The Period-Effective Temperature Relation for DBV White Dwarfs

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Astrophysical Context

Linear nonadiabatic pulsation theory suggests that there should be a period-effective temperature relation in pulsating white dwarfs of the ZZ Ceti type, in the sense that the cooler the pulsator, the larger the excited periods. Such a relation indeed exists in the empirical data, and has been known for at least 30 years. Figure 1 provides an updated view of this relationship, based on a sample of 60 bright pulsating DA white dwarfs that have been studied extensively by the Montréal group over the last two decades. Taking into account the uncertainties on the individual spectroscopic measurements, the difficulties in defining a meaningful "representative" period for these multiperiodic pulsators, and the real possibility of true scatter, the trend between excited period and effective temperature is quite clear.

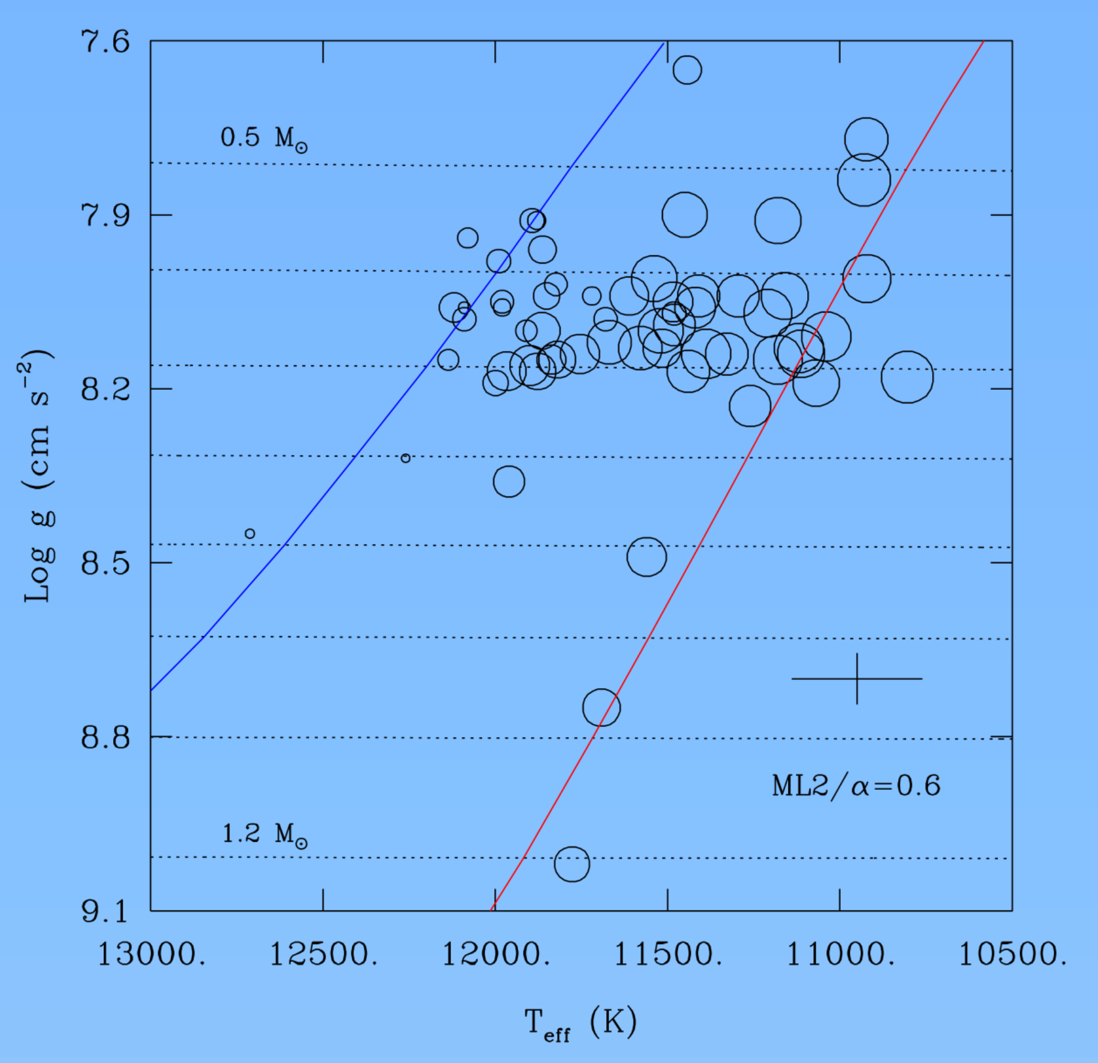


Figure 1 – Correlation between excited period and effective temperature or surface gravity for ZZ Ceti pulsators. The locations of 60 stars are specified by open circles whose sizes give a logarithmic measure of the representative period -- the straight mean of the shortest and longest observed periods -- for each star. The nearly horizontal dotted curves illustrate evolutionary tracks for H-atmosphere white dwarfs of different masses, from 0.5 $M_{\rm sun}$ above to 1.2 $M_{\rm sun}$ below in steps of 0.1 $M_{\rm sun}$. The two diagonal solid curves are the theoretical blue and red boundaries of the instability domain as obtained recently by Van Grootel et al. (2013, ApJ, 762, 57). Those explain very well the spectroscopic measurements, which were obtained with an assumed convective efficiency of ML2/α=0.6. The cross illustrates typical uncertainties on the derived atmospheric parameters. While a possible correlation between period and surface gravity does not stand out particularly, there is no doubt that, along an evolutionary track, the observed representative period tends to increase with decreasing effective temperature.

Given that the basic nonadiabatic physics is the same in both ZZ Ceti and V777 Her (DBV) white dwarfs, it follows that a similar period-effective temperature relation should also exist for the latter family of pulsators. This relation has remained elusive, however, because the sample of known DBV stars has remained small, particularly for those that have been well studied spectroscopically and photometrically. Currently, we know of the existence of only 21 V777 Her stars, compared to more than 150 ZZ Ceti stars. This is due to the fact that there are intrinsically less pulsators of the first kind per unit volume.

