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Driving in ZZ Ceti stars - Problem solved?

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Abstract. There is a fairly tight correlation between the pulsation periods and effective temperatures of ZZ Ceti stars (cooler stars have longer periods). This seems to fit the theoretical picture, where driving occurs in the partial ionization zone, which lies deeper and deeper within the star as it cools. It is reasonable to assume that the pulsation periods should be related to the thermal timescale in the region where driving occurs. As that region sinks further down below the surface, that thermal timescale increases. Assuming this connection, the pulsation periods could provide an additional way to determine effective temperatures, independent of spectroscopy. We explore this idea and find that in practice, things are not so simple.

1. Introduction

ZZ Ceti stars, also called DAVs, are the coolest known pulsating white dwarfs (see figure 1). They show only hydrogen in their spectra and are observed to pulsate in a narrow instability strip around 12000K. The number of known ZZ Ceti stars recently doubled (Mukadam 2004), and more have been found since (Mullally et al. 2005; Kepler et al. 2005; Castanheira et al. 2006; Castanheira 2006). With such a significant number of stars known, it was promising to study their ensemble characteristics in more depth (Mukadam 2004; Mukadam et al. 2005).

Even before the new ZZ Ceti's were discovered, a clear relation between their mean pulsating periods and spectroscopically determined effective temperatures was already apparent (Clemens 1993; Kanaan 1996). Cooler ZZ Ceti's show longer periods (see figure 3). Well aware of the dificulties associated with the spectroscopy of such stars, Mukadam et al. (2005) suggested that we could use this relation to obtain an independent measurement of temperatures for those stars.

We compared relevant thermal timescales of models with different effective temperatures. We looked in particular at driving through the κ-γ mechanism (Cox & Giuli 1968) and convective driving (Brickhill 1991; Goldreich & Wu 1999). We expected that if we picked the right convective efficiency, the mean periods would agree with the thermal timescales (to within a multiplicative constant). We would then use the effective temperatures of the models as a temperature scale.

Besides helping the ongoing effort to better define the ZZ Ceti instability strip, we then planned to apply the same method to the less numerous DBV stars (Helium atmospheres). Spectroscopic determinations of effective temperatures for those stars are difficult to do and uncertainties are large. We need more accurate temperature determinations for DBV stars because they can be used to learn about plasmon neutrinos, and the results are most sensitive to temperatures (Winget et al. 2004; Kim et al. 2005; Kim et al. 2006)

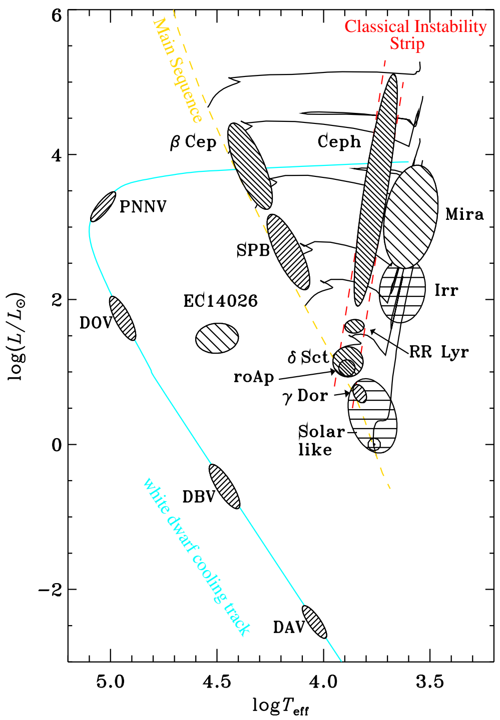

Fig. 1. H-R diagram showing the different classes of pulsating stars. In this article, we are interested in the DAV's.

