Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **442,** 2278–2281 (2014) doi:10.1093/mnras/stu1019

# Discovery of a new PG 1159 (GW Vir) pulsator

S. O. Kepler,[1]★ Luciano Fraga,[2] Don Earl Winget,[3] Keaton Bell,[3]
Alejandro H. Córsico[4] and Klaus Werner[5]

[1]*Instituto de Física, Universidade Federal do Rio Grande do Sul, 91501-900 Porto-Alegre, RS, Brazil*
[2]*Laboratório Nacional de Astrofísica, 37504-364 Itajubá, MG, Brazil*
[3]*Department of Astronomy and McDonald Observatory, The University of Texas at Austin, Austin, TX 78712-1083, USA*
[4]*Facultad de Ciencias Astronómicas y Geofísicas, Paseo del Bosque S/N, (1900) La Plata, and Consejo Nacional de Investigaciones Científicas y Ténicas (CONICET), 1900 La Plata, Argentina*
[5]*Institute for Astronomy and Astrophysics, Kepler Center for Astro and Particle Physics, Eberhard Karls University, Samd I, D-72076 Tübingen, Germany*

Accepted 2014 May 20. Received 2014 May 19; in original form 2014 April 9

## ABSTRACT

We report the discovery of pulsations in the spectroscopic PG 1159 type pre-white dwarf SDSS J075415.12 + 085232.18. Analysis of the spectrum by Werner et al. indicated $T_{\rm eff} = 120\,000 \pm 10\,000$ K, $\log g = 7.0 \pm 0.3$, mass $\mathcal{M} = 0.52 \pm 0.02\,{\rm M}_{\odot}$, C/He = 0.33 by number. We obtained time series images with the SOAR 4.1 m telescope and 2.1 m Otto Struve telescope at McDonald Observatory and show the star is also a variable PG 1159 type star, with dominant period of 525 s.

**Key words:** stars: individual: SDSS J075415.12 + 085232.18 – white dwarfs.

## 1 INTRODUCTION

White dwarf stars are the end product of evolution of all stars with initial masses up to around 8–10 $\rm M_{\odot}$, depending on the metallicity of the progenitor and its effect on mass-loss and the real value of the C($\alpha,\gamma$)O reaction rate. Their spatial and mass distributions contain information about star formation history and subsequent evolution in our Galaxy. As the most common endpoints of stellar evolution, white dwarf stars account for around 95 per cent of all evolved stars. The GW Vir stars, also called DOVs, are the pulsating variables in the spectroscopic PG 1159 class that links the (post-AGB) central stars of planetary nebulae and the H-deficient white dwarf cooling sequence. These stars are non-radial pulsators and lie in an instability strip bounded by effective temperatures $200\,000 \le T_{\rm eff} \le 75\,000$ K, excited by the $\kappa$-mechanism working through partial ionization of carbon and oxygen. Asteroseismological analysis of these stars has provided significant knowledge on the interiors of the late stages of stellar evolution (Winget & Kepler 2008; Althaus et al. 2010). There are 20 known GW Vir stars (Quirion 2009a; Quirion, Fontaine & Brassard 2009b; Woudt, Warner & Zietsman 2012). Finding new pulsators of this class can improve our knowledge of the asymptotic giant branch (AGB) and very late thermal pulse (VLTP) phases, as well as angular momentum loss throughout the extensive mass-loss phases (Charpinet, Fontaine & Brassard 2009; Córsico et al. 2011).

In our search for new spectroscopically confirmed white dwarf stars in the Sloan Digital Survey (SDSS; Kleinman et al. 2013), we identified SDSS J075415.12 + 085232.18 as a hot pre-white dwarf from the presence of He II and carbon lines in spectrum plate = 2945, MJD = 54505, fibre = 183 of this $g = 18.79$ star. It shows no detectable planetary nebula. Werner, Rauch & Kepler (2014) fitted its SDSS spectrum with non-local thermodynamic equilibrium models and obtained $T_{\rm eff} = 120\,000 \pm 10\,000$ K, $\log g = 7.0 \pm 0.3$, mass $\mathcal{M} = 0.52 \pm 0.02\,{\rm M}_{\odot}$, and C/He = 0.33 by number, indicating the star is a spectroscopic PG 1159 type star, i.e. hotter and with a more complex spectrum than a normal DO white dwarf, similar to the prototype (Liebert et al. 1989; Werner, Heber & Hunger 1989), which is also a pulsating star (e.g. McGraw et al. 1979; Winget et al. 1991; Kawaler & Bradley 1994; Costa et al. 2008). The observed $g = 18.79 \pm 0.01$ apparent magnitude, compared to an $M_g = 5.68$ for such effective temperature and gravity, implies a distance of $4.18 \pm 0.03$ kpc. Such a large distance merits the full extinction correction in that direction, 0.076 mag in $g$, which brings the distance to 4.04 kpc. Córsico & Althaus (2006a) and Córsico, Althaus & Miller Bertolami (2006b) computed fully evolutionary models and non-adiabatic pulsation models for stars in the GW Vir instability strip and found that they agree with the observed strip.