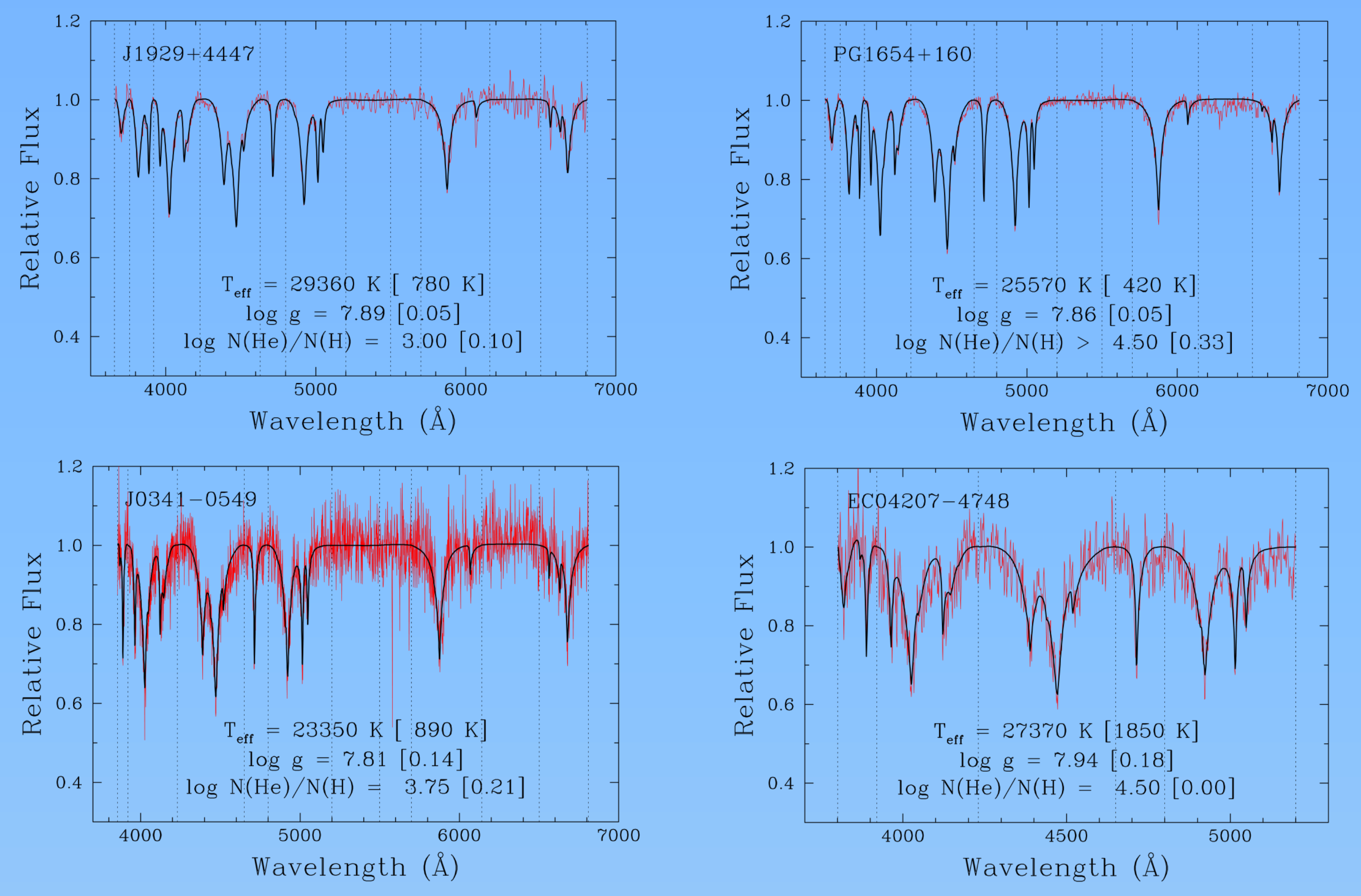
To remedy that situation, we have analyzed high S/N optical spectra of 10 DBV stars that were gathered over the years, some of which recently. We made sure that the total exposure time for each of these targets covers several pulsation cycles in order to obtain meaningful time-averaged spectra. In order to potentially increase our small sample, we relaxed that requirement and we examined the available low S/N, classification spectra of the remaining 11 objects in the known sample of DBV stars. Among those, there are 9 DBV pulsators culled from the SDSS project whose variability was first reported by Nitta et al. (2009, ApJ, 690, 560). Unfortunately, these targets are relatively faint, and due to the very poor S/N of most of the available SDSS spectra, we could make use of only two spectra, corresponding, not surprisingly, to the two brightest stars. For the other, fainter objects, the derived atmospheric parameters turned out to be only of statistical value, at best. We were also able to exploit the blue classification spectra of two additional V777 Her stars culled from the EC survey as reported in Kilkenny et al. (2009, MNRAS, 397, 453). Hence, we analyzed in a homogeneous way 10 high S/N spectra (supplemented by 4 low S/N spectra) using a method similar to that employed in the extended spectroscopic study of DB white dwarfs carried out by Bergeron et al. (2011, ApJ, 737, 28). Our results are summarized in Table 1 below.

Table 1. Known V777 Her stars with atmospheric parameters determined in this work. The top ten objects are those with high S/N spectra, while the four additional targets listed at the bottom of this table have low S/N, classification spectra.

