], E. Leibowitz[17], P. Ibbetson[17], H. Mendelson[17], E. G. Meištas[18], R. Kalytis[18], D. Ališauskas[19], D. O'Donoghue[12], D. Buckley[12], P. Martinez[12], F. van Wyk[12], R. Stobie[12], F. Marang[12], L. van Zyl[12], W. Ogloza[20], J. Krzesinski[20], S. Zola[20,21], P. Moskalik[22], M. Breger[23], A. Stankov[23], R. Silvotti[24], A. Piccioni[25], G. Vauclair[26], N. Dolez[26], M. Chevreton[27], J. Deetjen[28], S. Dreizler[28,29], S. Schuh[28,29], J. M. Gonzalez Perez[30], R. Østensen[31], A. Ulla[32], M. Manteiga[32], O. Suarez[32], M. R. Burleigh[33], and M. A. Barstow[33]

Received 20 April 2004 / Accepted 31 October 2004

Abstract. BPM 37093 is the only hydrogen-atmosphere white dwarf currently known which has sufficient mass ($\sim$1.1 $M_\odot$) to theoretically crystallize while still inside the ZZ Ceti instability strip ($T_{\rm eff} \sim 12\,000$ K). As a consequence, this star represents our first opportunity to test crystallization theory directly. If the core is substantially crystallized, then the inner boundary for each pulsation mode will be located at the top of the solid core rather than at the center of the star, affecting mainly the average period spacing. This is distinct from the "mode trapping" caused by the stratified surface layers, which modifies the pulsation periods more selectively. In this paper we report on Whole Earth Telescope observations of BPM 37093 obtained in 1998 and 1999. Based on a simple analysis of the average period spacing we conclude that a large fraction of the total stellar mass is likely to be crystallized.

Key words. stars: evolution – stars: individual: BPM 37093 – stars: interiors – stars: oscillations – white dwarfs

⋆ Based on observations obtained at: Observatório do Pico dos Dias (OPD) Brazil, the European Southern Observatory (ESO) Chile, South African Astronomical Observatory (SAAO), Mt. John University Observatory (MJUO) New Zealand, Siding Spring Observatory (SSO) Australia, and Cerro Tololo Inter-American Observatory (CTIO), a division of the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.

[1] Departamento de Física Universidade Federal de Santa Catarina, CP 476, 88040-900 Florianópolis, SC, Brazil
e-mail: kanaan@astro.ufsc.br
[2] Apache Point Observatory, 2001 Apache Point Road, PO Box 59, Sunspot, NM 88349, USA
[3] Department of Astronomy, 1 University Station Stop C1400, University of Texas, Austin, TX 78712, USA
[4] Instituto de Física, Universidade Federal de Rio Grande do Sul, CP 10501, 91501-970 Porto Alegre, RS, Brazil
[5] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
[6] Harvard-Smithsonian Center for Astrophysics, USA
[7] Departamento de Fisica e Quimica, UCS, Brazil
[8] Dept. of Physics & Astronomy, Iowa State University, USA
[9] Astronomy Dept., Southwest Missouri State University, USA
[10] Dept. of Physics & Astronomy, University of Delaware, USA
[11] Southwestern University, Georgetown, TX, USA
[12] South African Astronomical Observatory, South Africa
[13] Victoria University of Wellington, New Zealand
[14] Chatterton Astronomy Dept., University of Sydney, Australia
[15] Astronomical Observatory, Academy of Sciences, PR China
[16] Indian Space Research Organization, India
[17] Wise Observatory, Tel-Aviv University, Israel
[18] Institute of Theoretical Physics & Astronomy, Lithuania
[19] Vilnius University, Lithuania
[20] Mt. Suhora Observatory, Cracow Pedagogical University, Poland
[21] Astronomical Observatory, Jagiellonia University, Poland
[22] Copernicus Astronomical Center, Poland
[23] Institut für Astronomie, Universität Wien, Austria
[24] INAF – Osservatorio Astronomico di Capodimonte, Italy
[25] Dipartimento di Astronomia, Università di Bologna, Italy
[26] Université Paul Sabatier, Observatoire Midi-Pyrénées, France
[27] Observatoire de Paris-Meudon, France
[28] Institut für Astronomie und Astrophysik, Germany
[29] Universitätssternwarte Göttingen, Germany
[30] University of Tromsø, Norway
[31] Isaac Newton Group, Spain
[32] Departamento de Física Aplicada, Universidad de Vigo, Spain
[33] Dept. of Physics & Astronomy, University of Leicester, UK

1. Introduction

Since 1960 most astronomers have agreed that cool white dwarfs must eventually crystallize (Kirzhnitz 1960; Abrikosov 1960; Salpeter 1961). The process theoretically begins when the electrostatic interaction between the ions becomes much larger than the thermal energy. This effect is based on such well known physics that it has become widely accepted without ever having been tested empirically.

