The long term period stability of the hot DBV white dwarf EC 20058–5234

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Abstract. Since its discovery over a decade ago, the helium atmosphere pulsator EC 20058–5234 (QU T el) has been studied both spectroscopically, and also extensively using the techniques of time-series photometry. Model atmosphere fits to quality spectra obtained with one of the Magellan telescopes have confirmed its status as the hottest know DBV, so it currently defines the blue edge of the DBV instability strip. Extensive time-series photometry (primarily from Mt John in NZ but also including a Whole Earth Telescope run) clearly demonstrates that this white dwarf is a very stable low amplitude pulsator. This is consistent with its position at or near the blue edge of the DBV instability strip. However, of perhaps greater significance is the possibility of employing this period stability to look for a period change that can be sourced to the predicted neutrino-dominated cooling of the hot white dwarfs. This paper provides an update on this work.

1. Introduction
The white dwarf EC 20058–5234 (QU Tel, henceforth simply EC 20058) was discovered to be a variable by Koen et al. (1995) in 1994. Their work enabled its classification as a helium atmosphere (DBV) pulsator and identified 8 pulsation frequencies. A Whole Earth Telescope (WET) campaign in 1997, combined with a week of single-site photometry in 2004, resulted in nearly 180 hours of quality time-series photometry, which revealed a total of 18 pulsation frequencies for EC 20058 (Sullivan et al. 2008). Comparison with suitable models led to the identification of 11 individual pulsation modes.

The EC 20058 light curve is dominated by the presence of two dominant pulsation modes that produce approximately equal modulation amplitudes a little less than 1% (≈ 8 mm); they have periods of 257 s and 281 s respectively. The other frequencies in the light curve have smaller amplitudes. The WET run, combined with subsequent single-site observing at Mt John Observatory in NZ (eg Sullivan et al. 2007) indicated that EC 20058 was a stable low-amplitude pulsator (see Figure 1), and thus was a suitable object for endeavouring to measure an evolutionary period change using photometry obtained over a number of seasons. We report briefly here on the motivation for this work and the current state of the play.

2. Period stabilities of the pulsating white dwarfs
Two classes of pulsating white dwarfs (DAV and DBV) and one class of pulsating pre-white white dwarf (DOV) have been identified. For brevity we will simply refer to all three classes as pulsating
white dwarfs (WDs). The very hot object PG 1159−035 \((T_{\text{eff}} \sim 140\, \text{kK})\) is the prototype for the DOV class, and it has been extensively studied (eg Costa et al. 2008) since its discovery. The prototypes for the other two types are GD 358 \((T_{\text{eff}} \sim 25\, \text{kK})\) for the DBV class and ZZ Ceti \((T_{\text{eff}} \sim 12\, \text{kK})\) for the DAV class. For all three classes, the onset of pulsation is believed to arise as a result of evolutionary cooling of the respective stellar structures through temperature-dependent cooling strips which leads to partial ionization zones for the most abundant surface elements (Winget & Kepler 2008).

For the DAVs, partial ionization in the H surface layer drives the pulsation, while it is partial ionisation of He ions in the surface layers that is responsible in the DBVs. For the pre-white dwarf H-deficient DOVs, the situation is less certain and more complicated, but it is appears clear that the main drivers of pulsation are the C and O partial ionization zones in the surface layers (Winget & Kepler 2008). This explains the significant difference in temperature between the respective instability strips.