2. Pulsation driving and timescales

Pulsations in ZZ Ceti stars are driven in the partial hydrogen ionization zone. We looked at two processes, each of which are associated with a thermal timescale. The first process is the κ-γ mechanism, and the relevant timescale in this case is the thermal timescale at the base of the partial ionization zone (R_b). Like Winget et al. (1982), we assume that only modes that have periods of the same order as the thermal timescale are driven. This thermal timescale is the time it takes to transport energy from R_b to the surface of the star. It is equal to the heat content of the layers above R_b divided by the total luminosity:

$$\tau_{th} \sim \frac{\Delta M_r c_V T}{L_{tot}} \tag{1}$$

The second process is convective driving. Convective driving was proposed to attempt to resolve a discrepancy between the periods of the overstable modes and the above timescale. Noting that the convective turnover time was much shorter than the periods of the modes, Brickhill (1991) assumed that convection responded instantanously to the pulsations. Goldreich and Wu (1999) later revisited his theory of convective driving and arrived at a new thermal timescale, which is the time during which the convection zone can bottle up the flow that enters from below. This new timescale τ_c differs from the traditional thermal timescale by a multiplicative constant roughly equal to 4.

So we have two timescales for which we know the dependence on the local temperature. To compare with the observed periods, we need them in terms of effective temperature. Numerical calculations (Montgomery 2005) show that τ_c, and therefore also τ_{th} are proportional to the effective temperature to a power roughly equal to -90 (for DAVs). This result is insensitive to the convective efficiency. Therefore in a $\log P - \log T_{\rm eff}$ plane, we would expect the data to lie on a line with a slope of -90, no matter which of the two theories is the correct theory for driving in ZZ Ceti stars, and independently of the right convective efficiency.

3. Results

Figure 2 shows the data on a $\log P - \log T_{\rm eff}$ plane along with curves that show $\tau_c(T_{\rm eff})$ for different convective efficiencies. We see that indeed, the thermal timescale curves are parallel to each other, and we also see that they have a different slope than the data.

Figure 3 shows a subset of the data with error bars. We have retained stars in a narrower $\log g$ range (8.0 to 8.2) in a rudimentary attempt to remove the $\log g$ dependence of the

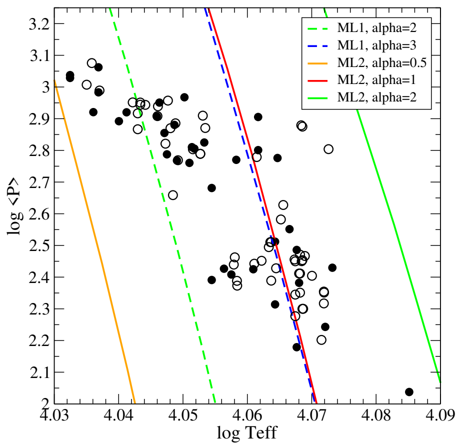

Fig. 2. The ZZ Ceti stars discovered before Mukadam et al. 2004 (filled circles), and the ones found by Mukadam et al. from SDSS data (open circles), along with τ_c for different convective efficiencies. In the legend, we designate Böhm-Vitense's treatment of convection (Böhm-Vitense 1958) by ML1, and the more efficient Böhm & Cassinelli convection (Böhm & Cassinelli 1971) by ML2. α is the ratio of the mixing length to the pressure scale height. There is a systematic offset of $\sim 300K$ between the two samples, probably caused by systematic differences between Bergeron's models atmospheres and Koester's, for which we artificially corrected by substracting 294 K from the "old" sample. The choice is somewhat arbitrary since we are only concerned with relative temperatures at this point. The three open circles at high effective temperature and high $< P >$ that seem to deviate from the correlation also happen to have high gravities. This is consistent with theory, which predicts that τ_c is significantly higher for high gravities (about an order of magnitude for $\Delta\log(g) = 0.6$)