BPM 37093 is a ZZ Ceti star (Kanaan et al. 1992) with an unusually high mass (1.10 $M_{\odot}$, Bergeron et al. 2004). White dwarfs this massive are subject to much higher pressures and densities in their cores, and we expect a 1.0 $M_{\odot}$ white dwarf to begin crystallizing at temperatures within or above the ZZ Ceti instability strip (Wood 1992; Winget et al. 1997). Our goal in observing BPM 37093 with the Whole Earth Telescope (WET, Nather et al. 1990) was to obtain seismological data to determine whether or not the stellar interior is crystallized. The fundamental objective was simply to detect as many independent pulsation modes as possible, and then to compare the observed frequencies with those calculated from white dwarf models that have been artificially crystallized to various degrees.

For years we have faced a troubling ambiguity between the effects of the crystallized mass fraction ($M_{\rm cr}$), the hydrogen layer mass ($M_{\rm H}$), and the stellar mass (M_*) and effective temperature ($T_{\rm eff}$). Changes to these four characteristics of white dwarf models can all modify the average spacing between the calculated pulsation periods (see Montgomery & Winget 1999, Eq. (7)). Fortunately, the latter two quantities can be constrained by fitting model atmospheres to spectroscopic observations, but the others can only be determined through asteroseismology. Recent improvements in our theoretical description of the composition transition zones between the stratified surface layers in our models (Córsico et al. 2002; Althaus et al. 2003) have helped to reduce the degeneracy between $M_{\rm H}$ and $M_{\rm cr}$. However, the huge number of possible parameter combinations, and the need for an efficient method of exploring them, remained serious obstacles to progress until recently (Metcalfe & Charbonneau 2003; Metcalfe et al. 2004).

Like the cool DAV G 29-38 (Kleinman et al. 1998), BPM 37093 exhibits irregular modulations in the amplitudes of its pulsation modes. On one occasion *all* of the modes vanished below the detection threshold of ~1 mma (Kanaan et al. 1998). However, the modes that disappeared were observed to reappear later with the same pulsation frequencies. This gives us confidence that we can learn more about this star by using the full set of frequencies that have been observed over time – a concept known as "time-ensemble" asteroseismology, pioneered by Kleinman et al. (1998). In this paper we report WET observations obtained in 1998 and 1999, and we use the identified pulsation periods to define a range for the average period spacing. This allows us to constrain $M_{\rm H}$ and $M_{\rm cr}$ by following the analysis of Montgomery & Winget (1999) with an updated prescription for the envelope composition transition zones.

2. Observations

In 1996 and 1997, observations of BPM 37093 were obtained from the 0.9 m telescope at CTIO and the 1.6 m telescope at Observatório Pico dos Dias (OPD, Brazil) respectively. The two initial goals of these observations were: 1) to identify as many pulsation modes as possible, to help constrain asteroseismological model fitting, and 2) to find stable pulsation modes suitable for measuring the rate of period change ($\dot{P}$), as has been done for other white dwarfs (Costa et al. 1999; Kepler et al. 2000a; Mukadam et al. 2003). Further analysis (see Sect. 3) revealed that no modes were stable enough to use for $\dot{P}$ measurements. After these two attempts to obtain single-site data on BPM 37093, it became clear that we would be unable to resolve the pulsation spectrum of this star from a single observatory. By 1997 we had already accumulated more than 100 h of photometry on BPM 37093, which led to the identification of only 4 pulsation modes with highly variable amplitudes (Kanaan et al. 1998).

BPM 37093 was chosen as the southern primary target for a Whole Earth Telescope campaign (XCOV 16) in 1998, and again in 1999 (XCOV 17) to coincide with simultaneous observations using the Hubble Space Telescope (HST). A journal of observations for the data obtained for these two campaigns is shown in Tables 1 and 2. Overall, we obtained more than 142 h of data in April−May 1998 with a duty cycle of 50% during the central 10 days, and an impressive 180 hours in April 1999 with a better duty cycle of 65% during the central 10 days. The latter observations included almost complete coverage during the two scheduled HST visits near the middle of the campaign, and preliminary results were reported by Nitta et al. (2000).

The primary goal of the HST observations was to use the limb darkening method devised by Robinson et al. (1995) to provide an independent determination of the spherical degree (ℓ) for each pulsation mode. Unfortunately, this method could be applied only to the modes with the highest amplitudes, and the observations were not sensitive enough to distinguish between $\ell = 1$ and $\ell = 2$. In this paper we infer ℓ based only on the average period spacing between modes.

3. Frequency analysis

One of the initial goals of our observations was to identify pulsation modes stable enough to measure the rate of period change ($\dot{P}$). As a white dwarf star cools over time, the slow change in the thermal structure should lead to a detectable increase in the pulsation periods. We expect that the periods in a crystallizing star should change more slowly than in other ZZ Ceti stars because the associated release of latent heat causes the temperature to drop more slowly than in a non-crystallizing star.

