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Watching ZZ Ceti evolve

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Abstract. We report preliminary results from our analysis of the stability of periods observed in the pulsating hydrogen atmosphere white dwarf ZZ Ceti (R548) based on observations that span 37 years from 1970 to 2007. We determine the rate of change of period with time to be $dP/dt = (0.8 \pm 1.9) \times 10^{-15}$ s/s using the O-C method and $dP/dt = (4.3 \pm 1.2) \times 10^{-15}$ s/s using the direct non-linear least squares fit NLSPDOT for the dominant period 213.13260643 s after correcting for proper motion. We do not claim either of these values as a measurement at this time, but hope to arrive at a conclusive result in the near future with more observations. The reduced uncertainty for both methods shows the improvement we obtained over the previous evolutionary constraint on ZZ Ceti (Mukadam et al. 2003). These dP/dt values are consistent within uncertainties with the measurement of $dP/dt = (3.57 \pm 0.82) \times 10^{-15}$ s/s for the period 215.2 s observed in another pulsating white dwarf G117-B15A (Kepler et al. 2005). Using the 213 s triplet spacing of 4 μ Hz, we compute the rotation period of ZZ Ceti to be 1.5 days.

1. Introduction

Non-interacting or single hydrogen atmosphere (DA) white dwarfs pulsate in a narrow instability strip located within the temperature range 10800–12300 K for $\log g \approx 8$. These DA variables (DAVs) are also called the ZZ Ceti stars, with pulsation periods in the range 70–1400 s, consistent with nonradial g-mode pulsations. Even though HL Tau 76 was the first pulsating white dwarf to be discovered, ZZ Ceti (R 548) is the prototype of the class because it was the first pulsator to be resolved. We show in subsequent sections that we have truly been able to resolve the pulsation spectrum of ZZ Ceti only now.

2. Why measure the evolutionary drift rates of the periods observed in ZZ Ceti?

Evolutionary cooling of the ZZ Ceti stars dictates the rise in their periods as a result of the increasing degeneracy (Winget, Hansen & van Horn 1983; Kepler et al. 2000). Our motivation in measuring the rate of change of period with time for ZZ Ceti (R548) is to ultimately measure

the cooling rate of the star. Measuring the cooling rates of white dwarfs proves helpful in calibrating the white dwarf cooling curve, reducing some of the theoretical uncertainty in white dwarf cosmochronometry (e.g. Winget et al. 1987; Hansen et al. 2002). We can also use the cooling rates of these stars to study exotic particles such as axions (Isern, Hernanz, & Garcia-Berro 1992; Bischoff-Kim et al. 2008).

3. Constructing an O-C diagram of ZZ Ceti with a doublet fit to the 213 s mode

The O-C technique can be used to improve the period estimates for any periodic phenomenon. The O stands for the observed value of the time of maximum (or time of zero) for a cycle or an epoch E that occurs in a data set. The C stands for its calculated value or ephemeris assuming an ideal stable clock. A non-linear trend in the O-C diagram shows that our measure of the period is changing. We set out to measure the rate of change of period with time (dP/dt) using the O-C technique for the dominant mode at 213 s, which we had so far believed to be a doublet. We found $dP/dt = (3.1 \pm 2.5) \times 10^{-15}$ s/s for the 213.13260643 s period based on 37 years of data from 1970 to 2007. We also determined $dP/dt = (2.6 \pm 2.8) \times 10^{-15}$ s/s for the 212.76842927 s period. We show the resultant O-C diagrams in Figure 1.

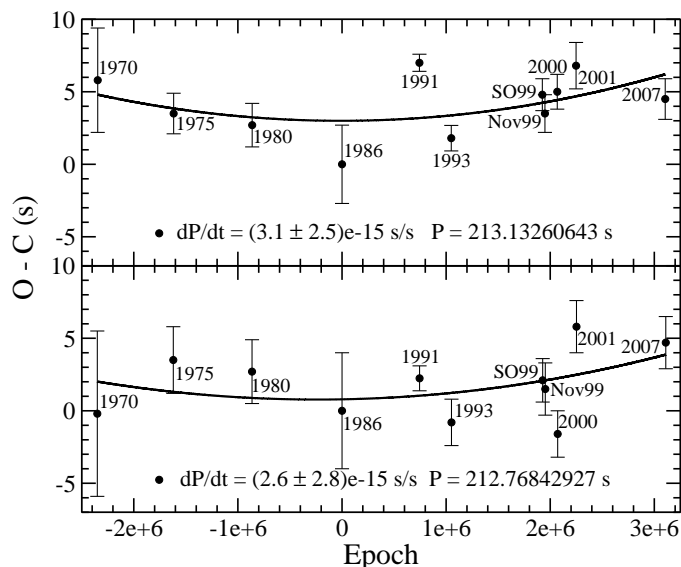


Figure 1. We show the O-C diagram for ZZ Ceti fitting a doublet to the 213 s mode

4. New observations with the highest signal-to-noise ratio for ZZ Ceti data

We acquired time-series photometry on ZZ Ceti from the 26th of August until the 7th of September 2007 using the prime focus CCD photometer Argos (Nather & Mukadam 2004) at the 2.1 m telescope at McDonald Observatory. These data constitute the highest signal-to-noise season of observations on ZZ Ceti which has mostly been observed using 1 m class telescopes and instruments based on photo-multiplier tubes with 35% intrinsic quantum efficiency. These high signal-to-noise data have allowed us to discover without ambiguity that the 213 s and 274 s modes are both triplets. Although we had checked for the existence of triplets previously, we could not conclusively prove their existence until now. We expect that both the 213 s and 274 s triplets are rotationally split $\ell=1$ modes. We measure the 213 s triplet spacing to be about $4 \mu\text{Hz}$ (see Figure 2), and compute the rotation period of ZZ Ceti to be 1.5 days.