WD	Name	V	$T_{\rm eff}$ (K)	log g (cm s^{-2})	log H/He	Period (s)	Reference
1929+448	J1929+4447	18.42(K_p)	29360(780)	7.89(0.05)	−3.00(0.10)	143−376	Zong et al. 2015
2246+120	PG 2246+121	16.73	27980(390)	7.92(0.05)	<−4.5(0.6)	256−329	Handler 2001
2005−525	EC 20058−5234	15.58	27670(400)	7.75(0.03)	<−4.0(0.2)	195−525	Dalessio et al. 2013
1351+489	PG 1351+489	16.4(B)	26350(430)	7.95(0.05)	<−4.5(0.3)	335−639	Redaelli et al. 2011
0954+342	CBS 114	17.2(B)	25860(670)	8.02(0.04)	<−4.0(0.2)	399−840	Metcalfe et al. 2005
1654+160	PG 1654+160	16.2(B)	25570(420)	7.86(0.05)	<−4.5(0.3)	431−913	Handler et al. 2003
1645+325	GD 358	13.65	24820(240)	7.91(0.02)	<−4.5(0.5)	423−962	Provencal et al. 2007
0513+260	KUV 05134+2605	16.70	24510(410)	8.21(0.05)	−3.75(0.15)	395−777	Bognár et al. 2014
1456+103	PG 1456+103	15.9(B)	24370(360)	7.94(0.08)	−3.25(0.07)	423−1016	Handler et al. 2003
1115+158	PG 1115+158	16.1(B)	23740(260)	7.92(0.07)	−3.70(0.12)	831−1072	Winget, Nather, & Hill 1987
0421−478	EC 04207−4748	15.3:	27370(1850)	7.94(0.18)	−4.5:	333−447	Kilkenny et al. 2009
1305+409	J1305+4056	17.46(g)	24150(880)	8.11(0.12)	−4.5:	658−913	Nitta et al. 2009
0341−058	J0341−0549	18.25(g)	23350(890)	7.81(0.14)	−3.75(0.21)	942−942	Nitta et al. 2009
0522−474	EC 05221−4725	16.6:	22910(2320)	8.10(0.22)	−4.5:	898−898	Kilkenny et al. 2009