However, the observations from CTIO in 1996 made it clear that $\dot{P}$ measurements would not be possible for BPM 37093. In Fig. 1 we show the evolution of daily Fourier Transforms (FTs), night by night during the 10 night run. On the tenth night, the pulsations vanished below the detection threshold. Comparing the other panels of Fig. 1, it is also clear that the amplitudes of the detected modes are highly variable. Kanaan et al. (1998)

Table 1. Journal of observations in 1998 (XCOV 16).

Run	Telescope	Date	Start (UT)	Length (s)
an-0069	CTIO 1.5 m	1998 Apr. 17	02:42:20	23 540
an-0070	CTIO 1.5 m	1998 Apr. 17	23:30:30	37 460
an-0071	CTIO 1.5 m	1998 Apr. 18	23:16:00	20 630
an-0072	CTIO 1.5 m	1998 Apr. 19	07:42:20	6790
an-0073	CTIO 1.5 m	1998 Apr. 20	23:20:10	37 350
dj-001	SAAO 1.9 m	1998 Apr. 21	21:04:00	19 400
an-0074	CTIO 1.5 m	1998 Apr. 21	23:25:40	36 770
dj-002	SAAO 1.9 m	1998 Apr. 22	17:32:00	20 150
an-0075	CTIO 1.5 m	1998 Apr. 22	23:20:40	36 860
ro107	OPD 1.6 m	1998 Apr. 23	03:57:00	5430
dj-003	SAAO 1.9 m	1998 Apr. 23	17:18:00	37 330
ro108	OPD 1.6 m	1998 Apr. 23	22:22:30	4700
ap2498q2	MJUO 1.0 m	1998 Apr. 24	09:02:10	31 110
dj-004	SAAO 1.9 m	1998 Apr. 24	17:29:00	37 350
an-0076	CTIO 1.5 m	1998 Apr. 24	23:43:30	35 230
ro111	OPD 1.6 m	1998 Apr. 25	00:12:10	6650
ap2598q1	MJUO 1.0 m	1998 Apr. 25	10:20:20	6060
ap2598q2	MJUO 1.0 m	1998 Apr. 25	12:50:00	14 280
dj-005	SAAO 1.9 m	1998 Apr. 25	17:34:00	33 580
ro112	OPD 1.6 m	1998 Apr. 26	01:50:30	7840
ro113	OPD 1.6 m	1998 Apr. 26	04:53:30	4210
ap2698q1	MJUO 1.0 m	1998 Apr. 26	08:06:00	30 410
dj-006	SAAO 1.9 m	1998 Apr. 26	17:14:00	37 880
an-0077	CTIO 1.5 m	1998 Apr. 27	03:17:20	21 770
ap2798q1	MJUO 1.0 m	1998 Apr. 27	13:17:30	37 460
dj-007	SAAO 1.9 m	1998 Apr. 27	19:21:00	38 030
gv-0522	ESO 2.2 m	1998 Apr. 28	01:01:10	24 570
db9801	SAAO 1.9 m	1998 Apr. 28	19:24:00	37 900
db9802	SAAO 1.9 m	1998 Apr. 29	19:14:00	32 880
gv-0523	ESO 2.2 m	1998 Apr. 29	23:21:00	21 770
db9803	SAAO 1.9 m	1998 Apr. 30	17:04:50	39 130
gv-0524	ESO 2.2 m	1998 Apr. 30	23:27:00	13 310
db9804	SAAO 1.9 m	1998 May 01	21:08:00	31 020
db9805	SAAO 1.9 m	1998 May 02	17:21:30	37 320
db9806	SAAO 1.9 m	1998 May 03	17:17:10	33 510

Table 2. Journal of observations in 1999 (XCOV 17).

