On the evolution and properties of AGB stars

Groenewegen, M.A.T.

Citation for published version (APA):
Chapter 11

Synthetic AGB evolution: IV. LPVs in the LMC

Abstract

We present a simple model to explain the observed properties of long-period variables (LPVs) in the LMC. It is assumed that pulsation only occurs in an instability strip in the HR-diagram. The instability strip is characterised by three parameters: the temperature at some reference luminosity, the width of the instability strip and the slope $dT_{\text{eff}}/dM_{\text{bol}}$. The first two are free parameters in the model. Based on observations we use $dT_{\text{eff}}/dM_{\text{bol}} = 275$ K mag$^{-1}$ for $M_{\text{bol}} > -5$ and 100 K mag$^{-1}$ for $M_{\text{bol}} < -5$. An additional complication is that the pulsation period depends rather sensitively on the effective temperature scale. The location of the AGB tracks in the HR-diagram (the zero point of the effective temperature scale) is the third free parameter.

From observations we derive that the ratio of the number of C-rich LPVs to the total number of carbon stars is $\sim 0.05$ and that the ratio of the number of oxygen-rich LPVs to the total number of oxygen-rich AGB stars is between 0.05 and 0.10.

Both a model with a Reimers mass loss law inside and outside the instability strip, and a model with the mass loss in the instability strip given by a scaled version of the Blöcker & Schönberner (1992) mass loss law, fit the observational constraints equally well.

We conclude that first harmonic pulsation can be excluded unless the canonical relation between (J-K) color and effective temperature (based on lunar occultation observations) gives temperatures which are too high by $\sim 20\%$, much larger than the estimated uncertainty of $\sim 8\%$ or possible systematic effects ($\lesssim 10\%$). Fundamental mode pulsation is therefore probably the dominant pulsation mode among LPVs in the LMC.

A second conclusion is that for most stars the instability strip is not the final phase of AGB evolution. Based on our calculations for individual stars we find that the AGB is terminated in the instability strip only for stars with initial masses $\lesssim 1.14 \ M_\odot$. More massive stars spend a considerable amount of time in the phase between the end of pulsation and the end of the AGB. We propose an alternative explanation for (some of) the non-variable OH/IR stars in the Galaxy.

1 Introduction

Many AGB stars are observed to pulsate. However, the details how the evolution of AGB stars of different masses is related to the different classes of variable stars (Miras, Semi-regulars (SRs) and Irregulars) and to the evolution of the pulsation period remain uncertain. Recent studies (Jura & Kleinmann 1992a, b, Kershbaum & Hron 1992) indicate that Miras and SRs with periods between 300 and 400 days have a scale height of about 250 pc, while Miras with periods between 100 and 300 days and SRs with periods between 200 and 300 days have a scale height of about 500 pc and thus have evolved from less massive progenitors. The situation for SRs with periods less than 200 days and the Irregulars is less clear.

Hughes (1989) and Hughes & Wood (1990) have performed a deep and extensive search for long-
period variables (LPVs) in the LMC. They found close to 1100 LPVs, about 470 showing large amplitude variations ($\Delta I \geq 0.9$, called Miras by them) and about 570 having smaller amplitudes (called SRs by them). Follow-on spectroscopy and near-infrared photometry has provided an indication of the C to M star ratio among the LPVs. The survey was complete down to $I \approx 18$, equal to the completeness limit reached in optical surveys for AGB stars. For obvious reasons their survey is most sensitive to large amplitude variables. From their figures we deduce that the detection probability for a variable with an amplitude $\Delta I = 1.2$ was close to 100%, but for a star with an amplitude of $\Delta I = 0.6$ only $\sim 50\%$. Thus the presently known LPVs in the LMC contain essentially all Miras and SRs with large amplitudes. By using this well defined population of LPVs, for which luminosity, period and chemical type are relatively well known, we will in this paper attempt to place the LPVs in the general context of AGB evolution.

