Discovery of the “missing” mode in HR 1217 by the Whole Earth Telescope

D. Kurtz\textsuperscript{1,2}, S.D. Kawaler\textsuperscript{3}, R.L. Riddle\textsuperscript{3}, M.D. Reed\textsuperscript{3,4}, M.S. Cunha\textsuperscript{5}, N. Silvestri\textsuperscript{6}, M. Wood\textsuperscript{6}, T.K. Watson\textsuperscript{7}, N. Dolez\textsuperscript{2}, P. Moskalik\textsuperscript{8}, S. Zola\textsuperscript{9}, E. Pallier\textsuperscript{2}, J.A. Guzik\textsuperscript{10}, T.S. Metcalfe\textsuperscript{11}, A. Mukadam\textsuperscript{11}, R.E. Nather\textsuperscript{11}, D.E. Winget\textsuperscript{11}, D.J. Sullivan\textsuperscript{12}, T. Sullivan\textsuperscript{12}, K. Sekiguchi\textsuperscript{13}, X. Jiang\textsuperscript{14}, R. Shobbrook\textsuperscript{15}, B.N. Ashoka\textsuperscript{16}, S. Seetha\textsuperscript{16}, S. Joshi\textsuperscript{17}, D. O’Donoghue\textsuperscript{18}, G. Handler\textsuperscript{18}, M. Mueller\textsuperscript{18}, J.M. Gonzalez Perez\textsuperscript{19}, J.-E. Solheim\textsuperscript{19}, F. Johannessen\textsuperscript{19}, A. Ulla\textsuperscript{20}, S.O. Kepler\textsuperscript{21}, A. Kanaan\textsuperscript{22}, A. da Costa\textsuperscript{21}, L. Fraga\textsuperscript{22}, O. Giovannini\textsuperscript{23}, and J.M. Matthews\textsuperscript{24}

\textsuperscript{1}Centre for Astrophysics, University of Central Lancashire, Preston PR1 2HE, UK, Department of Astronomy, University of Cape Town, Rondebosch 7701, South Africa
\textsuperscript{2}Observatoire Midi-Pyrénées, CNRS/UMR5572, 14 av. E. Belin, 31400 Toulouse, France
\textsuperscript{3}Department of Physics and Astronomy, Iowa State University, Ames, IA USA
\textsuperscript{4}Visiting Astronomer, CTIO, National Optical Astronomy Observatories
\textsuperscript{5}Centro de Astrofísica da Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
\textsuperscript{6}Department of Physics & Space Sciences and SARA Observatory, Florida Institute of Technology, Melbourne, FL, USA
\textsuperscript{7}Southwestern University, 1001 E. University Avenue, Georgetown, TX, USA
\textsuperscript{8}Nicolas Copernicus Astronomical Centre, ul. Bartycka 18, 00-716 Warszawa, Poland
\textsuperscript{9}Krakow Pedagogical University, ul. Podchorzących 2, Krakow, Poland
\textsuperscript{10}X-2, MS B220, Los Alamos National Laboratory, Los Alamos, NM 87545 USA
\textsuperscript{11}McDonald Observatory, and Department of Astronomy, University of Texas, Austin, TX 78712, USA
\textsuperscript{12}School of Chemical and Physical Sciences, Victoria University of Wellington, PO Box 606, Wellington, New Zealand
\textsuperscript{13}Subaru Observatory, NAOJ, Hilo, HI USA
\textsuperscript{14}National Astronomical Observatories and Joint Laboratory of Optical Astronomy, Chinese Academy of Sciences, Beijing, 100012, China
\textsuperscript{15}Research School of Astronomy & Astrophysics, Australian National University, Cotter Road, Weston, ACT 2611, Australia
\textsuperscript{16}Indian Space Research Organization, Vimanapura PO, Bangalore 560 017, India
\textsuperscript{17}State Observatory, Manora Peak, Naini Tal 263 129, India
\textsuperscript{18}South African Astronomical Observatory, PO Box 9, Observatory 7935, South Africa
\textsuperscript{19}Department of Physics, University of Tromso, N-9037 Tromso, Norway
\textsuperscript{20}Depto. de Fisica Aplicada, Universidade de Vigo, 36200 Vigo, Spain
\textsuperscript{21}Instituto de Fisica, UFRGS, Campus do Vale, C.P. 15051, Porto Alegre, RS, Brazil
\textsuperscript{22}Universidade Federal de Santa Catarina, Florianópolis, SC - Brazil
\textsuperscript{23}Departamento de Física e Química, Universidade de Caxias do Sul, 95001-970 Caxias do Sul, RS - Brazil
\textsuperscript{24}Dept. of Physics and Astronomy, University of British Columbia, Vancouver, Canada