Run	Telescope	Date	Start (UT)	Length (s)
saccd001	SAAO 0.75 m	1999 Apr. 06	23:43:00	10 680
saccd002	SAAO 0.75 m	1999 Apr. 07	21:16:33	3960
ap0899q1	SSO 1.0 m	1999 Apr. 08	10:38:00	20 130
ap0899q2	SSO 1.0 m	1999 Apr. 08	16:34:00	3620
ap0899q3	SSO 1.0 m	1999 Apr. 08	17:52:30	5460
ap0999q1	SSO 1.0 m	1999 Apr. 09	10:15:20	29 000
tsm-0033	CTIO 1.5 m	1999 Apr. 10	02:10:00	26 100
ap1099q1	SSO 1.0 m	1999 Apr. 10	09:04:40	36 680
saccd003	SAAO 0.75 m	1999 Apr. 10	18:00:00	22 060
tsm-0035	CTIO 1.5 m	1999 Apr. 11	05:55:00	6620
ap1199q1	SSO 1.0 m	1999 Apr. 11	08:59:50	37 110
saccd004	SAAO 0.75 m	1999 Apr. 11	18:09:00	33 300
ap1299q1	SSO 1.0 m	1999 Apr. 12	11:03:00	29 900
saccd005	SAAO 0.75 m	1999 Apr. 12	18:18:30	32 700
tsm-0042	CTIO 1.5 m	1999 Apr. 13	00:43:00	31 440
ap1399q1	SSO 1.0 m	1999 Apr. 13	09:35:00	9300
ap1399q2	SSO 1.0 m	1999 Apr. 13	12:29:00	25 000
saccd006	SAAO 0.75 m	1999 Apr. 13	18:17:20	16 920
tsm-0043	CTIO 1.5 m	1999 Apr. 13	23:48:00	34 410
ap1499q1	SSO 1.0 m	1999 Apr. 14	09:14:00	36 700
saccd007	SAAO 0.75 m	1999 Apr. 14	19:33:25	21 840
tsm-0044	CTIO 1.5 m	1999 Apr. 14	23:42:00	34 560
saccd008	SAAO 0.75 m	1999 Apr. 15	17:23:45	20 250
tsm-0045	CTIO 1.5 m	1999 Apr. 16	00:08:30	32 730
tsm-0046	CTIO 1.5 m	1999 Apr. 17	00:10:40	32 100
ap1799q1	MJUO 1.0 m	1999 Apr. 17	09:34:30	7970
saccd009	SAAO 0.75 m	1999 Apr. 17	17:17:40	32 220
ita180499	OPD 0.6 m	1999 Apr. 18	03:49:40	11 000
tsm-0047	CTIO 1.5 m	1999 Apr. 18	04:46:00	15 640
ap1899q1	MJUO 1.0 m	1999 Apr. 18	07:30:00	7690
ap1899q2	MJUO 1.0 m	1999 Apr. 18	11:36:00	8310
ap1899q3	MJUO 1.0 m	1999 Apr. 18	14:04:30	14 400
tsm-0048	CTIO 1.5 m	1999 Apr. 19	00:04:30	32 330
ap1999q1	MJUO 1.0 m	1999 Apr. 19	08:04:20	6950
ap1999q4	MJUO 1.0 m	1999 Apr. 19	15:05:50	10 500
ita190499	OPD 0.6 m	1999 Apr. 19	22:15:10	32 700
ro123	OPD 1.6 m	1999 Apr. 20	01:23:40	18 800
ita200499	OPD 0.6 m	1999 Apr. 20	03:33:24	8420
ita210499	OPD 0.6 m	1999 Apr. 21	22:15:07	18 080

demonstrated that these amplitude changes must be intrinsic to the star, rather than due to the beating of closely spaced modes, since there was no correlation between the changes in amplitude and phase. Such intrinsic behavior has been reported for other ZZ Ceti stars on a timescale of months (Kleinman et al. 1998), but not from night to night as observed in BPM 37093. These short-timescale variations will lead us to derive *average* amplitudes from the FTs of long data sets, but will still allow us to identify the pulsation modes which have the highest amplitudes and the longest lifetimes.

The FTs of the two WET campaigns on BPM 37093 are shown in Fig. 2. In each panel we have marked all of the peaks that exceed 4 times the observational noise level. During XCOV 16 we detected many more modes than were evident in the 1996 observations – of the 8 frequencies detected, only 2 coincide with those seen previously. Comparing this with XCOV 17, it seems clear that the detection of more independent modes in XCOV 16 can be attributed to the star itself, rather than to differences in our detection threshold. During the second WET campaign on BPM 37093 we detected 7 frequencies, of which 4 coincide with others seen previously. Only the 512 s and 661 s modes are unique to the data obtained for XCOV 17. The full list of frequencies detected in these two WET campaigns is shown in Table 3, along with the mode identifications of Metcalfe et al. (2004)[34] for those modes found in the preliminary analysis of Kanaan et al. (2000).

We can understand the erratic behavior of BPM 37093 by considering previous observations of other ZZ Ceti pulsators. Kleinman et al. (1998) documented very similar results for the star G 29-38, and proposed that each set of observations can provide a subset of the full spectrum of normal modes. The fundamental idea behind this hypothesis is that the underlying structure of the star does not change on the timescales of the observed amplitude variations. Instead, something in the excitation mechanism must select certain modes and exclude others

[34] For the 582 s mode, we adopt the $\ell = 2$ identification.