After a brief summary of our synthetic AGB evolution model (Sect. 2), the average duration of the LPV phase is derived from observations in Sect. 3. In Sect. 4 the observed period distribution of oxygen-rich and carbon-rich LPVs is fitted. We conclude in Sect. 5.

2 Synthetic AGB evolution

We have developed a model to calculate the evolution of AGB stars in a synthetic way (Groenewegen & de Jong 1993, paper I). This model is more realistic than previous synthetic evolution models in that more details on the evolution both prior to and on the AGB have been included. The variation of luminosity during the interpulse period was taken into account as well as the fact that, initially, the first few pulses are not yet at full amplitude and that the luminosity is lower than given by the standard core mass-luminosity relation. Most of the relations used are metallicity dependent. The model uses algorithms derived from recent evolutionary calculations for low- and intermediate-mass stars. The model is described in full detail in paper I. Some essential aspects, relevant to this paper, are briefly introduced here.

In the model stars are selected according to their probability to be on the AGB, which depends on the star formation rate, the initial mass function and the lifetime on the AGB (see paper I). With such an approach we can calculate for a population of stars distributions of relevant quantities like the luminosity function, or, in this paper, the period distribution.

The main free parameters of the model are the minimum core mass $M_c^{\text{min}}$ for (third) dredge-up to occur, the dredge-up efficiency $\lambda$ and the Reimers mass loss coefficient $\eta_{\text{AGB}}$.

In paper I, mass loss on the AGB was described by a Reimers (1975) law:

$$\dot{M}_R = \eta_{\text{AGB}} 4.0 \times 10^{-5} \frac{L}{M} \frac{M_\odot}{\text{yr}}$$

(1)

In this paper we also consider the mass loss law derived by Blöcker & Schönberner (1992) based on the results of the dynamical modelling of LPVs by Bowen (1988):

$$\dot{M}_\text{BS} = \eta_{\text{LPV}} 4.8 \times 10^{-9} \frac{L^{2.7}}{M^{2.1}} \dot{M}_R \frac{M_\odot}{\text{yr}}$$

(2)

where $\eta_{\text{LPV}}$ is a scaling factor, which is unity in Blöcker & Schönberner. The luminosity $L$ is not the quiescent luminosity but includes the effect of the luminosity variation during the flashcycle, i.e. the mass loss rate just after a TP is higher than during quiescence H-burning or in the luminosity dip. In paper I we found that $\eta_{\text{AGB}} \geq 3$ is needed to fit the initial-final mass relation for the low mass stars and that $\eta_{\text{AGB}} = 5$ provides the best fit to the high-luminosity tail of the carbon star luminosity function (LF). AGB evolution is ended when the envelope mass is
2. Synthetic AGB evolution

reduced to $\sim 10^{-3} \, M_\odot$.

The third dredge-up process is described as follows. Dredge-up operates only when the core mass is above a critical value $M_c^{\text{min}}$. In paper I we found that $M_c^{\text{min}} = 0.58 \, M_\odot$ is needed to reproduce the low-luminosity tail of the carbon star LF. During dredge-up an amount of material

$$\Delta M_{\text{dredge}} = \lambda \Delta M_c$$  \hspace{1cm} (3)$$
is added to the envelope, where $\Delta M_c$ is the core mass growth during the preceding interpulse period. The composition of the dredged up material is assumed to be (Boothroyd & Sackmann 1988): $X_{12} = 0.22$ (Carbon), $X_{16} = 0.02$ (Oxygen) and $X_4 = 0.76$ (Helium). In paper I we found that $\lambda = 0.75$ is needed to fit the peak of the carbon star LF. Hot bottom burning (HBB) has been included at the level of the RV $\alpha = 2$ case (see Appendix A of paper I).

