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Rate of change of the pulsation periods in the PG 1159 star PG 0122+200

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Abstract. The pre-white dwarf pulsators of PG 1159 type, or GW Virginis variable stars, are in a phase of rapid evolution towards the white dwarf cooling sequence. The rate of change of their nonradial g-mode frequencies can be measured on a reasonably short time scale. From a theoretical point of view, it was expected that one could derive the rate of cooling of the stellar core from such measurements. At the cool end of the GW Virginis instability strip, it is predicted that the neutrinos flux dominates the cooling. PG 0122+200 which defines the red edge of the instability strip is in principle a good candidate to check this prediction. It has been followed-up through multisite photometric campaigns for about fifteen years. We report here the first determination of the rate of change of its 7 largest amplitude frequencies. We find that the amplitudes of the frequency variations are one to two orders of magnitude larger than predicted by theoretical models based on the assumption that these variations are uniquely caused by cooling. The time scales of the variations are much shorter than the ones expected from a neutrino dominated core cooling. These results point to the existence of other mechanisms responsible for the frequency variability. We discuss the role of nonlinearities as one possible mechanism.

Keywords. neutrinos, stars:evolution, stars: individual (PG 0122+200), stars: oscillations, stars: white dwarfs

1. Introduction

The PG 1159 stars form an evolutionary link between the central stars of planetary nebulae and the white dwarf cooling sequence. A fraction of the PG 1159 stars does pulsate and constitutes the subgroup of the GW Vir type of variable stars. The asteroseismology of these variable stars provides invaluable insight on their internal structure and evolutionary status. Among the four known GW Vir stars, which have all been studied with the Whole Earth Telescope network (WET; Nather *et al.* 1990), PG 0122+200 is the coolest one. Its atmospheric parameters $T_{eff} = 80\,000$ K $\pm$ 4000 K, log g $= 7.5 \pm 0.5$, and abundances (C/He = 0.3, C/O = 3, N/He = 10^{-2} by numbers) are typical of the GW Vir stars (Dreizler & Heber 1998). At this effective temperature, PG 0122+200 presently defines the red edge of the GW Vir instability strip. O'Brien *et al.* (1998, 2000) have shown that at this phase of the pre-white dwarf evolution, the neutrino losses become

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important in the cooling process. For a 0.60 $M_\odot$ PG 1159 star at the effective temperature of PG 0122+200, they estimate that the ratio of the neutrino luminosity over the photon luminosity could be $1 \leqslant L_\nu/L_\gamma \leqslant 2$. This makes PG 0122+200 of particular interest to study neutrino physics if one could measure its cooling rate from asteroseismology.

The predicted neutrino luminosity depends on the stellar parameters, mainly the total mass and the effective temperature, which can be determined precisely in principle from asteroseismology. Determining the stellar parameters of a non-radial g-mode pulsator relies on the capacity to determine the period spacing between a large enough number of pulsation modes and to correctly identify their degree ℓ. In the best case, a detailed comparaison with realistic models provides an even more precise estimate of the stellar parameters. After the discovery of its pulsations (Bond & Grauer 1987), PG 0122+200 was observed in 1986 (O'Brien *et al.* 1996), and then through a number of multisite campaigns in 1990 (Vauclair *et al.* 1995), in 1996 when it was the priority target of a WET campaign (O'Brien *et al.* 1998), in 2001 and 2002 (Fu *et al.* 2007) and more recently in 2005. From the cumulative pulsation periods observed during these campaigns, it was possible to identify 23 periods as $\ell = 1$ modes, composed of 7 triplets and 2 single modes, and to derive a precise value of the average period spacing, $\Delta P = 22.9$ s (Fu *et al.* 2007). These results were used by Córsico *et al.* (2007) to derive precise constraints on the PG 0122+200 parameters, the most important ones for estimating the neutrino luminosity being the total mass ($M_* = 0.556$ (+0.009, −0.014) $M_\odot$) and the effective temperature ($T_{\rm eff} = 81540$ (+800, −1400) K) or alternatively the luminosity ($\log(L_*/L_\odot) =$ 1.14 (+0.02, −0.04)).