19 March 2022
ABSTRACT
HR 1217 is a prototypical rapidly oscillating Ap star that has presented a test to the theory of nonradial stellar pulsation. Prior observations showed a clear pattern of five modes with alternating frequency spacings of 33.3 µHz and 34.6 µHz, with a sixth mode at a problematic spacing of 50.0 µHz (which equals 1.5 × 33.3 µHz) to the high-frequency side. Asymptotic pulsation theory allowed for a frequency spacing of 34 µHz, but HIPPARCOS observations rule out such a spacing. Theoretical calculations of magnetoacoustic modes in Ap stars by Cunha (2001) predicted that there should be a previously undetected mode 34 µHz higher than the main group, with a smaller spacing between it and the highest one. In this Letter, we present preliminary results from a multi-site photometric campaign on the rapidly oscillating Ap star HR 1217 using the “Whole Earth Telescope”. While a complete analysis of the data will appear in a later paper, one outstanding result from this run is the discovery of a newly detected frequency in the pulsation spectrum of this star, at the frequency predicted by Cunha (2001).

Key words: Stars: oscillations – stars: variables – stars: individual (HR 1217) – stars: magnetic.

1 INTRODUCTION
After decades of trying, the search for solar-type oscillations in stars finally appears to have been successful (see, e.g., Bouchy & Carrier 2001 and Carrier et al. 2001). Although this led Gough (2001) to announce the “birth of asteroseismology”, for the past two decades asteroseismology has successfully investigated the interiors of many types of stars other than the solar-type stars. Remarkable success stories of observational and theoretical investigations of white dwarf stars and rapidly oscillating Ap stars have amply demonstrated the power of asteroseismology as a tool to advance our knowledge of the physics of stellar interiors and the details of stellar evolution (see, e.g., Kurtz et al 1989; Winget et al. 1991; Kawaler & Bradley 1994; Matthews et al. 1999).

With these successes, some mysteries have remained. In this Letter, we address apparently contradictory interpretations of the pulsation spectrum of the rapidly oscillating Ap star HR 1217. This star, discovered to be a pulsator by Kurtz (1982), was investigated with an extensive global campaign in 1986 (Kurtz et al. 1989). A key result from that data set was a list of six principal pulsation frequencies, reproduced in Table 1. As expected from the asymptotic theory of non-radial pulsations, five of the modes are nearly equally spaced in frequency.

The asymptotic frequency spacing, ν₀, is a measure of the sound crossing time of the star, which in turn is determined by the star’s mean density and radius. With a typical mass of Ap stars of about 2M☉, ν₀ reflects the radius of the star, with ν₀ scaling as R⁻³/₂. In the asymptotic limit, the number of nodes in the radial direction, n, is larger than the spherical degree ℓ. Assuming adiabatic pulsations in spherically symmetric stars the pulsation frequencies are, to first order,

\[ \nu_{n,\ell} = \nu_0 (n + \ell/2 + \epsilon), \]

where \( \epsilon \) is a (small) constant (Tassoul 1980, 1990). Without precise identification of the degree (ℓ) of the pulsation modes, asymptotic theory allows the frequency spacing to be uncertain by a factor of two, depending on whether modes of alternating even and odd ℓ are present (producing modes separated by \( \nu_0/2 \) in frequency), or only modes of consecutive n.