The effective temperature is calculated using the relations of Wood (1990) for AGB tracks in the HR-diagram:

$$\log T_{\text{eff}} = \begin{cases} 
\log (\text{bol} + 2.65 \log M)/15.7 - 0.12 \log (Z/0.02) + 3.764 & (M \leq 1.5M_\odot) \\
\log (\text{bol} + 4.00 \log M)/20.0 - 0.10 \log (Z/0.02) + 3.705 & (M > 2.5M_\odot)
\end{cases}$$  \hspace{1cm} (4)$$

where $M_{\text{bol}} = -2.5 \log L + 4.72$ and $\Delta$ is a correction term which accounts for the fact that the effective temperature increases at the end of the AGB phase when the envelope mass becomes small. The $\Delta$-term is calculated from Wood (1990):

$$\Delta = \begin{cases} 
0 & z \geq 0.8 \\
0.07 (0.8 - z)^{2.54} & z < 0.8
\end{cases}$$  \hspace{1cm} (5)$$

For stars with masses between 1.5 and 2.5 $M_\odot$ we interpolate in $\log T_{\text{eff}}$ using the mass $M$ as variable. The zero point of these relations was determined by Wood from the assumption that the star o Ceti (Mira) with a period of 330 days, $Z = Z_\odot$ and $M_{\text{bol}} = -4.32$, has a mass of 1 $M_\odot$ and is pulsating in the fundamental mode.

Fundamental mode and first harmonic pulsation periods are calculated as follows. The fundamental period (in days) is calculated following Wood (1990):

$$P_0 = \begin{cases} 
0.00851 R^{1.94} M^{-0.90} & M \leq 1.5M_\odot \\
0.00363 R^{2.00} M^{-0.77} & M \geq 2.5M_\odot
\end{cases}$$  \hspace{1cm} (6)$$

Wood found this relation to be reasonably independent of metallicity. For stars with masses between 1.5 and 2.5 $M_\odot$ we interpolate linearly in $P_0$ using $M$ as variable. The formalism to calculate the first overtone period is adopted from Wood et al. (1983):

$$P_1 = Q R^{1.5} M^{-0.5}$$  \hspace{1cm} (7)$$

with

$$Q = \begin{cases} 
0.038 + 5.5 \times 10^{-5} (P_1 - 100) & M \leq 0.85 \text{ and } P_1 \geq 100 \\
0.038 + 4.5 \times 10^{-5} (P_1 - 150) & 0.85 < M \leq 1.5 \text{ and } P_1 \geq 150 \\
0.038 + 2.5 \times 10^{-5} (P_1 - 300) & 1.5 < M \leq 2.5 \text{ and } P_1 \geq 300 \\
0.038 & \text{all other cases}
\end{cases}$$  \hspace{1cm} (8)$$

Equations (4-8) have been derived for oxygen-rich stars. Lacking any better estimate we will also use them for carbon stars. This assumption is discussed in Sect. 5.
In Sect. 4 we need to derive effective temperatures from observations. The effective temperatures for both oxygen-rich and carbon-rich stars are derived from (Bessell et al. 1983):

$$T_{\text{eff}} = \frac{7070}{(J-K)+0.88}$$

(9)

where the (J–K) color is in the Johnson system. This relation has been calibrated using effective temperature determinations from the lunar occultation observations of Ridgway et al. (1980a, 1980b). The accuracy of Eq. (9) is about 250 K. It is possible however that Eq. (9) gives too low effective temperatures for the carbon stars or that there is a systematic effect in applying this empirical equation, derived from stars in the solar neighbourhood, to LMC stars.

3 The duration of the LPV phase

In their study of LPVs in the LMC, Hughes (1989) and Hughes & Wood (1990) identified 594 definite and 449 probable LPVs in an 53 deg\(^2\) area. Of the definite LPVs, 247 showed large amplitude variations in their lightcurves ($\Delta I \geq 0.9$, called Miras) and 347 showed smaller variations ($\Delta I < 0.9$, called Semi-Regulars). Of the 449 probable LPVs, 224 showed Mira-like behaviour and 225 SR-like behaviour.