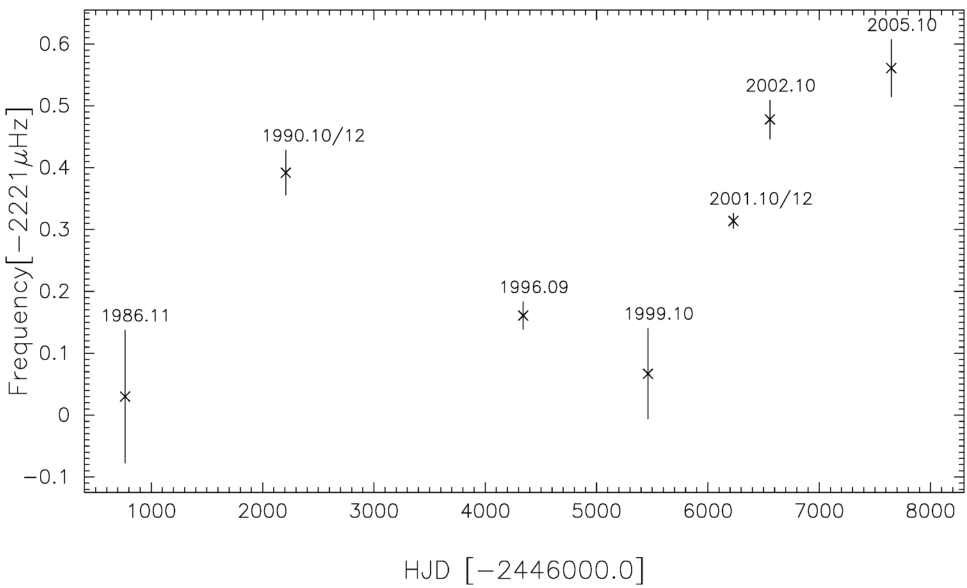

Figure 1. Evolution of the 2221 μHz frequency with time in PG 0122+200. The residual frequency, after subtraction of 2221 μHz is plotted as a function of time, expressed in Heliocentric Julian Days referred to a zero point at HJD = 2446000.0. Each frequency value is marked with the date of the corresponding campaign (year.month) and with the appropriate uncertainty. The value for 1986 is added for completness but this was a single site campaign. All other values correspond to multisite campaigns.

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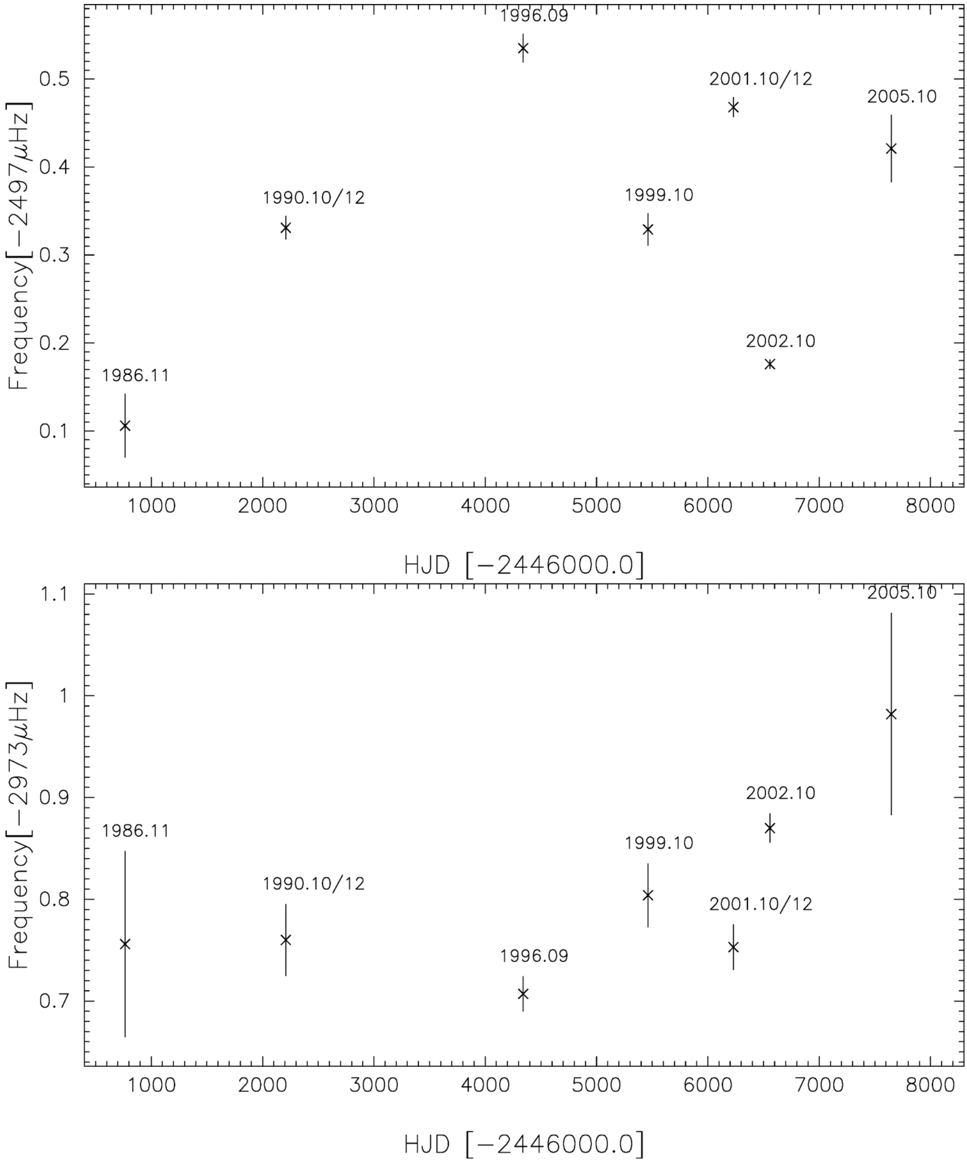

