Frequency variations in the PG 1159 pulsator
PG 0122+200

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Abstract. PG 0122+200 is the coolest PG 1159 pulsator. On theoretical basis, its cooling time scale was predicted to be dominated by neutrino emission. The measurement of the frequency variation (or \(\dot{P}\)) for a number of its pulsation modes would then provide an empirical estimate of the yet uncertain neutrino emission rate. To test this prediction, we reanalysed the time-series obtained during the seven observing campaigns spanning a time interval of 19 years. We determine the time variations for the seven largest amplitude modes. This includes two complete triplets and one component of a third triplet. We find that PG 0122+200 exhibits much larger frequency variations and on considerably shorter time scales than the ones predicted by cooling theory. We suggest that these variations are not dominated by the star cooling but instead by nonlinear coupling induced by rotation.

1. PG 0122+200, the coolest PG 1159 pulsator

The PG 1159 pulsator (or GW Vir variable star) PG 0122+200 is presently the coolest member of its class with a spectroscopic determination of \(T_{\text{eff}} = 80\) kK. It defines consequently the red edge of the GW Vir stars instability strip. That was a first justification for obtaining a better knowledge of its global parameters and of its internal structure. In addition, it was shown that its evolution time scale could be dominated by neutrino cooling (O’Brien et al. 1998). The prospect to get a direct empirical determination of the neutrino emission rate through a measurement of the rate of change of the pulsation periods, \(\dot{P}\), was a second motivation to follow up the star. For these reasons, a number of observing campaigns were organized, starting in 1986 with a monosite campaign, followed by six multisite campaigns in 1990, 1996, 1999, 2001, 2002 and 2005.

As most of the other pre-white dwarf and white dwarf pulsators, PG 0122+200 exhibits time variations of its pulsation modes amplitudes. Only a few pulsation modes show up at a given season. For instance, all the components of the multiplets generated by rotation (rotational splitting) are not generally seen during the same observing season as one or two of them fall below the detection limit of this particular run. The reconstruction of the whole multiplets is required in order to get a safe identification of the degree of the modes (\(\ell = 1\) for triplets or \(\ell = 2\) for quintuplets etc). It took a number of observing campaigns to finally get enough modes for a proper identification and to constrain the model of PG 0122+200.
The star shows 23 pulsation modes with periods between 336 s and 612 s, distributed in seven triplets and two single frequencies. All the pulsation modes are $\ell=1$ modes (Fu et al. 2007). The identification and frequency of the modes were used to constrain the model of the star with high accuracy (Corsico et al. 2007). The global parameters of PG 0122+200 derived from this asteroseismological study are: $M/M_\odot = 0.556^{+0.009}_{-0.014}$, $T_{\text{eff}} = 81.54 \pm 0.8 \, \text{kK}$, $g = 7.65^{+0.07}_{-0.02}$, $\log(L/L_\odot) = 1.14^{+0.02}_{-0.04}$, $M_{\text{env}}/M_\odot = 0.019 \pm 0.006$. The deduced distance of PG 0122+200 is $614^{+58}_{-32}$ pc and the mean rotation period derived from the rotational splitting measured in the seven triplets is 1.55 days. The accuracy on the global parameters of PG 0122+200 deduced from asteroseismology is significantly improved compared to previous spectroscopic determinations. Since the rate of neutrino production is sensitive to the total mass, effective temperature and luminosity of the star, determining those parameters with enough accuracy was a pre-requisite for estimating the importance of the neutrino emission on the cooling of the star.

### 2. What does the cooling theory predict?

According to the theoretical predictions of O’Brien & Kawaler (2000), the evolution of a pre-white dwarf corresponding to PG 0122+200, with a typical mass of $0.6 M_\odot$, should be dominated by cooling due to neutrino emission. At a $T_{\text{eff}} = 80 \, \text{kK}$, the ratio of the neutrino luminosity, $L_\nu$, on the photon luminosity, $L_\gamma$, is approximately 1.6 for a “normal” neutrino emission rate, as estimated from Itoh et al. (1989, 1992). However, since the neutrino emission rate is rather uncertain, O’Brien & Kawaler (2000) estimated the influence of a factor 3 uncertainty of this rate on the ratio $L_\nu/L_\gamma$. They find that this ratio may be in the range 1.2–2.0. This uncertainty translates into a 45% uncertainty on the age determination of the model. Similarly, this uncertainty on the neutrino emission rate results in a factor of $\approx 4$ difference in the predicted $\dot{P}$ in the range of periods observed in PG 0122+200 (O’Brien & Kawaler 2000). Inversely, if one could measure $\dot{P}$ for a number of pulsation modes, assuming that they are really measuring the cooling rate of the star, one could constrain empirically the value of the neutrino emission rate.

