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On the pulsation mode of Mira variables: evidence from the Large Magellanic Cloud

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ABSTRACT

Recent angular diameter measurements for Mira variables suggest that the radii of these stars are very large and consistent with pulsation in the first-overtone mode rather than the fundamental mode. On the other hand, non-linear pulsation models of Mira variables suggest that the observed pulsation velocity amplitudes can only be achieved during fundamental-mode pulsation, at least for stellar masses $\lesssim 2.0\,\mathrm{M}_{\odot}$. Here, we present some new observations of long-period variables (LPVs) in the LMC which show that the LPVs lie on two (K, $\log P$) sequences, one sequence being the well-known Mira sequence and the other being a sequence parallel to the Mira sequence but separated from it by $\Delta\log P \sim 0.35$. The LPVs on the Mira sequence have a wide range of amplitudes ($0.1 < \Delta I < 3$) while those on the second sequence have relatively small amplitudes ($\Delta I < 0.5$). The previously known LPVs of large amplitude ($\Delta I > 0.5$) in the LMC lie almost always on the Mira sequence. Theoretical models of LPVs predict a ratio of fundamental to first- or second-overtone period of $\Delta\log P \sim 0.3$–0.4, and overtone pulsators are expected to have smaller limiting amplitudes than fundamental-mode pulsators. Hence the above observations can be easily understood if the LPVs on the Mira sequence are fundamental-mode pulsators while LPVs on the second sequence are overtone pulsators. A second test of the pulsation mode is obtained by computing pulsation periods for model stars on the LMC old giant branch and comparing these periods with those of observed Mira variables. Once again, the fundamental-mode pulsators have periods consistent with those seen in the LMC Miras while the overtone periods are too short. The above results strongly suggest that Mira variables are fundamental-mode pulsators.

Key words: stars: AGB and post-AGB – stars: fundamental parameters – stars: late-type – stars: oscillations – stars: variables: other.

1 INTRODUCTION

A convincing identification of the pulsation mode of the Mira variables has yet to be made. This is somewhat surprising since the ratio of fundamental-mode period to first-overtone period in a Mira-like red giant variable is $\gtrsim 2$ (e.g. Fox & Wood 1982). Any reasonable estimate of the radius and mass of a Mira variable, coupled with a theoretical period–mass–radius relationship for each of the first few modes of pulsation, should determine the pulsation mode. This type of analysis has been performed many times in the past (e.g. Wood 1975a, 1990b; Whitelock 1986; Tuthill et al. 1994; Haniff, Scholz & Tuthill 1995; Feast 1996), using either direct measurements of Mira radii or a temperature scale based on radius measurements and model atmospheres. A mass of $1\,\mathrm{M}_{\odot}$ is usually assumed, based on kinematic studies of Mira variables in the Galaxy which indicate that typical Miras with periods of a few hundred days are old disc stars (Feast 1963; Jura & Kleinmann 1992). These studies tend generally to favour strongly the first overtone as the mode of Mira pulsation, although adoption of a warmer temperature scale appropriate for non-variable red giants can produce models consistent with fundamental-mode pulsation in Miras.

However, there is a major difficulty with the assumption that the Miras pulsate in the first-overtone mode. This is that, because the radii of first-overtone pulsators are very large, the gravities are small and the pulsation velocities achieved in the stellar atmosphere are much smaller than those observed (Hill & Willson 1979; Willson 1982; Bowen 1988; Wood 1990a; Bessell, Scholz & Wood 1996). Once again, the situation is not totally clear-cut since high-mass ($M \gtrsim 2\,\mathrm{M}_{\odot}$) or short-period ($P \lesssim 250$ d) theoretical overtone models of Mira variables can be made with pulsation velocity amplitudes close to those that are observed (Wood 1974; Tuchman 1991). Basically, the cause of the uncertainties listed above is the difficulty of determining the radii of Miras, which are

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very extended and gradually fade away into the interstellar medium rather than having sharp edges like the Sun.

Theoretical models of red giant pulsation show that, as a star evolves up the asymptotic giant branch (AGB), it develops unstable overtone modes, the most unstable of which becomes of lower order as luminosity increases: towards the end of the AGB the fundamental is the most unstable mode (Fox & Wood 1982). If the Mira variables are indeed fundamental-mode pulsators, then we might expect to see two distinct (K, log$P$) relations among the LPVs in the LMC, one corresponding to fundamental-mode pulsation (the Miras) and one corresponding to first-overtone pulsation (lower amplitude LPVs). Most importantly, there should be a distinct separation between these sequences (at a given luminosity) of $\Delta\log P \sim 0.34$, corresponding to the typical fundamental to first-overtone period ratio $P_0/P_1 \sim 2.2$. On the other hand, if the Miras are first-overtone pulsators, then one might expect another sequence of LPVs in the (K, log$P$) plane corresponding to second and higher overtone pulsation, but this sequence should be separated from the Mira sequence by a $\Delta \log P$ of only ~0.11, corresponding to $P_1/P_2 \sim 1.3$.