About 500 stars were classified as carbon- or oxygen-rich based on low resolution spectra or (J–K) color. Of 307 Miras, 119 were classified as carbon stars (38.8%), of 181 SRs investigated, 69 were classified as carbon stars (38.1%). Extrapolating to the total number of 1043 LPVs we derive an estimated number of 401 carbon-rich and 642 oxygen-rich LPVs. The same area in the LMC contains about 7500 carbon stars and between 6700 and 12000 oxygen-rich AGB stars (paper I).

The ratio of LPVs to the number of AGB stars is 0.053 for the carbon-rich and between 0.054-0.096 for the oxygen-rich AGB stars. Using the average lifetimes of the AGB phase (from paper I), this corresponds to a mean lifetime of the carbon-LPV and oxygen-LPV phase of $\sim 1.1 \times 10^4$ and $0.7-1.8 \times 10^4$ yrs respectively. Based on the observed C/M ratio of 0.63 in the LPV phase an independent estimated lifetime for the oxygen-rich LPV phase of $1.8 \times 10^4$ yrs is derived. Hughes & Wood derived a value of $\sim 1.5 \times 10^4$ yrs for the total LPV phase based on the number of definite LPVs only. Adding the probable LPVs, the lifetime of Hughes & Wood ($\sim 2.6 \times 10^4$ yrs) is in good agreement with our estimate ($2.9 \times 10^4$ yrs).

4 Fitting the period distribution of LPVs

In Fig. 1 the observed LF and period distribution of the carbon and oxygen-rich Miras (the solid line) and SRs (the dotted line) are plotted. The oxygen-rich SRs are concentrated towards lower luminosities and lower pulsation periods. For the carbon-rich LPVs the difference between Miras and SRs is much smaller. In the remainder of this section we will not distinguish between Miras and SRs and added the observed period distribution (weighted by number) to obtain the observed period distribution of LPVs in the LMC.

We first calculated the fundamental and first harmonic pulsation period distribution for the standard model of paper I according to Eq. (6-8), under the assumption that stars pulsate everywhere on the AGB. The resulting period distribution is compared to the observed one in Fig. 2. There is strong disagreement. Both the fundamental and the first harmonic period distributions are too broad, i.e. the model predicts pulsation at both too low and too high periods. This is true for both oxygen-rich and carbon stars.
4. Fitting the period distribution of LPVs

Figure 1: The luminosity function and period distribution of carbon and oxygen-rich 'Miras' and 'Semi Regulars' (SRs) variables (as defined by Hughes 1989) in the LMC from the data of Hughes (1989) and Hughes & Wood (1990). The Miras are represented by the solid lines, the SRs by the dotted line. There is a tendency (in particular for the oxygen-rich stars) for the SRs to have lower luminosities and lower periods than the Miras. All histograms are normalised to unity.

In Fig. 3 we show the evolution of two stars of 1.25 \( M_\odot \) (O) and 5 \( M_\odot \) (X) in the period-luminosity (P-L) diagram. The variation of the luminosity during the flashcycle is represented by a block profile (paper I). This is reflected in Fig. 3 where stars jump from one phase to another: the luminosity dip, quiescent H-burning and the shell flash. The assumption that pulsation occurs everywhere on the AGB results in periods which are both lower and higher than observed (the strip bounded by the two full lines in Fig. 3). This is true for both low and high initial masses. A similar conclusion is derived by Vassiliadis & Wood (1992).