## 2 OBSERVATIONS AND DATA REDUCTION

We first obtained time series photometry of SDSS J075415.12 + 085232.18 with the 4.1 m SOAR[1] telescope and using the SOAR

---

★E-mail: kepler@if.ufrgs.br

[1] Based on observations obtained at the Southern Astrophysical Research (SOAR) telescope, which is a joint project of the Ministério da Ciência, Tecnologia, e Inovação (MCTI) da República Federativa do Brasil, the U.S. National Optical Astronomy Observatory (NOAO), the University of North Carolina at Chapel Hill (UNC), and Michigan State University (MSU).

Published by Oxford University Press on behalf of the Royal Astronomical Society

Optical Imager (SOI; Schwarz et al. 2004) during the night of 2014 Jan 28 (Barycentric Julian Terrestrial Time – BJTT = 245 6685.720 0646). SOI is a mini-mosaic of two E2V 2k×4k CCDs covering a 5.26 × 5.26 $\text{arcmin}^2$ field of view at a plate scale of 0.077 arcsec $\text{pixel}^{-1}$. We obtained a total of 263 SOI frames with a Bessel-*B* filter, exposure time of 30 s and 4×4 binning, yielding a detector scale of 0.31 arcsec $\text{pixel}^{-1}$. The SOI data frames were reduced in the standard manner using the mosaic reduction (MSCRED) package in IRAF (Valdes 1998; Valdes & Tody 1998). The data reduction process includes bias subtraction, flat-fielding and cosmic ray cleaning. We performed the aperture photometry in the individual frames using DAOPHOT (Stetson 1991) routines in IRAF. From the Fourier analysis, we achieved a mean noise level of $\langle A\rangle = 1.4$ mma, and detected for the first time a periodicity, with a period of 525 s at 6.8 mma, therefore at $4.8\langle A\rangle$, well above the 1/1000 false alarm probability limit.

On the three consecutive nights of 2014 Feb 3–5 (BJTT = 245 6691.699 600 605) we obtained follow-up observations of the star with the Cassegrain-mounted ProEM camera and the PUOKONUI data acquisition software (Chote et al. 2014) at McDonald Observatory's 2.1 m Otto Struve telescope. From 3127 images with 10–30 s exposures, we confirmed the 525 s periodicity at 5.9 mma, compared to the average noise level $\langle A\rangle = 1.03$ mma. The frames were binned at 4×4, giving a 0.36 arcsec $\text{pixel}^{-1}$ plate scale across the 2.3 × 2.3 arcmin field of view. We performed aperture photometry on the calibrated images using the IRAF package CCD_HSP (Kanaan, Kepler & Winget 2002) and calculated barycentric corrections with the WQED software (Thompson & Mullally 2009).

We obtained additional time series observations with the SOAR Goodman Spectrograph (Clemens, Crain & Anderson 2004) in imaging mode during the night of 2014 Feb 27 (BJTT = 245 6715.519 2530). Goodman is mounted at the SOAR Optical Nasmyth and its detector is a 4k × 4k Fairchild 486 back-illuminated CCD, with an unbinned plate scale of 0.15 arcsec $\text{pixel}^{-1}$. We carried out the photometric observations with a S8612 red block filter, a region of interest of 800 × 800 $\text{pixel}^2$ and a 2 × 2 binning, yielding a field of view of 4 × 4 $\text{arcmin}^2$ and a plate scale of 0.3 arcsec $\text{pixel}^{-1}$. Each exposure lasted 30 s. We used the same method for the data reduction and photometry as for SOI data. From the Fourier analysis of a total 451 Goodman frames, we achieved a mean noise level of $\langle A\rangle = 0.94$ mma, with which we were able to detect three periodicities, 523.5 s at 7.0 mma, 457.2 s at 3.8 mma, and 439.2 at 3.5 mma, all above the 1/1000 false alarm probability.