Due to the compact mechanical structure of white dwarfs, the pulsation modes are expected to

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**Figure 1.** A selection of discrete Fourier transforms and the DFT windows for some of the EC20058 time-series photometry, covering the period from the 1997 Whole Earth Telescope run to July 2007. The vertical axes use units of millimodulation amplitude (mma) whereby 10 mma corresponds to a 1% modulation and the horizontal axes employ \(\mu\text{Hz}\). The period structure for this pulsator has proven to be quite stable, although there is some variation in the actual pulsation amplitudes from season to season. Although the existence of some combination frequencies suggests some nonlinearity in the generation of the light curve modulations it is obviously quite small; this is consistent with the folded light curves in Figure 3.
be very stable in period, and this is particularly true for the largely degenerate lower temperature DBV and DAV objects. The available observational material supports this prediction. However, extremely small period change rates ($\dot{P} = dP/dt$) are expected from cooling of the stellar material (a period increase or positive $\dot{P}$) and from contraction of the stellar structure (a period decrease of negative $\dot{P}$). The results from model calculations can be represented in the form (Winget, Hansen & Van Horn 1983)

$$\frac{\dot{P}}{P} = -a \frac{\dot{T}}{T} + b \frac{\dot{R}}{R}$$

where the $a$ and $b$ are positive constants of the order of unity. Order of magnitude estimates for $\dot{P}$ for the three classes of pulsating white dwarfs are given in Table 1.

| Type | $\dot{P}$ Comment |
|------|--------------------|
| DOV  | $+10^{-11}$ $\text{ss}^{-1}$ If $\dot{T}$ dominates, but $\dot{R}$ important |
| DBV  | $+10^{-13}$ $\text{ss}^{-1}$ $\dot{R}$ unimportant |
| DAV  | $+10^{-15}$ $\text{ss}^{-1}$ $\dot{R}$ unimportant |

Note that there are two orders of magnitude difference between the predicted $\dot{P}$s for the three classes of pulsator, and the very hot DOVs are expected to exhibit the largest change. Also note that for these latter objects both cooling and contraction should make significant contributions, but for both the DBVs and DAVs the near complete degeneracy of the core electrons providing mechanical support means that any radius change for the white dwarf is negligible for our purposes.

3. Observed white dwarf period stabilities

Table 2 summarises the relevant data for measured $\dot{P}$ values. As one might expect, the rapidly cooling DOV object, PG 1159, provided the first measurement. By analysing two-site time-series photometry obtained on PG 1159 in the early 1980s, Winget et al. (1985) actually ‘detected’ a period decrease for the 516s dominant pulsation mode of the order of $10^{-11}$ $\text{ss}^{-1}$, which conflicted with the predicted period increase of the same order. Furthermore, using additional photometry over an extended time base including Whole Earth Telescope (WET) multi-site data, Winget et al. (1991) ‘confirmed’ this decrease and provided a more precise estimate of $-2.49 \pm 0.06 \times 10^{-11}$ $\text{ss}^{-1}$ for the $\dot{P}$ of the 516s mode.

Although atmospheric contraction is important for the DOVs, the models predict that the effects of cooling (largely due to energy loss from core neutrino emission) should have a larger impact on the pulsation periods; hence this should lead to an observable period increase. Attempts to explain the surprising measured period decrease centred around the idea of mode trapping (Kawaler & Bradley 1994), in which the properties of particular pulsation modes are affected by resonances in the assumed stratified chemical layers of the star. The idea is that for some modes this allows the relatively less degenerate envelope, which is undergoing some contraction, to dictate the period change and hence the negative impact of a shrinking radius on the $\dot{P}$ can exceed the positive impact of a temperature reduction.

However, subsequently, armed with more data in the form of several multi-site WET data sets, Costa et al. (1999) convincingly demonstrated that the 516s mode in PG 1159 was actually
Table 2. A summary of relevant measured $\dot{P}$ values for pulsating white dwarf stars. The methods used are discussed in the text and are the phase cycle count procedure (O–C), a direct comparison of seasonal period measurements and a combination of both these methods. The blank row in the PG 1159 category indicates there a number of other periods that have measured $\dot{P}$ values for this star.