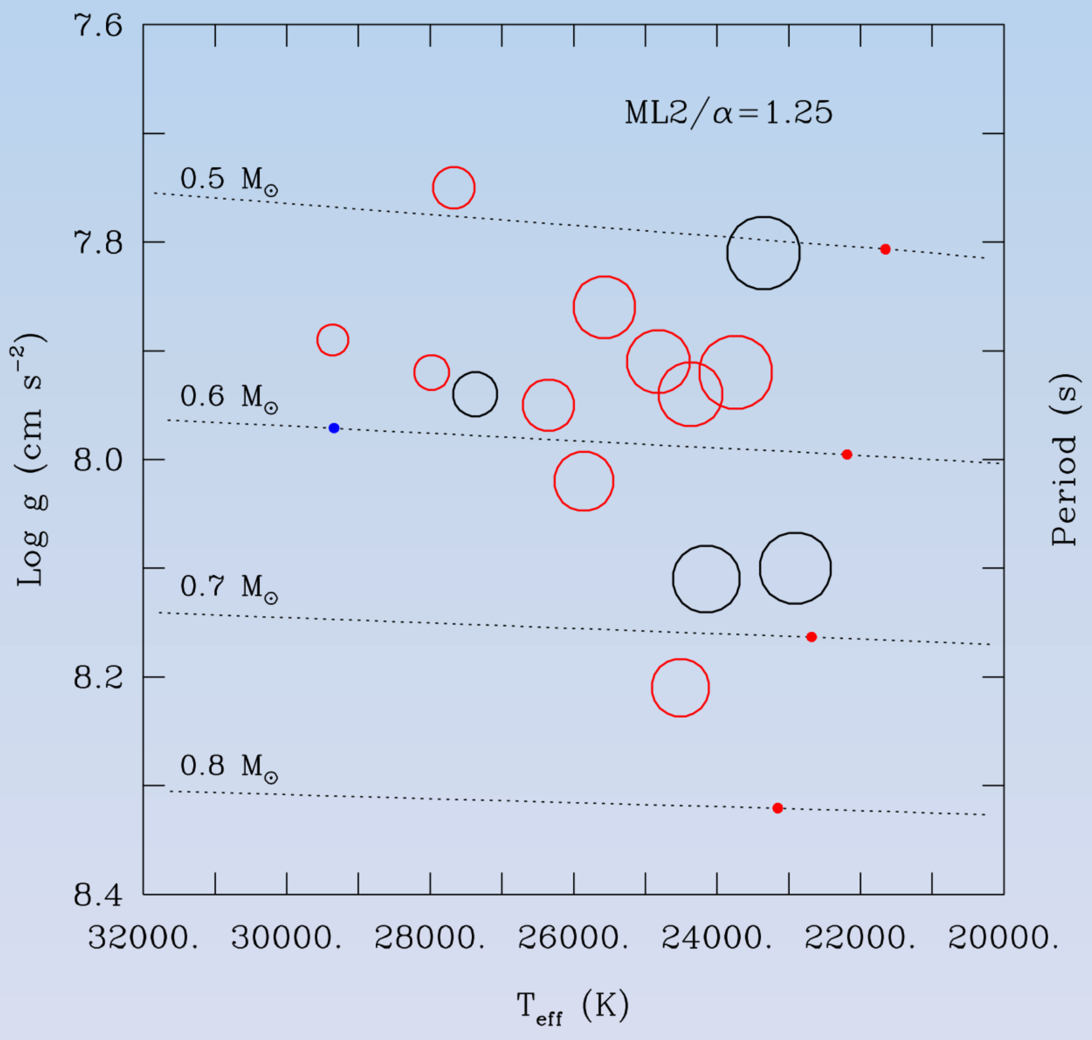
Sample Spectroscopic Fits

We show four examples of spectroscopic fits. Those include 1) J1929+4447, the hottest known DBV white dwarf and the only one observed photometrically with the *Kepler* satellite, 2) PG 1654+160, a star in the middle of the V777 Her instability strip, 3) J0341-0549, an object belonging to the SDSS sample of Nitta et al. (2009) and lying rather near the red edge, and 4) EC 04207-4748, a southern hemisphere DBV reported in Kilkenny et al. (2009). Note that a trace of hydrogen is detected in both J1929+4447 and J0341-0549 (formally making them DBA stars), while a good upper limit of log H/He < -4.5 has been obtained for PG 1654+160. A trace of log H/He = -4.5 has been assumed for EC 04207-4748 (only a blue spectrum that terminates well shortwards of the H_α line is available).



The DBV Instability Strip

Figure 2 depicts our mapping of the empirical V777 Her instability strip. For the first time, a clear correlation in the expected sense between period and effective temperature clearly emerges. On the other hand, as in the case of ZZ Ceti stars, a possible correlation between period and surface gravity is not evident. Ignoring the (real) scatter in surface gravity, Figure 3 provides another view of the period-effective temperature correlation. If the theoretical predictions were perfectly realistic, there should be a one-to-one correspondence between the representative observed period and the most unstable predicted one. Yet, one can easily observe that the actual period grows with decreasing effective temperature at a rate smaller than expected. In the light of the recent fundamental work carried out with 3D hydro simulations for ZZ Ceti stars (see, e.g., Tremblay et al. 2015, ApJ, 799,142), an exciting explanation may be that we are actually seeing, in DBV stars, the actual proof that the convective efficiency decreases with decreasing temperature as predicted by 3D work! Indeed, if that were the case, the most unstable period would not increase as quickly with decreasing $T_{\rm eff}$ compared to the case of the fixed efficiency used in our models.