Fig. 1 shows the Fourier transform of all data sets. Analysing the whole data set at once, we obtained 523.480 ± 0.005 s at 5.8 ± 0.8 mma, and 524.87 ± 0.008 s at 3.4 ± 0.8 mma, but the different instrument colour response prevents us from trusting these values. The spacing in frequency $\delta\nu \simeq 5.1$ μHz is similar to that for $\ell = 1$ modes of PG 1159−035 (4.1 μHz). If the spacing is real, it indicates a rotation period of 28 h, similar to those derived for other variable PG 1159 stars.

## 3 MODELLING AND SEISMOLOGY

The pulsation modelling and seismological analysis presented in this section rely on a set of stellar models that take into account the complete evolution of PG 1159 progenitor stars. The models were extracted from the evolutionary calculations presented by Althaus et al. (2005) and Miller Bertolami & Althaus (2006), who computed the complete evolution of model star sequences with initial masses on the zero-age main sequence ranging from 1 to 3.75 $M_{\odot}$. All of the post-AGB evolutionary sequences were computed using the LPCODE evolutionary code (Althaus et al. 2005) and were followed through the VLTP and the resulting born-again episode that gives rise to the H-deficient, and He-, C- and O-rich composition characteristic of PG 1159 stars. The masses of the resulting remnants are 0.530, 0.542, 0.556, 0.565, 0.589, 0.609, 0.664 and 0.741 $M_{\odot}$.

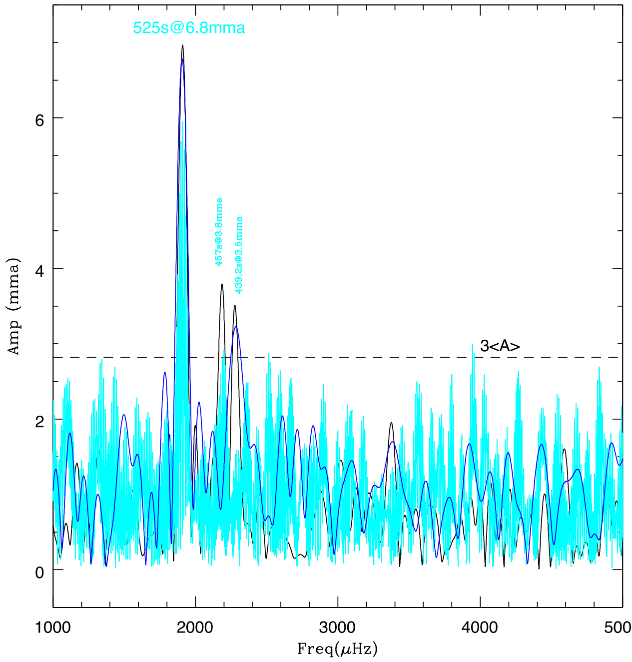

**Figure 1.** Fourier transform of the two SOAR data sets (black and blue lines), and the McDonald data set (cyan shaded). The $3\langle A\rangle$ line, corresponding to the false alarm probability of 1/1000, refers only to the equally spaced SOAR data set from 2014 Feb 27, the one with lowest noise, shown in black.

With only three periods detected for SDSS J075415.12 + 085232.18, we cannot estimate the mean period spacing, and cannot constrain the stellar mass by comparing with the mean period spacing of the models, as done in the case of other pulsating PG 1159 stars (e.g. Córsico et al. 2009). The way to infer the stellar mass, along with the effective temperature and also details of the internal structure of SDSS J075415.12 + 085232.18 is through their individual pulsation periods. This has been the approach employed by Córsico et al. (2007a,b, 2008, 2009) for the pulsating PG 1159 stars RX J2117.1 + 3412, PG 0122 + 200, PG 1159−035, PG 2131 + 066 and PG 1707 + 427, respectively.