| Object   | Type | Mode   | $\dot{P}$ (s s$^{-1}$) | Method | Reference          |
|----------|------|--------|------------------------|--------|-------------------|
| PG 1159  | DOV  | 516 s  | $-1.21 \pm 0.06 \times 10^{-11}$ | O–C    | Winget et al. (1985) |
|          |      | 516 s  | $-2.49 \pm 0.06 \times 10^{-11}$ | O–C    | Winget et al. (1991) |
|          |      | 516 s  | $+13.0 \pm 2.6 \times 10^{-11}$ | direct | Costa et al. (1999) |
|          |      | 516 s  | $+13.07 \pm 0.03 \times 10^{-11}$ | O–C    | Costa et al. (1999) |
|          |      | 539 s  | $-0.82 \pm 0.04 \times 10^{-11}$ | O–C    | Costa et al. (1995) |
|          |      | 516 s  | $+13.146 \pm 0.003 \times 10^{-11}$ | combn  | Costa & Kepler (2008) |
|          |      | 539 s  | $-0.34 \pm 0.02 \times 10^{-11}$ | combn  | Costa & Kepler (2008) |
|          |      | ...    | ...                    | ...    | ...               |
| GD 358   | DBV  | ...    | (unstable modes)       | ...    | Kepler et al. (2003) |
| EC 20058 | DBV  | 257 s  | (promising)            | O–C    | Sullivan et al. (2008) |
|          |      | 281 s  | (promising)            | O–C    | Sullivan et al. (2008) |
| G 117–B15A | DAV | 215 s  | $+3.6 \pm 0.8 \times 10^{-15}$ | O–C    | Kepler et al. (2005) |
| ZZ Ceti  | DAV  | 213 s  | $\leq 5.5 \pm 1.9 \times 10^{-15}$ | O–C    | Mukadam et al. (2003) |
| L 19–2   | DAV  | 192 s  | $\leq 3.0 \times 10^{-14}$ | O–C    | O’Donoghue ... (1987) |

undergoing a period increase in agreement with model predictions. The superior quality of the WET data sets and the relatively large period change rate in PG 1159 allowed them to directly detect a $\dot{P}$ of $+13 \pm 3 \times 10^{-11}$ s s$^{-1}$ for the 516 s mode by calculating the best periods for four seasonal data sets over an interval of 10 years; they then improved the precision for this correct value to yield $\dot{P} = +13.07 \pm 0.03 \times 10^{-11}$ by employing the O–C method. But there still remained some mystery as this new measured value was an order of magnitude larger than the values inferred from realistic models.

It is something of a cautionary tale to understand the key factors in this change of sign for the measured $\dot{P}$ value of the 519 s mode in PG 1159. Unquestionably, these are difficult measurements. The earlier measurements of Winget et al. employed the sensitive O–C method, in which the phases of the selected frequency in each photometric data set are established by least squares fitting and then an accurate period is used to construct an ‘observed-minus-calculated’ time of maxima for each data set as a function of the number of elapsed periods or cycles. If this plot is linear then a correction to the starting period can be obtained, but if there is some curvature then this indicates a non zero $\dot{P}$ value. The problem with this method is that any cycle-count errors due to missing data between the photometry sets (and a possible large number of elapsed cycles) leads to erroneous conclusions.

Even though PG 1159 is a relatively stable pulsator, it is also a rich multi-periodic pulsator with many different frequencies present in the light curve – nearly 200 at the last count (Costa et al. 2008). Underestimating the uncertainties in establishing the times of maxima (ie the phases) for the different data sets appears to underly the identification of an erroneous $\dot{P}$ in the earlier work. The most recent work on this pulsator (Costa & Kepler 2008) has yielded $\dot{P}$ values for no less than 27 of the periods and with 11 of them having period decreases. It is clear that this object is rather complex, and mode trapping is definitely required to understand the variation
in the sign of the $\dot{P}$ values among the modes. The order of magnitude discrepancies between the measured $\dot{P}$s and predicted ones also need to be explained. At face value, one would expect the DBVs to be the next class of pulsating white dwarf to yield a $\dot{P}$ measurement. The class prototype, GD 358, is the brightest one of these objects and has been studied extensively, including via several WET runs. However it is a large amplitude and relatively unstable pulsator (Kepler et al. 2003), which is consistent with it being near the red edge of the DBV instability strip: it has proven to be an unsuitable candidate for evolutionary $\dot{P}$ measurements. On the other hand, EC 20058 is a small amplitude stable pulsator (and it currently defines the blue edge of the instability strip); it looks to be a much better prospect for an evolutionary measurement, as discussed in the last section.