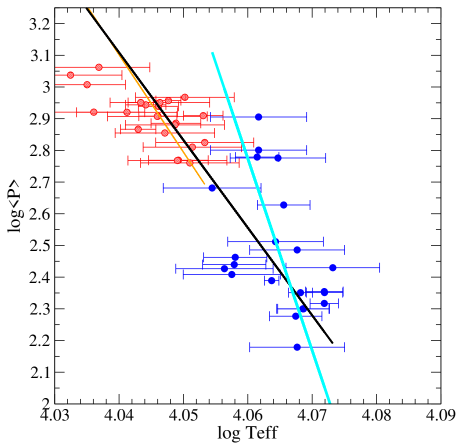

Fig. 3. A subset of the ZZ Ceti stars (those with $\log g$ between 8.0 and 8.2) and different fits. The black line is a fit to the whole subset (slope = -28), the thin grey (orange) line is a fit to the cool end stars (slope = -31), and the thick grey (light blue) line is a fit to the hot end stars (slope = -61). The boundary between the cool (cDAVs) and hot stars (hDAVs) is 11320 K.

timescales. We fit one line to the cool DAVs, one to the hot DAVs, and a third to the full effective temperature range. The boundary is at 11320K. The slopes of the three lines are, respectively, -31, -61, and -28. Uncertainties are large and those results are not entirely incompatible with the expected slope of -90. The difference in slope between the red-edge pulsators and the blue-edge pulsators is not statistically significant (again because of the uncertainties) but theoretically the blue-edge pulsators don't show significant convection zone.

We do note, however, that departures from the models become important for cooler stars. It looks like a saturation mechanism is at work, which prevents modes much higher than 1000s from being driven, though that is not the only explanation.

4. Some ideas

In our analysis, we have made a few assumptions. First we assumed that the convective efficiency remains the same as the stars cools. Maybe convection becomes less effective with decreasing effective temperature, which would explain the observed shorter timescales.

While this may seem to go against common wisdom, there are a few physical processes which could work against convection for cooler stars. Magnetic fields may become more important as the star cools and the depth of the convection zone increases. One could easily imagine the magnetic field lines constraining the motion of the plasma and inhibiting the convection, leading to a lower convective efficiency.

Most red edge ZZ Ceti stars show large amplitude pulsations. The linear approximations break down, and one could easily imagine that such high amplitude pulsations could have an effect on the convective efficiency. At the red edge, the pulsation amplitudes can be as high as 20% at the surface (Kleinman 1995). At those amplitudes, the energy carried by the pulsations is non-negligible, which would lead to a less efficient convection. This of course fails to explain why the red edge ZZ Ceti's that are not high amplitude pulsators deviate from the theoretical thermal timescales in the same way the others do.

Maybe it is our assumption that the weighted mean period (i.e. the period(s) of the dominant mode(s)) is $\sim \tau_c$ that is flawed. Again, this may not work so well where non-linearities are important. At lower effective temperature, the convection zone grows deeper, and when deep enough, maybe its motion affects the timescales.

The most obvious explanation, and maybe the best one we have is that modes with periods higher than about 1200 seconds are suppressed through a different mechanism. Lack of surface reflection comes to mind (Hansen et al. 1985). Modes with long wavelengths (long periods) are not reflected very efficiently in the outer layers of the stars where the density falls off exponentially, and lose their energy. This places an upper limit on the periods of the driven modes. Hansen et al. (1985) did a simple non-adiabatic calculation and found that modes with periods greater than 3000s could not sustain themselves in ZZ Cetis, although it is possible that The actual limit may be more like 1200s.

5. Conclusion

We set out to develop an independent method to determine temperatures for ZZ Ceti stars, with the intention to apply the same method later to DBV stars. We based our analysis on the assumtpion that the period(s) of the dominant mode(s) should be at least proportional to timescales corresponding to several theories of driving in ZZ Ceti stars. In actually doing the calculations, we found that this was not the case. While the theory predicts that in the $\log < P > - \log T_{\rm eff}$ plane, the data should lie on a line with slope ~ -90. We find the actual slope to be less steep. We give a few ideas to explain the discrepancy, but this remains somewhat of a mystery, which would be very interesting to elucidate in order to not only obtain better effective temperatures, but also to improve our understanding of driving in ZZ Ceti stars.

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