Figure 2. Same as Figure 1 for the three components of the triplet at 2490-2493-2497 μHz.

2. The rate of change of the pulsation periods

2.1. *The predictions of the model*

The evolutionary model by Córsico *et al.* (2007) relies on the neutrino production rate by Ito *et al.* (1989, 1992). According to the predictions of the best model, the rate of change of the pulsation periods ($\dot{P}$ = dP/dt) varies between $1.22{\times}10^{-12} ss^{-1}$ for the $\ell = 1$, k = 12 mode of period 336.68 s and $3.26{\times}10^{-12} ss^{-1}$ for the $\ell = 1$, k = 24 mode of period 611.15 s. These values translate into evolutionary time scales between $1.2{\times}10^{7}$ and $6{\times}10^{6}$ years. On the fifteen years time scale covered by the multisites campaigns reported here, one should not have detected frequency variations of the pulsation modes larger than $-5{\times}10^{-3}\mu\text{Hz} \leqslant \delta\text{f} \leqslant -4{\times}10^{-3}\mu\text{Hz}$ (i.e. $6{\times}10^{-4}$ s $\leqslant \delta\text{P} \leqslant 1.5{\times}10^{-3}$ s in the

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period variations). Such small variations are not reachable within 15 years given the present uncertainties on the frequency determination. We estimate that it would take ≈50 years to get a significant $3\times\sigma$ signature of a frequency change induced by the cooling.

2.2. *The measured frequency variations*

We have reanalysed the data obtained since 1986 and redetermined the frequencies and the amplitudes in a homogenous way using the Period04 software (Lenz & Breger 2005). Since the uncertainties derived by Period04 only estimate the internal consistency of the solution, they are underestimated. We derived more realistic uncertainties through Monte-Carlo simulations. We were able to follow the frequency variations by the direct method for the 7 largest amplitude modes. This includes the three components of the triplets at 2221, 2224, 2228 μHz and at 2490, 2493, 2497 μHz and the prograde component of a third triplet at 2973 μHz. The other modes either do not show up in a large enough number of observations or have too low amplitude for a significant detection of frequency variations. The frequency variation of the retrograde component of the first triplet at 2221 μHz is shown in Fig. 1. The Fig. 2 shows the frequency variation for the three components of the second triplet and Fig. 3 the variation for the prograde component of the third triplet. Among these 5 modes, only the largest amplitude ones, at 2221 μHz, 2497 μHz and 2973 μHz, are present in all the observing campaigns. The other frequencies show similar behaviour. Since the variations are clearly nonlinear with time, the (O-C) method does not apply.