The $\dot{P}$ values for the modes observed in PG 0122+200 have been obtained by Corsico et al. (2007) for the best fit model of the star, which is computed with the “normal” neutrino emission rate. They correspond to cooling timescales in the range 6–12 Myr. The period variations expected on the $\approx 15 \, \text{yr}$ covered by the multisite campaigns (19 yr if one includes the 1986 monosite campaign) would not exceed $6 \times 10^{-4} \, \text{s}$ to $1.5 \times 10^{-3} \, \text{s}$, depending on the mode. In frequency, this corresponds to variations of only a few nHz. With the frequency determination accuracy presently achieved by the best quality multisite campaigns, we estimate that it would require $\approx 50 \, \text{yr}$ to obtain a frequency variation detection at the $3\sigma$ level.

### 3. What the star does?

We have reanalysed the time-series obtained during all the campaigns in an homogeneous way, using the Period04 software (Lenz & Breger 2005). The frequencies, amplitudes and phases were obtained by nonlinear least square fits. Realistic uncertainties on the frequencies were estimated by Monte-Carlo simulations. We were able to determine the frequency variations for the seven largest amplitude modes; this includes the two complete triplets at 2221-2224-2228 $\mu\text{Hz}$ and at 2490-2493-2497 $\mu\text{Hz}$ and the prograde component of a third triplet at 2973 $\mu\text{Hz}$. All these modes are not always seen in the data except for the dominant mode at 2497 $\mu\text{Hz}$ (400 s), which is the prograde component within its triplet. Fig. 1 shows the result for this mode. The unpublished result of the additional 2005 multisite campaign is shown for completeness so that the frequency variation is shown on a total time interval of 19 years. It shows clearly that the frequency variation for this mode is much larger than predicted from cooling theory (a few tenths of $\mu\text{Hz}$ instead of a few nHz). The time scale of the variation is also much shorter than the expected...
Figure 1. Frequency variation of the largest amplitude mode in PG 0122+200: the frequency of the 2497 µHz mode, after subtraction of 2497 µHz, is plotted as a function of time. Each data point is marked with the date of the seasonal observing campaign as (year.month). All observing campaigns were multisite campaigns except the first one in 1986. Error bars are estimated from Monte-Carlo simulations.

cooling time scale, of the order of years instead of a few Myr. Each of the other six modes, not shown here, exhibits frequency variations of its own.

4. Conclusions and interpretation

The seven largest amplitude modes of pulsation in PG 0122+200 show much larger frequency variations and on a considerably shorter timescale than expected would they result from the cooling of the star, whatever would be the impact of the neutrino emission efficiency on the cooling rate. The disagreement is by orders of magnitude and the frequency variations are not a monotonic function of time. This cannot be accounted for by uncertainty on the neutrino emission rate. We conclude that the frequency time variations observed in PG 0122+200 is not dominated by the star cooling. One can exclude the influence of a companion orbiting the star (brown dwarf or planet) since the frequency variations observed for different modes are not periodical (as far as one can say from at most seven data points), are not in phase and have not the same amplitude.

The analysis of the period changes in PG 1159-035, the well studied prototype of the PG 1159 pulsators, shows quite similar results (Costa & Kepler 2008). In the case of PG 1159–035, the period variations of a larger number of pulsation modes were obtained, with different behaviour from mode to mode. Interestingly, the analysis of the both stars PG 1159–035 and PG 0122+200 span a time interval of 19 years and in both cases, the dominant mode is the prograde component of a ℓ=1 triplet. However, the dominant mode in PG 1159–035, at 516 s, shows a quite linear increase with time, while the dominant mode in PG 0122+200, at 400 s, exhibits a more complex
time variation.

We interpret the observed frequency variations as the signatures of nonlinear mode coupling due to rotation, as suggested by Goupil et al. (1998). In this case, the second-order effect of rotation produces a frequency mismatch within the triplets induced by rotation for the $\ell=1$ modes. The sum of the frequencies of the $m=+1$ and $m=-1$ components differs from twice the frequency of the $m=0$ component within a triplet. The coupling between the components of the triplets is then governed by the ratio of the frequency mismatch by the growth rate of the mode. Three different regimes may appear according to the value of this ratio. When it is small, the triplet is in a frequency lock regime. When the ratio is large, the triplet follows the linear behaviour and the frequencies are the ones predicted by linear theory. For intermediate value, both the frequencies and the amplitudes of the components are time modulated. In the case of PG 0122+200, our results suggest that all the modes are in the intermediate regime. In the case of PG 1159−035, different modes are in different regimes and the dominant mode at 516 s seems to be unaffected by nonlinear coupling. A better knowledge of the regime followed by different modes and a determination of the typical modulation time scales for those modes which are in the intermediate regime would give important insight on their growth rates.

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