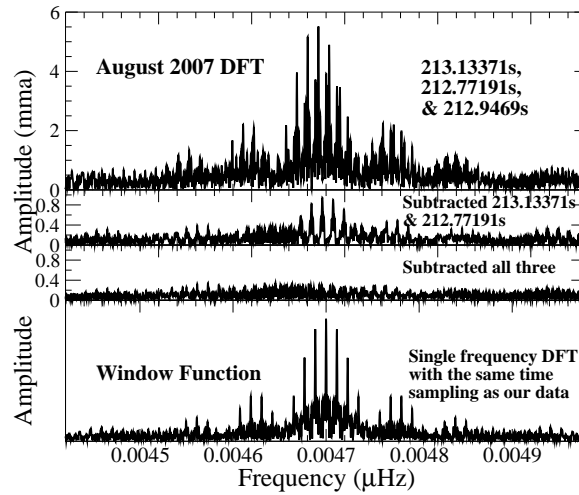


Figure 2. Our highest signal-to-noise data on ZZ Ceti from 2007 demonstrates that the 213 s mode is a triplet.

We revised the O-C diagram with new phases obtained by simultaneously fitting all frequencies of the 213 s triplet (see Table 2). The reduction in uncertainties obtained for the new dP/dt values shows the improvement obtained with a triplet fit (see Figure 3).

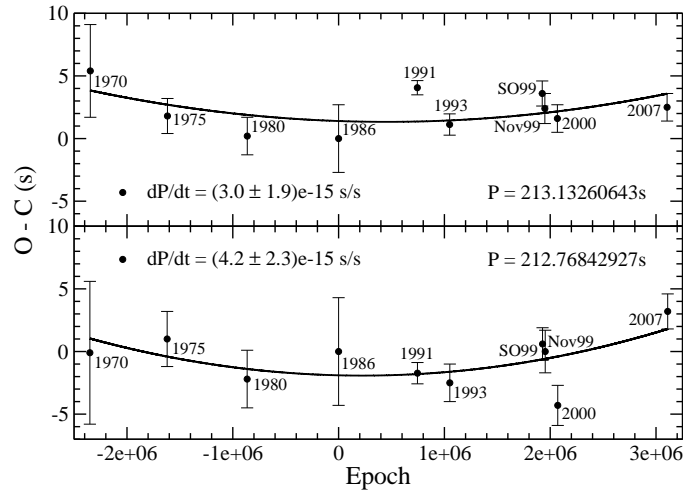


Figure 3. We show the O-C diagram for ZZ Ceti fitting a triplet to the 213 s mode

Table 1. Best Fit dP/dt values obtained

Period (s)	dP/dt from O-C Method (s/s)	dP/dt from NLSPDOT (s/s)
$213.13260643 \pm 0.00000034$	$(0.8 \pm 1.9) \times 10^{-15}$	$(4.3 \pm 1.2) \times 10^{-15}$
$212.76842927 \pm 0.00000040$	$(2.0 \pm 2.3) \times 10^{-15}$	$(3.3 \pm 1.9) \times 10^{-15}$

Table 2. O-C Tables for $P = 213.13260643$ s (left) and $P = 212.76842927$ s (right)

Epoch	O-C (s)	Epoch	O-C (s)
-2346428	5.4 ± 3.7	-2350444	-0.1 ± 5.7
-1617531	1.8 ± 1.4	-1620300	1.0 ± 2.2
-862740	0.2 ± 1.5	-864217	-2.2 ± 2.3
0	0 ± 2.7	0	0 ± 4.3
743875	$4.06 \pm .57$	745148	-1.73 ± 0.85
1049404	$1.12 \pm .85$	1051200	-2.5 ± 1.5
1924342	3.6 ± 1.0	1927636	0.6 ± 1.3
1949381	2.4 ± 1.2	1952718	0 ± 1.7
2067847	1.6 ± 1.1	2071386	-4.3 ± 1.6
3104809	2.5 ± 1.1	3110124	3.2 ± 1.4

5. Theoretical prediction of dP/dt based on the best-fit seismological model

We performed asteroseismological fits using the five periods observed in ZZ Ceti at 213 s, 274 s, 333 s, 318 s, and 187 s. We allowed the effective temperature to be within the range of 11700–12200 K, and fixed the helium layer mass to be $\text{Log } M_{\text{He}} = -2.0$. We constrained the stellar mass to be within the range $0.55\text{--}0.58 M_{\odot}$, and the hydrogen layer mass to be $\text{Log } M_{\text{H}} = -5.0$.

We used models with ramp core profiles (see Bischoff-Kim et al. 2008), varying two core parameters: the edge of the homogeneous core where the oxygen abundance begins to drop off and secondly the central oxygen abundance. The latter is strongly constrained to 60–80% in the best fit model, and correlated with the location of the edge of the homogeneous core. Our best core parameter fits with uncertainties less than 1 s consist of a central oxygen abundance of 60–80%. Our best prediction of the rate of period change with time is $dP/dt = (8.3 \pm 0.046) \times 10^{-15}$ s/s assuming the 213 s mode is $\ell=1$.

The observational results from both the O-C method and the nonlinear least squares fit NLSPDOT are not consistent with the model fit dP/dt value. Invoking weakly interacting particles like axions will only increase the discrepancy between model and observations. While our models are presently unable to reproduce the observed dP/dt value for ZZ Ceti, the empirical value should serve to constrain model white dwarfs in the end.

Acknowledgments

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