As can be seen on the various figures, the behaviour of the variations varies for different frequencies. The amplitude of the frequency variations are much larger than expected from the model predictions which are based on the assumption that the cooling, possibly dominated by neutrino luminosity, is the unique cause of the frequency changes. We observe frequency variations of the order of a fraction of μHz instead of the predicted 10^{-3} μHz. The frequencies vary on time scales of the order of a few years, considerably shorter than the cooling time scale.

3. Conclusions and interpretation

The multisite campaigns of observations of PG 0122+200 covering a period of 15 years (extending to 19 years if one includes a first single site campaign) show that the frequencies vary with time. The amplitude of the variations are one to two orders of magnitude larger than the ones derived from the best fit model of Córsico *et al.* (2007) and they do not follow a simple function of time. Their typical time scales are much shorter than the expected cooling time, for any reasonable assumption on the rate of neutrino production. Similar results have been observed in the prototype of the GW Vir pulsators PG 1159-035 (Costa & Kepler 2008). This result indicates that the observed frequency variations are not dominated by cooling. They are not either induced by an orbiting companion, i.e. a planet or a brown dwarf (which is the case of the sdB pulsator V391 Peg: Silvotti *et al.* 2007) since the variations of different frequencies are not correlated in phase and do not have the same amplitudes and time scales. We have to think about other mechanism(s). One potential mechanism producing such frequency and amplitude variations is the resonant coupling induced by rotation within triplets, as discussed by Goupil *et al.* (1998), who showed that, depending on the value of the ratio of the frequency mismatch induced in a triplet by second order effect of rotation and the mode growth-rate, one may encounter three different regimes. If this ratio is small, the frequencies are forced to be equally spaced within the triplet; this is the frequency lock regime. If the ratio

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is large, the resonant coupling is inefficient and the frequencies keep their nonresonant properties, i.e. keep their linear values. In the intermediate case, both the amplitudes and the frequencies undergo time modulation. The variations observed in PG 0122+200 indicate that the star could be in this intermediate regime. PG 0122+200 is clearly a good target to further explore this type of nonlinearities.

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Discussion

Turck-Chieze: Could we imagine variation of the outer layers or activity of these stars?

Vauclair: The hottest PG1159 stars still show mass-loss going-on. In the case of the hottest one (RXJ2117+3412) the mass-loss rate is of the order of 10^{-7} $M_{\odot}$/yr. Any change of period oscillation with time would certainly depends on the mass loss process in this case, through the change in the surface layers structure and boundary conditions. However, in PG0122+200, there is no mass loss detected. The observed changes of period oscillations are not probably related on a stellar activity processes.

Ludwig: What sets observationally the precision to which the oscillation frequencies can be determined?

Vauclair: The precision to which the oscillation frequencies can be determined depends mainly on the length of the time series. The results I have shown some from multisite campaigns (except for the first 1986 data). It also depends on the amplitude of the mode, the frequency of a large amplitude mode is more precisely determined than the one of a smaller amplitude one. – Note also that it is essential to resolve the rotational splitting. In most case, the rotational splitting is of the order of a few μHz. Multisite campaigns resulting in a frequency resolution of 1 to 2 μHz are necessary, i.e., campaigns of at least 5 days. Most of our campaigns are 7 to 15 days long.

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CHRISTENSEN-DALSGAARD: What is the magnitude of PG 0122? It would be very interesting to observe such star with Kepler; this could provide accurate determination of period changes over several years.

VAUCLAIR: PG 0122+200 is a B = 16.3, V = 16.8 faint star. Many of the newly discovered PG 1159 stars (from the SDSS) are fainter than 17. Of course, it would be extremely interesting to observe such rapid pulsators with Kepler for period change measurements. We carefully searched for white dwarf pulsators in the Kepler field. Unfortunately there is no known white dwarf pulsators in the Kepler field. We started a search for white dwarfs in the Kepler field, form Strömgren photometry. The following step will be to test the candidates with the right colors (to be inside the Z Ceti instability strip) for variability.

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