The results of the 1986 campaign were inconclusive as to whether ν₀ was 68 µHz or 34 µHz. The principal frequencies seen in the data are given in Table 1; they correspond to those found by Kurtz et al. (1989) for the 15 day stretch of best coverage (for comparison with the new data presented in Table 3). The highest frequency of HR 1217 in those data was 50 µHz higher than the fifth mode, suggesting that ν₀ was 34 µHz. But the fine structure of the spacings was suggestive of alternating ℓ values. Fortunately, the two possible values could be assessed if the luminosity of the star were precisely known. If ν₀ were 34 µHz, then the radius of HR 1217 would be large enough that it would be far removed from the main sequence (i.e. more evolved) and therefore more luminous (Heller & Kawaler 1988). Matthews et al. (1999) used the HIPPARCOS parallax measurement to place HR 1217 unambiguously close to the Main Sequence – meaning that ν₀ is indeed 68 µHz. This deepened the “mystery of the sixth frequency”, now \( 3/4 \nu_0 \) higher. No clear theoretical construct could explain it.

The asymptotic frequency spacing given in the equation above is valid only for linear adiabatic pulsations in spherically symmetric stars. However, the magnetic field, the chemical inhomogeneities, and rotation all contribute to break the spherical symmetry in roAp stars. Therefore, it is important to know the effects that these deviations from spherical symmetry have on the theoretical amplitude spectra of roAp stars, before comparing the latter with the observed amplitude spectra. The effects of the chemical inhomogeneities have been discussed recently by Balmforth...
et al. (2001), but those will not concern us further here. The effects of the magnetic field on the oscillations of roAp stars (Dziembowski & Goode 1996; Bigot et al. 2000; Cunha & Gough 2000), as well as the conjoined effect of rotation and magnetic field (Bigot 2002), have been determined by means of a singular perturbation approach. While generally the magnetic field effect on the oscillations is expected to be small, Cunha & Gough (2000) found that, at the frequencies of maximal magnetocoustic coupling, the latter is expected to become significantly large, resulting in an abrupt drop of the separation between mode frequencies.

The observational consequence of the results of Cunha & Gough (2000) suggests that we should see equally spaced modes in roAp stars, with an occasional mode much closer to its lower frequency counterparts. More recently, Cunha (2001) suggested that the explanation of the strange separation between the last two modes observed in HR 1217 could rest on the occasional abrupt decrease of the large separations predicted by Cunha & Gough (2000). For this prediction to hold, she argued that the observations of Kurtz et al. (1989) must have missed detecting a mode at a frequency 34 µHz higher than that of the fifth mode they observed. She predicted that new, more precise measurements would find this “missing mode” if the Alfvénic losses were not large enough to stabilise it. Detailed re-examination of the data from 1986 shows no peak at the key position approximately 33 µHz above f5 at the 0.1 mma level.

In 2000 November, we began an extensive, coordinated global photometry campaign on HR 1217 using the Whole Earth Telescope. A complete analysis of this extensive data set, which addresses many other aspects of roAp stars, is in preparation. In this Letter, we present a preliminary analysis of data from that run that clearly shows a previously unseen pulsation mode at a frequency about 36 µHz above the fifth frequency, as predicted by Cunha (2001). In the next section, we describe the observational procedures and the data coverage and reduction. Section 3 presents the preliminary frequency analysis, and the results are discussed in Section 4, along with a brief discussion of the impact of this result on the theory of pulsations of roAp stars.