We employed the extensive set of $\ell = 1$, 2 *g*-mode adiabatic pulsation periods used in Córsico et al. (2007a, b, 2008, 2009). For details of the adiabatic pulsation code (LP-PUL code) and methods employed to produce the set of periods, see Córsico & Althaus (2006a). We analysed more than about 3000 PG 1159 models covering a wide range of effective temperatures [$5.4 \gtrsim \log(T_{\text{eff}}) \gtrsim 4.8$], luminosities [$0 \lesssim \log(L_*/\mathrm{L}_{\odot}) \lesssim 4.2$], and stellar masses ($0.530 \leq M_*/\mathrm{M}_{\odot} \leq 0.741$). Even though the radial order *k* associated with the observed periods (∼440–524 s) is large (as we shall see below), the pulsation *g*-modes of SDSS J075415.12 + 085232.18 are probably not in the asymptotic regime (see, for instance, Córsico & Althaus 2006a). Because the models are evolutionary, not started from a polytrope, they cannot achieve any combination of mass, luminosity and effective temperature, and do not cross each other in the Hertzsprung–Russell diagram. The best solutions, quoted, are not just samples of possible solutions, but limited solutions. As there are three independent modes, one can estimate up to three parameters of the models.

**Table 1.** Observed and theoretical periods for the best model fit in Case 1.

| $\Pi_{\rm obs}$ | $\Pi_{\rm theor}$ | $\ell$ | $k$ |
|---|---|---|---|
| 439.2 | 438.9 | 1 | 18 |
| 457.2 | 458.1 | 1 | 19 |
| 523.5 | 522.5 | 1 | 22 |

We seek pulsation models that best match the individual pulsation periods of SDSS J075415.12 + 085232.18. The goodness of the match between the theoretical pulsation periods ($\Pi_k$) and the observed individual periods ($\Pi_{{\rm obs},\,i}$) is measured by means of a quality function defined as

$$\chi^2(M_*, T_{\rm eff}) = \frac{1}{N}\sum_{i=1}^{N} \min[(\Pi_{{\rm obs},i} - \Pi_k)^2], \tag{1}$$

where $N$ (=3) is the number of observed periods. In the absence of any additional information, we assume that the three observed periods of SDSS J075415.12 + 085232.18 correspond to eigenmodes with azimuthal order $m = 0$, but Metcalfe (2003) shows the effect of the assumption is negligible. We evaluate the function $\chi^2(M_*, T_{\rm eff})$ for evolutionary models with stellar masses of 0.530, 0.542, 0.556, 0.565, 0.589, 0.609, 0.664, 0.741 $M_\odot$. The PG 1159 model that shows the lowest value of $\chi^2$ is adopted as the 'best-fitting model'. Since we do not know at the outset the harmonic degree ($\ell$) identification of the observed modes, we have to distinguish three cases.

### 3.1 Case (1): all $\ell = 1$ modes

Here, we consider that all the three measured periods are associated with modes with $\ell = 1$. We obtain a best-fitting solution characterized by: $M_* = 0.556\,M_\odot$, $T_{\rm eff} = 130\,100$ K and $L/L_\odot = 170$. A comparison between the observed and theoretical periods, along with the derived $\ell$ and $k$ (radial order) values associated with this solution is shown in Table 1.

The quality function for this case is displayed at the upper panel of Fig. 2.

### 3.2 Case (2): mixed $\ell = 1$ and $\ell = 2$ modes

In this case, we consider that the observed periods are associated with a mix of $\ell = 1$ and $\ell = 2$ modes. We perform a period fit in which the value of $\ell$ for the theoretical periods is not fixed, but instead is obtained as a result of our period fit procedure, with allowed values of $\ell = 1$ and $\ell = 2$. The solution is displayed in the central panel of Fig. 2 and has $M_* = 0.556\,M_\odot$, $T_{\rm eff} = 128\,300$ K, $L/L_\odot = 156$. The agreement between theoretical and observed modes is shown in Table 2.