The naive assumption that AGB stars always pulsate is incorrect. The LPV phase is, on average, a brief one (~6% of the total AGB phase). Thus, either all AGB stars go through a brief LPV phase, or, only a small fraction of AGB stars is LPV during their entire AGB life. There are several arguments to favor the first hypothesis, i.e. a majority of AGB stars going through a brief LPV phase rather than a minority having a prolonged LPV phase. Firstly, as shown in Fig. 2 and 3, any prolonged LPV phase results in period distributions which are too broad. Secondly, LPVs are observed over a wide range of masses, from low mass stars in Galactic globular clusters (Menzies & Whitelock 1985) to the more massive OH/IR stars. If most intermediate mass stars
Figure 2: The predicted (solid lines) fundamental mode ($P_0$) and first harmonic ($P_1$) pulsation period distribution for the standard model of paper I calculated under the assumption that stars pulsate during their entire AGB life. The dotted line represents the observed period distribution. All histograms are normalised to unity.

can become a LPV then each star can only be a LPV for a short time interval. We consider an instability strip of the form:

$$T_l = T_l^0 + \frac{dT_{eff}}{dM_{bol}}(M_{bol} + 5)$$

$$T_h = T_h^0 + \frac{dT_{eff}}{dM_{bol}}(M_{bol} + 5)$$

(10)

where $T_l$ and $T_h$ are the low and high end effective temperatures of the instability strip. The width of the instability strip ($T_h - T_l$) determines the overall duration of the LPV phase, while the position of the instability strip in the HR-diagram determines the C/M ratio in the instability strip. The free parameters are $T_l^0$ and $T_h^0$. The third free parameter is the location of the AGB tracks in the HR-diagram (the zeropoint of the effective temperature scale; Eq. 4). This complication is necessary since the pulsation periods are sensitive to the stellar radius (Eqs. 6-8) and hence the effective temperature. The value of $\eta_{AGB}$ has to be modified when the zero point of the effective temperature scale is changed to give identical evolutionary behaviour on the AGB ($\dot{M} \sim \eta_{AGB} \dot{R} \sim \eta_{AGB} T_{eff}^{-2}$).

The slope $\frac{dT_{eff}}{dM_{bol}}$ can be determined from observations. Feast et al. (1989) have derived a relation between ($J$–$K$) color, averaged over the lightcurve, and log P for Miras in the LMC. Combining Eq. (9) with the mean P-L-relation of Hughes & Wood (1990) we derive $\frac{dT_{eff}}{dM_{bol}} \approx 275$ K mag$^{-1}$
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Figure 3: The (fundamental) Period-Luminosity relation for stars of 1.25 $M_\odot$ (O) and 5 $M_\odot$ (X) for the standard model of paper I calculated under the assumption that pulsations occurs during the entire AGB. The $P_1$-L relation is qualitatively similar. The observed period range for a given luminosity is given by the two full lines. The time evolution of the 1.25 $M_\odot$ model is indicated (lifetimes in $10^3$ yrs). The interval between points plotted is 1000 years. The evolution of the 5 $M_\odot$ model is similar. Because the luminosity variation during the interpulse period was assumed to be a block profile, stars jump from the luminosity dip to the quiescent H-burning phase to the thermal flash.

for $M_{\text{bol}} > -5$ and $\approx 100 \text{ K mag}^{-1}$ for $M_{\text{bol}} < -5$.

The constraints to the model are the duration of the LPV phase relative to the total AGB phase for both oxygen-rich and carbon-rich stars, the observed pulsation period distribution for both oxygen-rich and carbon-rich stars, and the observed effective temperatures of Miras in the LMC (Feast et al. 1989). Later on we will also discuss the ability of the models to reproduce the observed M–P relation for galactic stars. Based on the results of Sect. 3, a duration of the C-star LPV phase relative to the carbon star AGB phase of 0.053 and a C/M ratio in the instability strip of 0.63 are used as constraints.

It should be emphasized that when we refer to the effective temperature of LPVs, we implicitly assume the effective temperature of a non-pulsating star. The pulsation will trigger variations in the effective temperature resulting in real LPVs to have effective temperatures which may be outside the instability strip.