### 2 OBSERVATIONS

The WET run on HR 1217 began on 2000 November 6 at selected sites, and continued through early 2000 December.

| Number | Frequency (µHz) | Frequency Spacing (µHz) | Amplitude (mma) |
|--------|----------------|-------------------------|----------------|
| f1     | 2619.51±0.05   | -                       | 0.28±0.03      |
| f2     | 2652.92±0.02   | 33.41±0.05              | 1.09±0.03      |
| f3     | 2687.58±0.03   | 34.66±0.04              | 0.94±0.03      |
| f4     | 2721.02±0.02   | 34.44±0.04              | 1.16±0.03      |
| f5     | 2755.49±0.04   | 34.47±0.04              | 0.49±0.03      |
| f6     |                | < 0.09                  |                |
| f7     | 2806.26±0.06   | 50.77±0.07              | 0.25±0.03      |

The bulk of the data, with the best global coverage, were obtained during 2000 November 14–30. A complete analysis of all of the available data is currently underway. For this Letter, we concentrate on the central portion of the WET run, with data from five sites. This subset of the full data set provides high signal-to-noise and a reasonable global coverage. It also extends over slightly more than one rotation cycle of HR 1217. Since the pulsation amplitude is modulated with the rotation period, this data subset is just long enough to begin to resolve rotational sidelobes of the main peaks.

Table 2 lists the individual observing runs in this data set. The telescopes used range in aperture from 0.6 m to 2.1 m. Data from all sites were obtained using photoelectric photometers, with 10 s individual integrations. At Beijing Astronomical Observatory, McDonald Observatory, Mauna Kea Observatory, and Observatorio del Teide, the observers used three-channel photometers that are functionally similar to the equipment described in Kleinman et al. (1996). The South African Astronomical Observatory observations were made with a single-channel photometer, and the observations at CTIO with a two-channel photometer. At all sites, observations were made through a Johnson B filter, along with neutral density filters when needed to keep the count rates below $10^6$ s$^{-1}$. Following the procedures described in Kleinman et al. (1996), the sky background was continuously monitored with the three-channel instruments. At sites using two-channel and single channel photometers, the sky was obtained several times during the night at irregular intervals, and then interpolated during reduction.

As can be seen in Table 2, we obtained 215.2 hr of observations during the interval from 2000 November 14–30, resulting in a duty cycle of 53%. Longitude coverage was adequate, though the longitudes around central Asia were not as well covered as the others.

### 3 FREQUENCY ANALYSIS

The Fourier transform (FT) of the reduced data, in the frequency range where the pulsations are significant, is shown in in the top panel of Figure 1. The spectral window, shown in the middle panel of the figure, shows the response of the FT to a single, noise-free sinusoid sampled at the same times as the light curve of HR 1217. The side peaks correspond to aliases of 1 d$^{-1}$ and 2 d$^{-1}$. They are approximately 40% of the amplitude of the principal peak, and are caused by the (small) daily gaps present in the data causing incomplete global coverage.

The principal periodicities that we found in HR 1217 are listed in Table 3. Following initial identification of the main peaks in the FT, we did a successive least-squares fit to the light curve including all of the main peaks. We then included the rotational sidelobes in the fit, sequentially. Throughout this process we prewhitened the data by removing noise-free sinusoids at the fitted frequencies, amplitudes, and phases. We stopped when none of the remaining peaks was above...
Table 2. Observing log of selected high-speed photometry of HR 1217 from the Whole Earth Telescope Extended Coverage Campaign 20 (WET Xcov20)