The DAV objects have to date provided one $\dot{P}$ measurement that is in agreement with model predictions and one upper limit that is close to these values (see Table 2). Quality time-series photometry over a 30-year baseline for G 117$-$B15A has enabled Kepler et al. (2005) to determine a value of $\dot{P} = +3.6 \pm 0.8 \times 10^{-15}$ for this object, which is a very fine achievement. A less comprehensive data set has been used by Mukadam et al. (2003) to establish the upper limit for the object ZZ Ceti given in Table 2. A less impressive upper limit for the DAV L 19--2 has been determined by O’Donoghue and Warner (1987), but note that this author has archival data that should significantly improve this limit.

For both the DBV and DAV classes the expected $\dot{P}$ values for the periods are too small to usefully employ the direct measurement of seasonal periods to detect a change in their values or even provide a check on other methods. One must rely on the O–C method and be very vigilant for possible cycle count errors. In view of the PG 1159 saga described above, extreme caution is warranted. In some ways, establishing an upper limit that is consistent with model predictions is an easier task, and this has been the case for the DAVs, until the recent positive result for G 117$-$B15A.

4. Neutrino cooling of white dwarfs

Neutrino emission from white dwarfs cores has been included in relevant models since the 1960s following earlier developments in weak interaction physics. Its effect largely drives the thermal behaviour of the hot stages of the white dwarf cooling sequence, including effective temperatures down to the DBV instability strip for white dwarfs with typical masses (Winget et al. 2004).

Although there are a number of possible mechanisms, such as plasmon neutrinos, bremsstrahlung neutrinos and photoneutrinos, the underlying processes have a common feature: they all involve the transformation of a virtual electron-positron pair into a neutrino-antineutrino pair, rather than recombination back into a photon. Since this transformation is mediated by the weak interaction, it is unlikely in the extreme: in round figures, one expects to see one neutrino-antineutrino pair in every $\sim 10^{19}$ events. However, in the regime of interest in the long-lived gravitationally bound hot dense plasmas at the core of a white dwarf, this process is nevertheless predicted to be significant and lead to a one-way leakage of energy from the white dwarf that adds to the emission of photons from the atmosphere.

The key steps are as follows. Electron-positron pairs are produced from the thermally generated photons. But these must be virtual particles as there is insufficient energy in the $\sim$ keV photons (even in the high-energy thermal tail) to provide the 1.02 MeV rest mass energy of the pair. Overwhelmingly, these pairs annihilate back into a photon within the constraints of the energy-time uncertainty principle; but ‘every now and then’ either an exchange of a charged W± vector boson or the creation of a neutral $Z^0$ leads to a transformation into a real neutrino-antineutrino pair (eg Misiaszek et al. 2006). Feynman diagrams depicting the relevant processes are provided in Figure 2.

Since the rest mass-energy of the final state neutrinos is significantly less than the typical photon energy (not long ago it was thought to be zero), satisfying energy conservation is not a
problem. However, overall momentum conservation must also be satisfied and interaction with another external body is required: in the plasmon process, coupling to the collective motions of the plasma performs this task. And it is the plasmon process that dominates neutrino production in white dwarf cores (Kantor & Gusakov 2007, Itoh et al. 1996).

5. The potential for EC 20058

As mentioned previously, EC 20058 has proven to be a very stable low amplitude pulsator. The two dominant modes (257 s and 281 s) look to be the best candidates for measuring $\dot{P}$ values, and their frequencies are resolved in several hours of quality time-series photometry. However, the 281 s periodicity has two adjacent satellite frequencies separated from the main peak by 70 $\mu$Hz and 81 $\mu$Hz respectively (Sullivan et al. 2008), so longer runs are required to properly isolate this frequency. Hence the 257 s mode offers the best possibilities.