The fitting procedure is as follows. We consider four zero points of the effective temperature scale: the original zero point of paper I (Eq. 4) and zero points lower by 0.02 dex, 0.05 dex and 0.10 dex. The value of $\eta_{\text{AGB}}$ has to be modified when the zero point of the effective temperature scale is changed, as discussed before, in particular, $\eta_{\text{AGB}} = 5.0, 4.6, 4.0, 3.15$ are used respectively. For the moment $\eta_{\text{AGB}}$ is assumed to be equal inside and outside the instability strip. In the program, pulsation periods are calculated for stars in the instability strip, i.e. $T_1 \leq T_{\text{eff}} \leq T_h$. The temperatures $T_1^0$ and $T_h^0$ are determined to fit the assumed duration of the carbon star LPV phase and the C/M ratio in the instability strip. The predicted period distribution for both
Figure 4: The calculated fundamental mode ($P_0$) and first harmonic ($P_1$) pulsation periods (the solid lines), compared to the observed period distribution (the dotted lines). The periods are calculated under the assumption that pulsation only occurs in an instability strip in the HR-diagram, bounded by the temperatures $T_1$ and $T_h$, given by Eq. (10). These calculations are performed for the zero point of the effective temperature scale of paper I (top left panel), a zero point lowered by 0.02 dex (top right), lowered by 0.05 dex (bottom left) and lowered by 0.1 dex (bottom right). The values of $T_1^0$ and $T_h^0$ are given in the text. The mass loss rate law is given by Eq. (1). All histograms are normalised to unity.

M- and C-stars is then compared to the observed period distribution. The results of the calculations are shown in Fig. 4. For $\Delta \log T_{\text{eff}} = 0, -0.02, -0.05, -0.10$ relative to the zero point adopted in paper I, we find $T_1^0 = 3330, 3180, 2970, 2640$ K and $T_h^0 = 3380, 3227, 3014, 2682$ K respectively. The $\Delta \log T_{\text{eff}} = -0.02$ model for fundamental mode pulsation provides the best overall fit. The predicted effective temperatures of LPVs at $M_{\text{bol}} = -5$ ($T_{\text{eff}} \approx 3200$ K) is in agreement with the observed value ($T_{\text{eff}} = 3180$ K) derived from the data in
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Figure 5: The calculated fundamental mode ($P_0$) pulsation period distribution (the solid lines), compared to the observed period distribution (the dotted lines). The periods are calculated under the assumption that pulsation only occurs in an instability strip in the HR-diagram, bounded by the temperatures $T_i$ and $T_h$, given by Eq. (10). The zero point of the effective temperature scale is equal to (left part) and 0.02 dex lower than the scale used in Paper I (right part). The mass loss scaling parameter outside the instability strip, $\eta_{\text{AGB}}$, is 5.15 (left side) and 4.7 (right side). The mass loss scaling parameter inside the instability strip, $\eta_{\text{LPV}}$, is 0.055 (left side) and 0.05 (right side). All histograms are normalised to unity.

Feast et al. (1989). At other luminosities the agreement is equally good since the slope $\frac{dT_{\text{eff}}}{dM_{\text{bol}}}$ is not a free parameter but determined by observations. When the period distribution for M- and C-stars are considered separately a $\Delta \log T_{\text{eff}} \approx -0.01$ model would best fit the M-star period distribution while a $\Delta \log T_{\text{eff}} \approx -0.03$ model would best fit the carbon star period distribution. The small remaining discrepancy between the observed and the predicted period distributions may be due to uncertainties in the pulsation constants or a difference in pulsation constants between carbon- and oxygen-rich stars.

Extrapolating our results we estimate that a reasonable fit to the observed period distributions could also be achieved for the first harmonic pulsation mode if $\Delta \log T_{\text{eff}} \approx -0.12$. The predicted effective temperature at $M_{\text{bol}} = -5$ would be $\sim 2550$ K. This would imply that Eq. (9) gives temperatures too high by $\sim 20\%$, much larger than the uncertainty quoted for Eq. (9) which is $\sim 8\%$. Based on these arguments we favor fundamental mode pulsation as the (dominant) mode of pulsation in LPVs in the LMC.