| Run Name   | Date       | Start (UT) | Start (hr) | Run Observatory | Tel (m) |
|------------|------------|------------|------------|----------------|---------|
| sa-od044   | Nov 14     | 21:03:00   | 5.04       | SAAO           | 1.9     |
| mdr-142    | Nov 15     | 01:28:10   | 5.06       | CTIO            | 1.5     |
| sa-od045   | Nov 15     | 19:20:00   | 7.05       | SAAO           | 1.9     |
| teide01    | Nov 16     | 00:42:10   | 3.56       | Teide           | 0.8     |
| mdr-143    | Nov 16     | 01:23:00   | 7.23       | CTIO            | 1.5     |
| no1700q2   | Nov 17     | 07:28:00   | 3.38       | Mauna Kea      | 0.6     |
| mdr-144    | Nov 17     | 20:26:06   | 7.54       | CTIO            | 1.5     |
| teiden04   | Nov 17     | 22:09:10   | 6.05       | Teide           | 0.8     |
| no1800q1   | Nov 18     | 07:22:30   | 4.25       | Mauna Kea      | 0.6     |
| sa-od047   | Nov 18     | 23:29:00   | 1.45       | SAAO           | 1.9     |
| no1900q2   | Nov 19     | 10:14:20   | 3.85       | Teide           | 0.8     |
| sa-od048   | Nov 19     | 18:55:00   | 7.15       | SAAO           | 1.9     |
| teiden06   | Nov 19     | 22:05:30   | 6.06       | Teide           | 0.8     |
| no2000q1   | Nov 20     | 07:37:00   | 6.07       | Mauna Kea      | 0.6     |
| sa-od049   | Nov 20     | 18:51:00   | 7.30       | SAAO           | 1.9     |
| sa-m0005   | Nov 21     | 19:26:50   | 6.67       | SAAO           | 0.75    |
| no2300q1   | Nov 23     | 07:15:50   | 4.59       | Mauna Kea      | 0.6     |
| teiden10   | Nov 23     | 22:05:40   | 5.47       | Teide           | 0.8     |
| sa-m0006   | Nov 24     | 18:18:00   | 7.76       | SAAO           | 0.75    |
| no2500q1   | Nov 25     | 07:03:00   | 6.67       | Mauna Kea      | 0.6     |
| teiden12   | Nov 25     | 22:09:20   | 5.61       | Teide           | 0.8     |
| joy-012    | Nov 26     | 03:55:50   | 4.10       | McDonald        | 2.1     |
| no2600q2   | Nov 26     | 06:59:30   | 6.47       | Mauna Kea      | 0.6     |
| sa-m0007   | Nov 26     | 18:28:40   | 7.42       | SAAO           | 0.75    |
| no2700q1   | Nov 27     | 06:38:00   | 5.55       | Mauna Kea      | 0.6     |
| jxj-0127   | Nov 27     | 13:44:10   | 4.75       | Beijing AO     | 0.85    |
| sa-m0008   | Nov 27     | 18:27:50   | 7.57       | SAAO           | 0.75    |
| teiden14   | Nov 27     | 22:28:20   | 3.72       | Teide           | 0.8     |
| sa-h-046   | Nov 28     | 18:54:30   | 6.41       | SAAO           | 1.9     |
| teiden15   | Nov 28     | 22:01:50   | 5.52       | Teide           | 0.8     |
| no2900q1   | Nov 29     | 06:41:00   | 6.77       | Mauna Kea      | 0.6     |
| sa-gd465   | Nov 29     | 20:30:30   | 5.14       | SAAO           | 1.9     |
| teiden16   | Nov 29     | 21:18:50   | 2.59       | Teide           | 0.8     |
| joy-028    | Nov 30     | 03:54:20   | 5.24       | McDonald        | 2.1     |
| no3000q1   | Nov 30     | 06:40:50   | 6.77       | Mauna Kea      | 0.6     |
| sa-gd466-9 | Nov 30     | 19:30:20   | 6.26       | SAAO           | 1.9     |

The bottom panel of Fig. 1 shows the FT of the residual light curve following the removal of 14 frequencies, on the same scale as the top panel. There are some residual peaks in this plot at interesting frequencies. Analysis of the full data set, including runs outside of the subset that we used, shows that some of these are real. They will be described in further detail in the full analysis of the data which is in preparation.

The frequencies listed in Table 3 are from the fit that included all 14 frequencies.