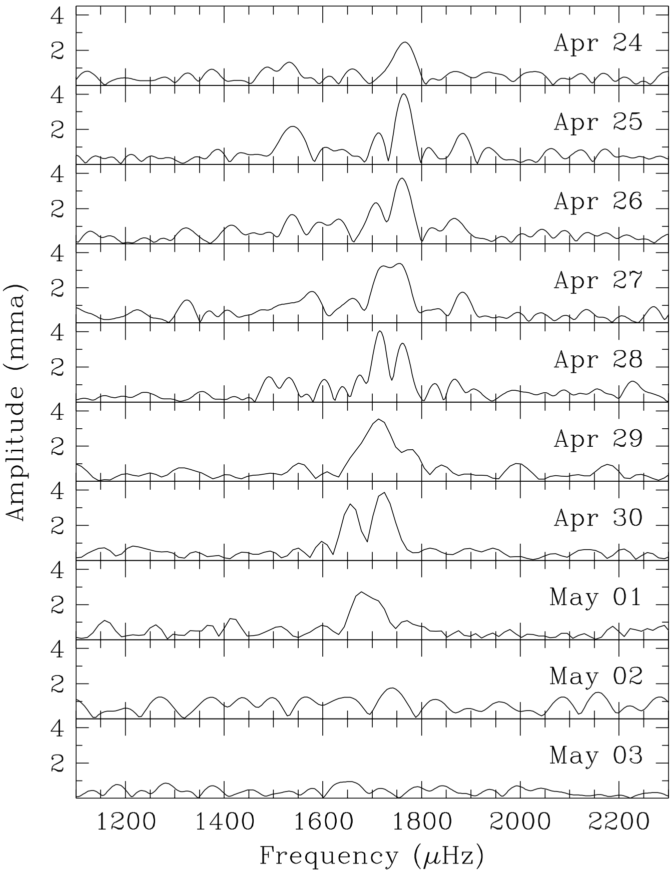

Fig. 1. Nightly FTs of BPM 37093 during ten nights of observations from CTIO in 1996. The amplitudes are highly variable on short timescales. All of the modes vanish below the detection threshold on the final night.

in a manner that varies over time. Setting aside the question of what specifically causes these amplitude modulations, we only need to assume that the observed frequencies are, in each case, normal modes of oscillation that can be described by spherical harmonics. Such an assumption rests on a firm body of evidence (Robinson et al. 1982; Kepler et al. 2000b; Clemens et al. 2000), and is also supported by the fact that modes which disappear below the detection threshold are observed to reappear later *with the same frequencies*.

4. Interpretation

We adopt for our analysis the full set of frequencies that have been observed in BPM 37093 over time, giving preference to the WET campaigns for their superior frequency precision. For the isolated frequencies we assume that each mode has an azimuthal order $m = 0$ (see Metcalfe 2003), and for the modes consisting of two closely-spaced frequencies we use the average of the two. For modes that were observed in both campaigns, we use the frequency from the observation with the highest amplitude. This leads to a total of 7 independent modes that have been identified as $\ell = 2$ by Metcalfe et al. (2004). The average period spacing between consecutive radial overtones for these 7 modes is $\langle \Delta P \rangle = 17.6 \pm 1.1$ s. This implies that the $\ell = 2$ identification should be correct for the majority

Table 3. Frequencies detected from two WET campaigns.

XCOV	Frequency (μHz)	Period (s)	$\langle$Amplitude$\rangle$ (mma)	Identification k	ℓ	m
17	1513.2	660.8	0.475			
17	1569.5	637.2	0.650			
16	1570.6	636.7	1.741	34	2	−1
17	1578.5	633.5	1.310	34	2	+1
16	1579.2	633.2	1.081			
16	1629.9	613.5	1.131	18	1	0
16	1664.9	600.7	0.875	32	2	0
16	1718.2	582.0	1.032	31	2	0
17	1767.1	565.9	0.458			
16	1768.5	565.5	1.174	30	2	−1
16	1777.6	562.6	0.879	30	2	+1
17	1820.8	549.2	0.801			
16	1823.5	548.4	1.149	29	2	0
17	1882.9	531.1	1.156	28	2	0
17	1954.1	511.7	0.679	27	2	0

of the modes, since an $\ell = 1$ identification would yield a much larger period spacing ($\langle \Delta P \rangle \sim 30$ s, Montgomery & Winget 1999).

Montgomery & Winget (1999) performed a detailed study of the various model parameters that could affect the average period spacing for $\ell = 2$ modes. They defined a scaling relation for $\langle \Delta P \rangle$ which had contributions from variations to four parameters, including the stellar mass and effective temperature ($M_*, T_{\rm eff}$) and the hydrogen layer mass and crystallized mass fraction ($M_{\rm H}, M_{\rm cr}$). Fortunately, M_* and $T_{\rm eff}$ can both be constrained by spectral profile fitting. The most recent estimates for BPM 37093 come from Bergeron et al. (2004), who found $M_* = 1.10\ M_\odot$ and $T_{\rm eff} = 11\,730$ K. The values of the other parameters can only be determined through asteroseismology, but Montgomery & Winget (1999) found a troubling degeneracy between $M_{\rm H}$ and $M_{\rm cr}$ that could not be broken using only the observed $\langle \Delta P \rangle$.