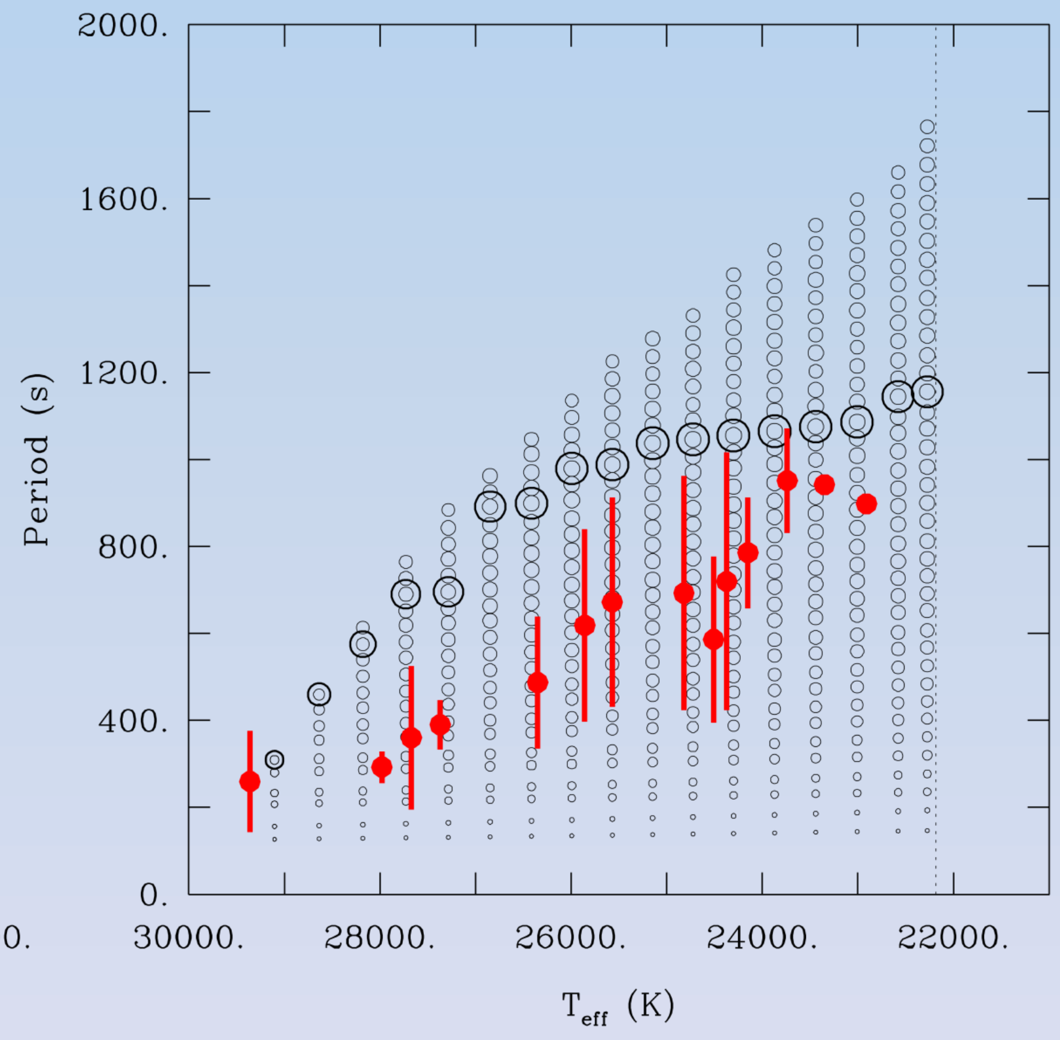


Figure 2 – The plot on the left is similar to Figure 1, but refers to the V777 Her stars. The circles in red are associated with the 10 stars with high S/N spectra, while those in black are associated with the 4 DBV's with low S/N data. The small red dots define the red edge for each of the four evolutionary sequences illustrated here, while the single blue dot corresponds to the blue edge computed with the nonadiabatic Liège pulsation code MAD in TDC (time dependent convection) mode as described in Van Grootel et al. (2013) for the 0.6 $M_{\rm sun}$ sequence. The expected correlation between period and effective temperature along an evolutionary sequence is clearly seen. Note that the period data on which is based part of that figure were taken from the references listed in Table 1. Note further that both the spectroscopic analysis and the nonadiabatic pulsation calculations have been carried out within the framework of the ML2/α=1.25 version of the Mixing-Length Theory, the appropriate calibration for DB white dwarfs.

Figure 3 – The plot on the right provides another view of the period-effective temperature correlation observed and expected in DBV white dwarfs. The empirical correlation is illustrated by the red dots appearing in the middle of vertical heavy line segments, which map the actual observed period range for each target (except for two objects for which discovery light curves have only revealed a single dominant mode so far). In comparison, the predicted spectrum of excited periods as derived from our detailed TDC calculations for the 0.6 $M_{\rm sun}$ sequence is shown by the small open circles whose sizes provide a logarithmic measure of the imaginary part of the eigenfrequency: the bigger the dot, the more unstable the mode. The most unstable predicted mode for each model along the part of the evolutionary sequence considered here is indicated by a bigger concentric heavy circle.