In our calculations we adopted a Reimers law in the instability strip. There is observational evidence that in LPVs pulsation and mass loss are related (De Giola-Eastwood et al. 1981, Schild 1989, Wood 1990, Whitelock 1990). We therefore also consider a mass loss rate in the instability strip which is based on Blöcker & Schönberner’s (1992) fit to the modelling of LPVs by Bowen (1988). Outside the instability strip we keep Eq. (1). We performed some test calculations to determine $\eta_{\text{LPV}}$ (cf. Eq. 2) since the absolute values of the mass loss rates derived by Bowen are uncertain due to uncertainties in his model. Furthermore, the mass loss rates and effective temperatures in the LMC and in the Galaxy may be different. We proceeded as follows. A value
for $\eta_{LPV}$ was assumed. We first determined the value of the mass loss scaling parameter outside the instability strip ($\eta_{AGB}$) by considering the carbon star luminosity function and the C/M ratio of AGB stars (see paper I). As before, we then optimised the fit to the period distribution by modifying the zero point of the effective temperature scale. We calculated the $\dot{M}$–$P$ relation for some stars and guessed a new value for $\eta_{LPV}$. The model which best fits the period distribution of the M-stars has the following parameters: $\Delta \log T_{\text{eff}} = 0.0$, $\eta_{LPV} = 0.055$, $\eta_{AGB} = 5.15$, $T^0_\text{f} = 3350 \text{ K}$, $T^0_\text{R} = 3390 \text{ K}$. The model which best fits the period distribution of the C-stars has the following parameters: $\Delta \log T_{\text{eff}} = -0.02$, $\eta_{LPV} = 0.05$, $\eta_{AGB} = 4.7$, $T^0_\text{f} = 3175 \text{ K}$, $T^0_\text{R} = 3210 \text{ K}$. The (fundamental) period distributions for both models are shown in Fig. 5. They fit the observed distribution equally well as the simpler model where the mass loss is equal in and outside the instability strip.

The $\dot{M}$–$P$ relation is shown for the Reimers and for the BS model (both with $\Delta \log T_{\text{eff}} = -0.02$) in Fig. 6. For comparison we show the observed relations in the Galactic bulge (Whitelock 1990) and the solar neighbourhood (Schild 1989 and Wood 1990). The error in the observed relations is about 0.2–0.5 dex in $\dot{M}$ for a given $P$. The relation of Wood is in disagreement with that of Schild and Whitelock, which suggests that the AGB lifetimes of the low mass stars derived by Vassiliadis & Wood (1992) have been overestimated. The slope in the $\dot{M}$–$P$ relation is well fitted for the BS mass loss law in the instability strip. This is due to the $L^{3.7}$ dependence of the mass loss rate. With a Reimers law ($\sim L$) the slope in the $\dot{M}$–$P$ relation can not be reproduced as well.
5. Discussion and conclusions

Our exploratory quantitative study into the pulsational properties of LPVs in the LMC leads to two conclusions: (1) fundamental mode pulsation is the (dominant) pulsation mode of LPVs in the LMC, and (2) for most AGB stars the instability strip where (large amplitude) pulsation occurs is not the final phase of AGB evolution. The mode of pulsation of LPVs has long been a point of controversy. Recently, a consensus seems to have been reached in favor of fundamental mode pulsation (Hill & Willson 1979, Bowen 1988, Wood 1990). Our results support this. Based on our model we exclude first harmonic pulsation unless Eq. (9) overestimates the temperatures by ~20%, which is much larger than the quoted uncertainty of ~8%. Equation (9) was derived for Galactic stars but has traditionally been used for the LMC as well. Based on Eq. (4) we estimate that for fixed mass and luminosity a star in the LMC has a 8-10% lower effective temperature than a corresponding star in the Galaxy. This possible systematic effect does not affect the conclusion about the fundamental mode being the dominant mode of pulsation in LPVs in the LMC.