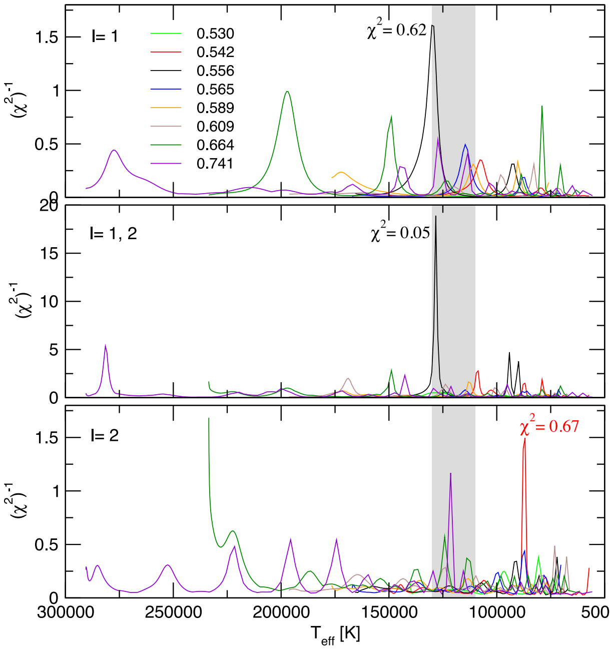

**Figure 2.** The inverse of the quality function of the period fits in terms of the effective temperature. The vertical grey strip indicates the spectroscopic $T_{\rm eff}$ and its uncertainties. Upper panel corresponds to the case in which the three periods are associated with $\ell = 1$ modes, middle panel shows the situation in which there is a mix of $\ell = 1$ and $\ell = 2$ modes, and lower panel displays the case in which the three modes are $\ell = 2$.

**Table 2.** Observed and theoretical periods for the best model fit in Case 2.

| $\Pi_{\rm obs}$ | $\Pi_{\rm theor}$ | $\ell$ | $k$ |
|---|---|---|---|
| 439.2 | 439.2 | 1 | 18 |
| 457.2 | 457.5 | 2 | 34 |
| 523.5 | 523.3 | 1 | 22 |

**Table 3.** Observed and theoretical periods for the best model fit in Case 1.

| $\Pi_{\rm obs}$ | $\Pi_{\rm theor}$ | $\ell$ | $k$ |
|---|---|---|---|
| 439.2 | 440.5 | 2 | 30 |
| 457.2 | 457.1 | 2 | 31 |
| 523.5 | 524.1 | 2 | 36 |

### 3.3 Case (3): all $\ell = 2$ modes

Finally, we assume that all three identified periods are associated with $\ell = 2$, even though it is improbable that a pulsating pre-white dwarf star shows only quadrupole modes. The solution is displayed in the bottom panel of Fig. 2 and has $M_* = 0.542 M_\odot$, $T_{\rm eff} = 86\,900$ K, $L/L_\odot = 21$ (Table 3). This solution, already unlikely from the point of view of geometrical cancellation, gives too low of a temperature, compared with the spectral determination. A secondary solution is observed for $M_* = 0.741\,M_\odot$ and $T_{\rm eff} = 121\,600$ K, but it can be discarded because of its very high mass value, as compared with the spectroscopically inferred mass ($0.52 \pm 0.02\,M_\odot$) of SDSS J075415.12 + 085232.18.

The agreement between theoretical and observed periods of the solution in Case (2) is excellent, with two $\ell = 1$ modes and one $\ell = 2$, and the mean difference of 0.17 s is within observational and theoretical uncertainties. This solution agrees with the spectral temperature, $T_{\rm eff} = 120\,000 \pm 10\,000$ K, and is within the real uncertainty (i.e. including systematic uncertainties) of the spectroscopic mass: $M_* = 0.52 \pm 0.02$.

To estimate the quality of our best fits, we compute the Bayes Information Criterion (BIC; Koen & Laney 2000):

$$\mathrm{BIC} = N_{\mathrm{p}}\left(\frac{\log N}{N}\right) + \log\sigma^2,$$

where $N_{\mathrm{p}}$ is the number of free parameters, and $N$ the number of observed periods. The BIC parameter estimates the absolute quality of the period fit, by accounting for situations in which there are different numbers of observed periods and free parameters. In our case, $N_{\mathrm{p}} = 2$ (stellar mass and effective temperature), and $N = 3$. The smaller the value of BIC, the better the quality of the fit. We obtain BIC = 0.11 for Case (1), BIC = −0.98 for Case (2), and BIC = 0.14 for Case (3). The period fit of Case (2) is excellent, as reflected by the corresponding BIC value. It could be compared with the BIC value of current asteroseismological period fits of pulsating white dwarfs (see, for instance, Bischoff-Kim & Østensen 2011).

## 4 DISCUSSION

Time series imaging show SDSS J075415.12 + 085232.18 is a non-radial pulsator in the PG 1159 pre-white dwarf class, also called GW Vir. Its spectral effective temperature $T_{\mathrm{eff}} = 120\,000 \pm 10\,000$ K and C/He = 0.33 by number is comparable to the prototype, and the main period at 525 s is also comparable to the 516 s main periodicity of PG 1159−035. Its low pulsation amplitude led to a small number of periodicities detected, contrary to the prototype, which has the largest number of independent pulsations detected after the Sun. That PG 1159 stars probably have no atmospheric convection layer might explain the absence of combination frequencies, even when large amplitudes are detected, as in PG 1159−035 itself (Costa et al. 2008). These stars evolve fast, leading to substantial period change due to cooling and contraction, that should allow a detectable period change in a few years (Winget, Hansen & van Horn 1983). Therefore, the star should be monitored at least yearly to allow evolutionary changes determinations (Costa & Kepler 2008).