To get beyond the degeneracy, we need to use the *individual* pulsation periods in addition to $\langle \Delta P \rangle$. Fundamentally, this is possible because variations to $M_{\rm H}$ change the individual periods through "mode trapping", while variations to $M_{\rm cr}$ affect mainly the average period spacing. If BPM 37093 is partially crystallized, the inner boundary for each pulsation mode will be located at the top of the solid core rather than at the center of the star. This reduces the size of the resonant cavity, increasing the average period spacing and modifying the periods of *all* of the modes. By contrast, the hydrogen layer produces a sharp chemical gradient somewhere near the surface. Any individual mode whose eigenfunction is large in this region can interact with the chemical gradient and become "trapped" – its period will be shifted more than the periods of other modes. Clearly, each mode will be modified in a different manner through this interaction.

Montgomery & Winget (1999) understood that the signatures of $M_{\rm H}$ and $M_{\rm cr}$ are in principle distinct. However, by focusing only on the average period spacing they were unable to place strong constraints on either $M_{\rm H}$ or $M_{\rm cr}$. Our present models are somewhat improved: Montgomery & Winget used

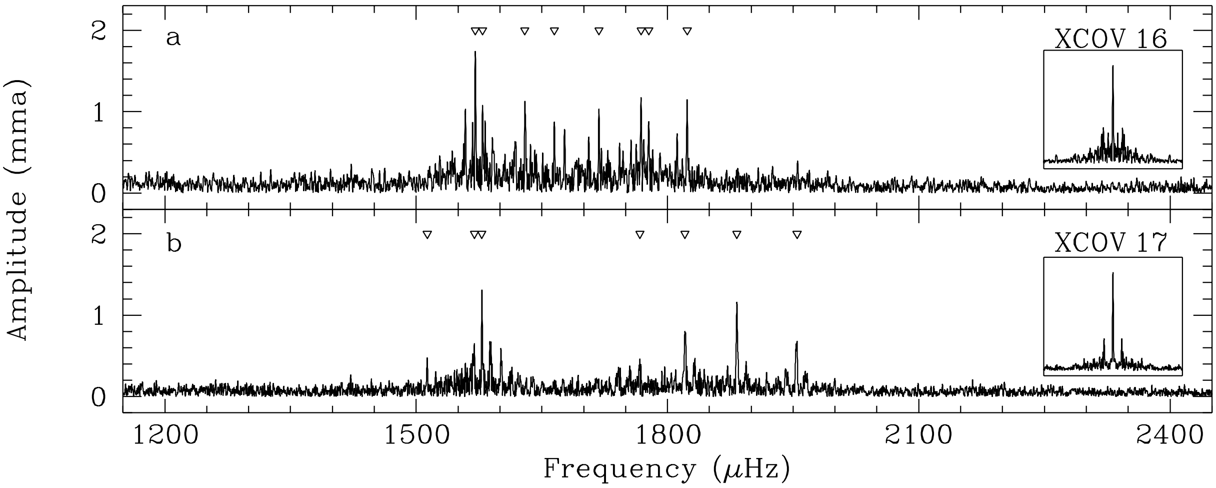

Fig. 2. Fourier Transforms and window functions at the same scale for the Whole Earth Telescope observations of the ZZ Ceti star BPM 37093 obtained during **a)** the XCOV 16 campaign in 1998, and **b)** the XCOV 17 campaign in 1999.

hydrogen profiles that were derived assuming diffusive equilibrium in the trace element approximation. This produced unrealistically sharp chemical gradients at the base of the hydrogen layer, leading to stronger mode trapping in their models. This was demonstrated by Córsico et al. (2002), who compared models that assumed diffusive equilibrium in the trace element approximation with models that computed the abundance profiles based on time-dependent diffusion calculations. In a recent extension of this work to massive ZZ Ceti stars, Althaus et al. (2003) described an improved method of calculating diffusive equilibrium profiles that compare favorably with the fully time-dependent results (see their Fig. 18). We have incorporated this method of computing the hydrogen abundance profiles into the code used by Montgomery & Winget (1999). However, since the sharpness of the hydrogen transition zone should mainly affect the mode trapping properties of the models, we expect that our new average period spacings will differ only slightly from those computed by Montgomery & Winget (1999).