In addition to single-site data obtained from Mt John in NZ over a number of seasons, the Clay 6.5 m Magellan telescope has been used (Sullivan et al. 2007) to obtain both time-series photometry (July 2003) and time-series spectroscopy (July 2004). A DFT for the Magellan photometry is given in Figure 1.

Figure 3 demonstrates in an alternative way to the DFT plots that EC 20058 exhibits little sign of nonlinearities in the light curve variations. Both the 2003 Magellan photometry and July 2004 Mt John photometry have been folded at the two periods corresponding to the dominant modes in order to obtain pulse shapes for these frequencies. A sine function has then been least squares fitted to each data set. It is clear that there is no evidence of a significant departure from a sinusoidal pulse shape in all four cases, in agreement with the absence (except for some small peaks) of harmonic content in the WET data set (Sullivan et al. 2008).

Model fitting of the 2004 integrated Magellan spectra by Detlev Koester yielded an effective surface temperature for EC 20058 nearly as high as 31 kK with no assumed H component in the atmosphere, and a value of $\sim$ 29 kK if the atmosphere contains a small (undetectable) H component (Sullivan et al. 2007). Hence, this object is quite a hot DBV.

We also have a firm idea of the mass of this star. Both the log $g$ values obtained from the spectral fitting and the asteroseismic analysis presented in Sullivan et al. (2008) are consistent with a mass for EC 20058 of about 0.55 M$_{\odot}$. So, the combination of a high effective temperature and a typical white dwarf mass means that the evolutionary period change in this pulsator should
be driven primarily by the core neutrino flux, as this energy loss mechanism is expected to exceed that due to the surface photon flux by a factor of two or so. Given the lack of complications arising from model-dependent contraction rates with this object, a measurement of $\dot{P}$ can be used to not only directly check the predicted neutrino emission rates, but also verify the actual existence of these weak interaction processes in the untested low-energy regime (Winget et al. 2004).

It is true that a positive $\dot{P}$ was eventually detected for the dominant 516 s mode in the DOV PG 1159, and that neutrino cooling undoubtedly plays a significant role here. However, modelling uncertainties, including the effects of contraction, the measurement of both period increases and decreases for different modes and $\dot{P}$ values an order of magnitude more than ‘best’ model values, make this theory-observation confrontation somewhat complicated and uncertain.

Figure 4 schematically illustrates the extended photometric data sets available for the EC 20058 $\dot{P}$ measurements. Most of the photometry has been obtained from Mt John in NZ, but we also have seasonal data obtained from Chile over the last few years (Provencal 2008). We aim to soon converge on a $\dot{P}$ conclusion, with particular emphasis on the epoch between 2004 and 2008 underwriting the measurement.

It is important to note that due to the expected $\dot{P}$ being $\sim 10^{-13}$ ss$^{-1}$ the direct method of searching for a period change that has been so important in the case of PG 1159 is not useful here, as it is not sensitive enough. For the DOV objects the expected period change of $\sim 10^{-11}$ ss$^{-1}$ translates into a $|\Delta P| \approx 3 \times 10^{-3}$ s or 3 msec in 10 years. Costa et al. (1999), using quality data sets, were actually able to measure for the interval 1983 to 1993, an unambiguous change of $\sim$...
40 msec in the period of the 516 s mode of PG 1159. The theoretical equivalent figure for the DBV EC 20058 over a 10-year interval is $|\Delta P| \sim 3 \times 10^{-5}$ s. Given the quality of the available data sets and the real uncertainties in the seasonal period determinations, there is no hope of measuring such a change directly.

We will need to identify a correct value for $\dot{P}$ on the basis of the O–C method alone. An important part of this process is establishing realistic uncertainties for the phase fitting. We are employing procedures similar to the Monte Carlo methods described by Costa et al. (1999) and Costa and Kepler (2000) to achieve this.

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