Table 3. Principal frequencies in HR 1217 in 2000

| Number | Frequency [µHz] | Frequency Spacing [µHz] | Amplitude [mmag] |
|--------|-----------------|-------------------------|------------------|
| f1     | 2619.51 ±0.03   | -                       | 0.24 ±0.02       |
| f2     | 2652.96 ±0.01   | 33.45 ±0.04             | 0.95 ±0.02       |
| f3     | 2687.58 ±0.02   | 34.62 ±0.04             | 0.68 ±0.03       |
| f4     | 2720.96 ±0.02   | 34.95 ±0.04             | 1.29 ±0.02       |
| f5     | 2755.35 ±0.03   | 34.39 ±0.04             | 0.34 ±0.02       |
| f6     | 2791.48 ±0.03   | 36.13 ±0.04             | 0.29 ±0.02       |
| f7     | 2806.43 ±0.14   | 14.95 ±0.14             | 0.22 ±0.07       |

4 RESULTS

4.1 Comparison with the 1989 data

Early in the run, it became clear that HR 1217 was pulsating with the same frequencies that were present in the 1986 data analysed by Kurtz et al. (1989). Tables 1 and 3 show that the principal frequencies from the 1986 study (f1 through f5 and f7) are highly consistent over a time span of 15 yr. Some of the amplitudes of these modes are higher in 2000 and some lower by small amounts than they were in 1986.
but it is the frequencies (and presence or absence) of the modes that are of interest here.

The chief difference between the 2000 data and 1986 data is the presence of a frequency at 2791 $\mu$Hz listed as $f_6$ in Table 3. That mode was not detected in the data of Kurtz et al. (1989 - Table 1) but was a clear signal in the WET Xcov20 2000 data. To ensure that this frequency is not an artefact of the data reduction algorithm, we repeated the frequency analysis of our data fitting just the large-amplitude peaks $f_2$, $f_3$, $f_4$, and $f_5$, and their rotational sidelobes (if present). We then removed those 10 frequencies. The results are illustrated in Fig. 2. This figure shows the original FT, and the FT of the data simulated by including $f_2$-$f_5$ and their rotational sidelobes. Clearly, there is excess signal at the positions of $f_1$ and $f_7$, but also at 2791 $\mu$Hz as well.

Thus we conclude that the “new” frequency, $f_6$, is real. Table 3 shows that it lies at nearly $\nu_o/2$ above $f_5$, as expected if it is a normal $p$–mode and $\nu_o \approx 68\mu$Hz. It is much closer to $f_7$ than $\nu_o/2$, as predicted by Cunha (2001).

4.2 Implications for roAp stars

Cunha (2001) speculated that the position of the $f_7$ peak in the Kurtz et al. (1989) data is consistent with her model of the normal mode structure in Ap stars when magnetic fields are important to the pulsation dynamics. Since that peak was $\frac{1}{2}\nu_o$ above $f_5$ (which is inexplicable in asymptotic theory), she suggested that there should be a peak at $\nu_o/2$ above $f_5$. That is precisely what we see in the data from the WET run in November 2000 with the discovery of $f_6$.

As discussed earlier, other explanations for the frequency spacing pattern from $f_5$ to $f_7$ are in direct conflict with the now well-determined HIPPARCOS luminosity of HR 1217. We therefore conclude that the frequency pattern in HR 1217 suggests that the pulsations we see in this star are consistent with normal $p$–mode pulsations whose frequencies are, in some cases, strongly affected by the magnetic field of the star.

Cunha (2001) suggested that large Alfvénic losses could help explain the missing $f_6$ in the 1986 data, as these losses are maximal at the frequencies where the large separations experience the abrupt decrease. This energy loss could either stabilize the mode or contribute to decrease its amplitude (although it is not clear how the growth rates relate to the amplitude of the modes in roAp stars).