We implicitly assumed that all LPVs found by Hughes are (thermal pulsing-) AGB stars and not e.g. early-AGB stars. For the carbon stars this assumption is of course valid but for the oxygen-rich stars this may not be the case. When the observed LF of oxygen-rich LPVs is compared to the (predicted) LF of oxygen-rich AGB stars (Fig. 7) one sees that the two LF almost overlap. If the LPV population would contain a significant number of low-luminosity early-AGB (E-AGB) stars one would expect that the LF of LPVs would be more concentrated towards low luminosities, especially since the E-AGB phase lasts much longer than the TP-AGB phase. We conclude that most LPVs found in the Hughes survey are indeed (TP-) AGB stars.

Independent of the exact assumptions on the shape of the instability strip and the mass loss rate in and outside the instability strip, AGB evolution does not end in the instability strip for most stars. This is emphasized in Table 1 where some characteristic lifetimes have been listed for individual stars for the models with \( \eta_{\text{AGB}} = 4.6 \), \( \eta_{\text{LPV}} = 0 \) and \( \eta_{\text{AGB}} = 4.7 \), \( \eta_{\text{LPV}} = 0.05 \) (in both cases \( \Delta \log T_{\text{eff}} = -0.02 \)). Only stars between 0.98 and 1.14 \( M_\odot \) end the AGB in the
### Table 1: Results for some masses

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Notes. Listed are the initial mass (\(M_\odot\)), the metallicity Z, the lifetime of the M, S, C and the total AGB phase, the lifetime before, in and after the instability strip (in \(10^3\) years). The first line is for the model with \(\eta_{\text{AGB}} = 4.6\), \(\eta_{\text{LPV}} = 0.0\), the second line for \(\eta_{\text{AGB}} = 4.7\), \(\eta_{\text{LPV}} = 0.05\). In both cases is \(\Delta \log T_{\text{eff}} = -0.02\).

Instability strip. More massive stars spend a considerable amount of time to the right (in the HR-diagram) of the instability strip and stars below 0.98 \(M_\odot\) do not reach the instability strip. Although this is contrary to the widespread belief that AGB evolution ends when the star is an LPV, all observations of LPVs in the LMC point to a different conclusion.

In the Galaxy there is the class of the non-variable OH/IR stars (Habing et al. 1987). If a similar scenario holds for the Galaxy as we derive for the LMC, the non-variable OH/IR stars can be interpreted as massive stars (\(M_{\text{initial}} > 3.5 M_\odot\)) which are now in the phase between the end of the instability strip and the end of the AGB. This is an alternative explanation to the one proposed by Habing et al. (1987). Based on the fact that the spectrum of (some) non-variable OH/IR stars is redder than normal OH/IR stars, suggesting that the inner radius of the dust shell has moved away from the star (due to a lower present-day mass loss) Habing et al. suggested that the non-variable OH/IR stars are in the process of moving from the AGB to the post-AGB phase. In our scenario the drop in the mass loss rate is due to the transition from the high-mass-loss instability strip to the lower-mass-loss final AGB phase.
Van der Veen (1989) showed that stars in region IV and V of the IRAS color-color diagram with energy distributions similar to the non-variable OH/IR stars originate from $\sim 4$ $M_\odot$ stars and have present-day mass loss rates of $10^{-6} - 10^{-5}$ $M_\odot$/yr, surprisingly high for post-AGB mass loss which is typically only $10^{-8} - 10^{-6}$ $M_\odot$/yr.

The transition from the AGB to the post-AGB phase is a brief one ($\sim 10^3$ years, see e.g. Slijkhuis 1992). The Habing et al. scenario cannot explain why so many of the OH/IR stars are non-variable (van Langevelde 1992 finds that $\sim 20\%$ of OH/IR stars in the Galactic center are non-variable). In our scenario the non-variable OH/IR phase lasts about $10^4 - 10^5$ years relative to a total AGB phase of $1 - 5 \times 10^6$ years (see Table 1). If these lifetimes also apply to the Galaxy we predict about $10 - 20\%$ non-variable OH/IR stars, in reasonable agreement with observations.

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