As a simple illustration of the potential of our observations, we calculated $\langle \Delta P \rangle$ for a small grid with various combinations of $M_{\rm H}$ and $M_{\rm cr}$. We fixed the mass, temperature, and helium layer thickness to the values used for Fig. 10b of Montgomery & Winget (1999), but we assumed a uniform O core. We show this grid of models in Fig. 3 with the shaded 1σ range of the average period spacing from the WET observations of BPM 37093. As expected, the average period spacing of the 0% crystallized model is virtually identical to that found by Montgomery & Winget (1999). However, due to the different assumed C/O profiles, the crystallized curves have shifted with respect to the results of Montgomery & Winget (1999).

Unfortunately, the degeneracy between $M_{\rm H}$ and $M_{\rm cr}$ is still present, but we have not yet used the hidden third dimension of the grid: at each point we have also computed the root-mean-square differences between the observed and calculated periods ($\sigma_{\rm P}$), to exploit the information contained in the *individual* modes. Although the observed range of $\langle \Delta P \rangle$ can accommodate values of $\log(M_{\rm H}/M_*)$ between −5 ($M_{\rm cr}$ = 80−90%) and −8 (uncrystallized), not all hydrogen layer masses are equally successful at reproducing the individual modes. The model with

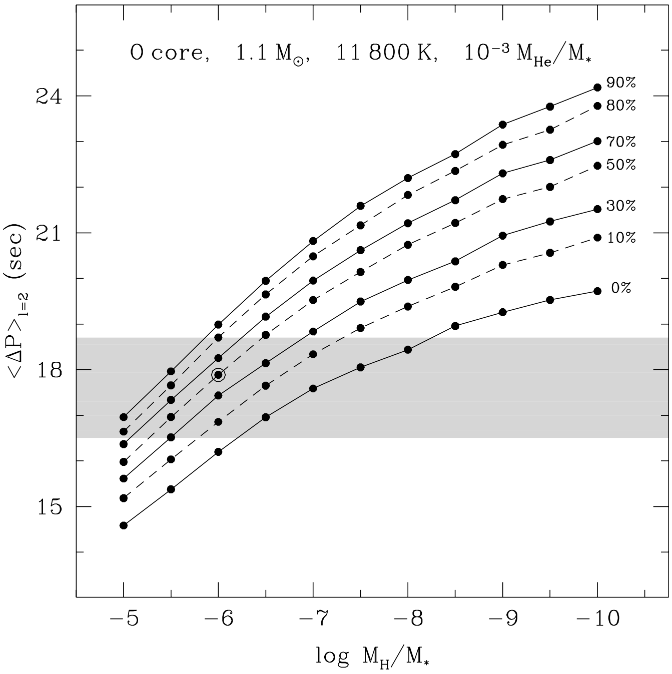

Fig. 3. The average period spacing of a small grid of models with various combinations of $M_{\rm H}$ and $M_{\rm cr}$. The 1σ range of the observed average period spacing for BPM 37093 is shown as a shaded area, and the circled point indicates the model with the smallest rms difference between the observed and calculated periods (see text for details).

$\log(M_{\rm H}/M_*) = -6$ and $M_{\rm cr} = 50\%$ has $\sigma_{\rm P} = 1.08$ s, which is substantially better than anything else in this small grid (the next best model has $\sigma_{\rm P} = 1.70$ s). A theoretical model with this same set of structural parameters is expected to be between 66−92% crystallized for a C/O mixture, or even more crystallized if the core is composed of an O/Ne mixture (see Córsico et al. 2004, for some recent calculations).

Of course, the individual modes also contain information about the mass, temperature, helium layer, and core composition. If we have fixed these parameters incorrectly, it is likely that we have found a *locally optimal* match to the observed periods rather than the global solution. Montgomery & Winget (1999) recognized this difficulty, and discussed the need for an automated procedure to search this enormous parameter-space. Such a procedure, based on a parallel genetic algorithm, has recently been developed (Metcalfe & Charbonneau 2003) and applied to this problem. The initial results from this large-scale exploration of the models have been published separately by Metcalfe et al. (2004), who present a more detailed discussion of the initial model fitting results.

5. Discussion

The Whole Earth Telescope has once again deciphered the complex pulsation spectrum of an astrophysically interesting white dwarf star. BPM 37093 is the only known ZZ Ceti star massive enough to allow a seismological test of crystallization theory, and previous attempts to understand it from single site observations were not successful. The superior frequency precision and extended coverage of two WET campaigns finally allowed us to document a series of 9 independent pulsation modes in this star. While it is always useful to search for additional frequencies to help constrain the model fitting, the observational requirements of this project have now largely been satisfied.

The limiting factor in our ability to test crystallization theory through asteroseismology of BPM 37093 is now computational. The initial study of Metcalfe et al. (2004) was limited to several fixed masses and core compositions, but *all* of their optimal models suggested that a large fraction of the core is crystallized – a result that is qualitatively supported by our simple analysis of the average period spacing. We have only fit $M_{\rm cr}$ to the nearest 0.1 M_*, but Montgomery & Winget (1999) showed that the pulsations are sensitive to changes of 0.01 M_* in this parameter. As computers get faster, we should be able to extend the genetic algorithm based model fitting method to treat $M_{\rm cr}$, M_* and the composition of the liquid portion of the core as fully adjustable parameters. In the meantime, we should apply the same fitting procedure to lower mass ZZ Ceti stars that are not expected to be crystallized, as a check of the method.