Since $f_6$ is observed in the present data, the possibility that the Alfvénic losses are large enough to stabilise this mode can be ruled out, at least at the time of these observations. Whether at the time of the previous observations the efficacy of the magnetoacoustic coupling (which depends, among other things, on the exact frequency of the mode and on the characteristics of the magnetic field) was different, is something to which we do not have an answer. An attempt to monitor the amplitude of $f_6$, as well as that of the other modes, in the future might, therefore, be worthwhile. However, the magnetic field does produce an important observable effect on the frequency of $f_7$.

With the detection of $f_6$, we move closer to a detailed understanding of the pulsation mechanism in roAp stars. Most intriguingly, this result for HR1217 suggests that, with appropriately detailed models, we may soon be able to probe the magnetic field structure below the surfaces of these stars through their pulsation frequencies – another application of asteroseismology to probing stellar interiors.

ACKNOWLEDGMENTS

We gratefully acknowledge support from the U.S. National Science Foundation through grant AST-9876655 to Iowa State University, and funding by UNESCO through the International Institute of Theoretical and Applied Physics at Iowa State. M.C is supported by FCT-Portugal through the grant PD/18893/98 and the grant POCTI/1999/FIS/34549 approved by FCT and POCTI, with funds from the European Community programme FEDER. PM is supported by KBN (Poland) through grant 5-P03D-012-20.
REFERENCES

Balmforth, N.J., Cunha, M.S., Dolez, N., Gough, D.O., Vauclair, S., 2001, MNRAS, 323, 362

Bigot, L., 2002, in Radial and Nonradial Pulsations as probes of Stellar Physics, IAU colloquium 185, eds. C. Aerts, J. Christensen-Dalsgaard and T. Bedding, ASP Conf. Ser., in press

Bigot, L., Provost, J., Berthomieu, G., Dziembowski, W.A., Goode, P.R., 2000, A&A, 356, 218

Bouchy, F., Carrier, F., 2001, A&A, 374, 5

Carrier, F., Bouchy, F., Kienzle, F., Bedding, T.R., Kjeldsen, H., Butler, R.P., Baldry, I.K., O’Toole, S.J., Tinney, C.G., Marcy, G.W., 2001, A&A, 378, 142

Cunha, M.S., 2001, MNRAS, 325, 373

Cunha, M.S., Gough, D., 2000, MNRAS, 319, 1020

Dziembowski, W., Goode, P.R., 1996, ApJ, 458, 338

Gough, D.O., 2001, Science, 291 (5512), 2325

Heller, C.H., Kawaler, S.D., 1988, ApJL, 329, L43

Kawaler, S.D., & Bradley, P.A. 1994, ApJ, 427, 415

Kleinman, S.J., Nather, R.E., & Phillips, T., 1996, PASP, 108, 356

Kurtz, D.W., 1982, MNRAS, 200, 807

Kurtz, D.W., Matthews, J.M., Martinez, P., Seeman, J., Cropper, M., Clemens, J.C., Kreidl, T.J., Sterken, C., Schneider, H., Weiss, W.W., Kawaler, S.D., Kepler, S.O., van der Peet, A., Sullivan, D.J., and Wood, H.J., 1989, MNRAS, 240, 881

Matthews, J.M., Kurtz, D.W., Martinez, P., 1999, ApJ, 511, 422

Tassoul M., 1980, ApJS, 43, 469

Tassoul M., 1990, ApJ, 358, 313

Winget, D.E., Nather, R.E., Clemens, J.C., Provencal, J., Kleinman, S.J., Bradley, P.A., Wood, M.A., Claver, C.F., Grauer, A.D., Hine, B.P., Hansen, C.J., Fontaine, G., Wickramasinghe, D.T., Achilles, N., Marar, T.M.K., Seetha, S., Ashoka, B.N., O’Donoghue, D., Warner, B., Kurtz, D.W., Buckley, D.A., Vauclair, G., Chevreton, M., Dolez, N., Barstow, M.A., Solheim, J.E., Ulla, A.M., Kanaan, A., Kepler, S.O., Henry, G.A., and Kawaler, S.D., 1991, ApJ, 378, 326