## ACKNOWLEDGEMENTS

S. O. Kepler is supported by CNPq and FAPERGS-Pronex-Brazil.

## REFERENCES

Althaus L. G., Serenelli A. M., Panei J. A., Córsico A. H., García-Berro E., Scóccola C. G., 2005, A&A, 435, 631

Althaus L. G., Córsico A. H., Isern J., García-Berro E., 2010, A&AR, 18, 471

Bischoff-Kim A., Østensen R. H., 2011, ApJ, 742, L16

Charpinet S., Fontaine G., Brassard P., 2009, Nature, 461, 501

Chote P., Sullivan D. J., Brown R., Harrold S. T., Winget D. E., Chandler D. W., 2014, MNRAS, 440, 1490

Clemens J. C., Crain J. A., Anderson R., 2004, Proc. SPIE, 5492, 331

Córsico A. H., Althaus L. G., 2006, A&A, 454, 863

Córsico A. H., Althaus L. G., Miller Bertolami M. M., 2006, A&A, 458, 259

Córsico A. H., Althaus L. G., Miller Bertolami M. M., Werner K., 2007a, A&A, 461, 1095

Córsico A. H., Miller Bertolami M. M., Althaus L. G., Vauclair G., Werner K., 2007b, A&A, 475, 619

Córsico A. H., Althaus L. G., Kepler S. O., Costa J. E. S., Miller Bertolami M. M., 2008, A&A, 478, 869

Córsico A. H., Althaus L. G., Miller Bertolami M. M., García-Berro E., 2009, A&A, 499, 257

Córsico A. H., Althaus L. G., Kawaler S. D., Miller Bertolami M. M., García-Berro E., Kepler S. O., 2011, MNRAS, 418, 2519

Costa J. E. S., Kepler S. O., 2008, A&A, 489, 1225

Costa J. E. S. et al., 2008, A&A, 477, 627

Kanaan A., Kepler S. O., Winget D. E., 2002, A&A, 389, 896

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

Kleinman S. J. et al., 2013, ApJS, 204, 5

Koen C., Laney D., 2000, MNRAS, 311, 636

Liebert J., Wesemael F., Husfeld D., Wehrse R., Starrfield S. G., Sion E. M., 1989, AJ, 97, 1440

McGraw J. T., Liebert J., Starrfield S. G., Green R., 1979, White Dwarfs and Variable Degenerate Stars. University of Rochester, Rochester, NY, p. 377

Metcalfe T. S., 2003, Balt. Astron., 12, 247

Miller Bertolami M. M., Althaus L. G., 2006, A&A, 454, 845

Quirion P.-O., 2009, Commun. Asteroseismol., 159, 99

Quirion P.-O., Fontaine G., Brassard P., 2009, J. Phys.: Conf. Ser., 172, 012077

Schwarz H. E. et al., 2004, Proc. SPIE, 5492, 564

Stetson P. B., 1991, in Grosbøl P. J., Warmels R. H., eds, ESO Conf. and Workshop Proc. No. 38, 3rd ESO/ST-EFC Data Analysis Workshop. European Southern Observatory, Garching, p. 187

Thompson S. E., Mullally F., 2009, J. Phys.: Conf. Ser., 172, 012081

Valdes F. G., 1998, in Albrecht R., Hook R. N., Bushouse H. A., eds, ASP Conf. Ser. Vol. 145, Astronomical Data Analysis Software and Systems VII. Astron. Soc. Pac., San Francisco, p. 53

Valdes F. G., Tody D., 1998, Proc. SPIE, 3355, 497

Werner K., Heber U., Hunger K., 1989, in Wegner G. A., ed., Lecture Notes in Physics Vol. 328, IAU Colloq. 114: White Dwarfs. Springer-Verlag, Berlin, p. 194

Werner K., Rauch T., Kepler S.O., A&A, 564, A53

Winget D. E., Kepler S. O., 2008, ARA&A, 46, 157

Winget D. E., Hansen C. J., van Horn H. M., 1983, Nature, 303, 781

Winget D. E. et al., 1991, ApJ, 378, 326

Woudt P. A., Warner B., Zietsman E., 2012, MNRAS, 426, 2137

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