The Sloan Digital Sky Survey (SDSS) has recently discovered several new ZZ Ceti stars that may also be massive enough to test crystallization theory (Mukadam et al. 2004). All of the new pulsators in the SDSS sample are significantly fainter than the previously known white dwarfs, so larger telescopes will probably be required to resolve their pulsation spectra. Several current and planned space missions (MOST, Walker et al. 2003; COROT, Baglin et al. 2002) promise to revolutionize the field of asteroseismology in the coming decade. However, none of them is likely to contribute to our understanding of pulsating white dwarfs stars, which are too faint to be observed by these satellites. The Whole Earth Telescope remains the instrument of choice for these fainter targets. The availability of larger ground-based telescopes may allow the WET concept to be extended to 2 m and 4 m class instruments. With a growing harvest of new objects from SDSS, the future looks bright for white dwarf asteroseismology.

Acknowledgements. This work was partially supported by NASA, NSF, Brazilian institutions FAPERGS, CNPq, CAPES, and FINEP, and by the Smithsonian Institution through a CfA Postdoctoral Fellowship. PM is partially supported by Polish KBN grants 5 P03D 012 20 and 5 P03D 030 20.

References

Abrikosov, A. 1960, Zh. Eksp. Teor. Fiz., 39, 1798
Althaus, L. G., Serenelli, A. M., Córsico, A. H., & Montgomery, M. H. 2003, A&A, 404, 593
Baglin, A., Auvergne, M., Catala, C., et al. 2002, in ASP Conf. Ser., 259, IAU Coll., 185, Radial and Nonradial Pulsationsn as Probes of Stellar Physics, 626
Bergeron, P., Fontaine, G., Billères, M., Boudreault, S., & Green, E. M. 2004, ApJ, 600, 404
Córsico, A. H., Benvenuto, O. G., Althaus, L. G., & Serenelli, A. M. 2002, MNRAS, 332, 392
Córsico, A. H., García-Berro, E., Althaus, L. G., & Isern, J. 2004, A&A, 427, 923
Clemens, J. C., van Kerkwijk, M. H., & Wu, Y. 2000, MNRAS, 314, 220
Costa, J. E. S., Kepler, S. O., & Winget, D. E. 1999, ApJ, 522, 973
Kanaan, A., Kepler, S. O., Giovannini, O., & Diaz, M. 1992, ApJ, 390, L89
Kanaan, A., Kepler, S. O., Giovannini, O., et al. 1998, Baltic Astron., 7, 183
Kanaan, A., Nitta-Kleinman, A., Winget, D. E., et al. 2000, Baltic Astron., 9, 87
Kepler, S. O., Mukadam, A., Winget, D. E., et al. 2000a, ApJ, 534, L185
Kepler, S. O., Robinson, E. L., Koester, D., et al. 2000b, ApJ, 539, 379
Kirzhnitz, D. A. 1960, Soviet Phys. – JETP, 11, 365
Kleinman, S. J., Nather, R. E., Winget, D. E., et al. 1998, ApJ, 495, 424
Metcalfe, T. S. 2003, Baltic Astron., 12, 247
Metcalfe, T. S., & Charbonneau, P. 2003, J. Comput. Phys., 185, 176
Metcalfe, T. S., Montgomery, M. H., & Kanaan, A. 2004, ApJ, 605, L133
Montgomery, M. H., & Winget, D. E. 1999, ApJ, 526, 976
Mukadam, A. S., Kepler, S. O., Winget, D. E., et al. 2003, ApJ, 594, 961
Mukadam, A. S., Mullally, F., Nather, R. E., et al. 2004, ApJ, 607, 982
Nather, R. E., Winget, D. E., Clemens, J. C., Hansen, C. J., & Hine, B. P. 1990, ApJ, 361, 309
Nitta, A., Kanaan, A., Kepler, S. O., et al. 2000, Baltic Astron., 9, 97
Robinson, E. L., Kepler, S. O., & Nather, R. E. 1982, ApJ, 259, 219
Robinson, E. L., Mailloux, T. M., Zhang, E., et al. 1995, ApJ, 438, 908
Salpeter, E. E. 1961, ApJ, 134, 669
Walker, G., Matthews, J., Kuschnig, R., et al. 2003, PASP, 115, 1023
Winget, D. E., Kepler, S. O., Kanaan, A., Montgomery, M. H., & Giovannini, O. 1997, ApJ, 487, L191
Wood, M. A. 1992, ApJ, 386, 539