CCD observations of star clusters in the LMC have revealed many LPVs with amplitudes in V of a few tenths of a magnitude to several magnitudes. Pre-CCD searches for LPVs in the Magellanic Clouds (see references in Wood, Moore & Hughes 1991) have revealed ~1000 LPVs. However, these objects are of relatively large amplitude. The largest survey, by Hughes (1989), revealed LPVs of amplitude $\Delta I \gtrsim 0.5$. Hughes (1989) categorized those objects with amplitude $\Delta I < 0.9$ as semiregular (SRa) variables by analogy with the amplitude definition for Galactic semiregular variables (a Galactic LPV with visual light amplitude <2.5 mag and a reasonably regular light curve is classified as a semiregular, while LPVs with larger amplitudes are classified as Mira variables). The larger amplitude LPVs in the LMC were classified by Hughes as Miras. The SRa and Mira classes in the Galaxy and the LMC seem to merge smoothly into each other in properties. In particular, Hughes & Wood (1990) showed that the LMC Miras and SRa variables fell on the same (K, log$P$) relation to within the errors of single-phase observation. This result shows that the Hughes (1989) SRas cannot be assigned to first-overtone mode pulsation while the Miras are assigned to fundamental-mode pulsation, since the period ratio of ~2.2 between these two modes would lead to well-separated (K, log P) relations if two separate pulsation modes were involved. However, a situation where the Miras were first-overtone pulsators and the SRas were second-overtone pulsators could not be ruled out (the ratio P_1/P_2 is relatively small and typically ~1.3).

The first aim of this paper is to look for secondary (K, log$P$) sequences among the newly discovered LPVs in the LMC. Since many of these LPVs have amplitudes lower than those of previously known LPVs in the LMC, there is a reasonable chance that these objects could be pulsating in modes higher than that of the Miras. We note that Wood (1975b) and Barthes & Tuchman (1994) have previously tried finding multiple modes in the light curves of *individual* local Miras in order to identify the dominant pulsation mode, but the signal-to-noise ratio of the possible secondary modes in these large-amplitude stars is very low and the results are very uncertain.

In a second approach, we fit theoretical models to giant branches at luminosities below those at which large-amplitude variability starts, and then extend those giant branches into the Mira regime where the models are compared with observations of LMC Miras in order to identify the Mira pulsation mode. A brief discussion of some of the results presented here is given in Wood (1995) along with a general discussion of the problem of determining the mode of pulsation of the LPVs.

2 OBSERVATIONAL DATA

The LPVs used in this study were discovered around the LMC cluster NGC 1850 at the northern end of the LMC bar (Sebo & Wood 1995), and the pair of clusters NGC 2058 and NGC 2065 at the southern end of the LMC bar (Sebo & Wood, in preparation). Infrared J and K magnitudes were obtained on two occasions for each object using the 2.3-m telescope at Siding Spring Observatory. The infrared camera CASPIR was used on the dates 1994 May 29 and 1995 May 14, while the single-channel infrared photometer was used on 1994 December 19 with a 10-arcsec aperture. The infrared observations are given in Table 1. Table 2 shows mean K magnitudes and $J-K$ colours, along with the periods, mean V magnitudes and mean $V-I$ colours from Sebo & Wood (1995, and in preparation). The J and K means are averages of the data in

Table 1. Infrared observations of LPVs.

Variable	Date	K	J-K
NGC 1850			
347	940529	12.41	0.72
	950514	12.10	0.77
587	940529	12.06	1.11
	950514	12.17	1.33
670	940529	10.49	1.85
	950514	10.50	1.81
1038	940529	9.23	1.40
	950514	8.73	1.45
1906	940529	11.15	1.73
	950514	11.14	1.77
2093	940529	11.42	1.32
	950514	11.53	1.30
2268	940529	10.86	1.27
	950514	10.84	1.34
NGC 2058/65			
V403	941219	11.40	1.28
	950514	11.49	1.25
V446	941219	10.96	1.86
	950514	10.77	1.51
V523	941219	10.48	1.37
	950514	10.11	1.37
V569	941219	10.93	1.72
	950514	10.87	1.57
V607	941219	11.95	1.16
	950514	11.87	1.18
V627	941219	11.86	1.37
	950514	11.93	1.09
V741	941219	10.74	1.84
	950514	10.65	1.90
V1111	941219	10.92	1.72
	950514	11.22	2.26
V1243	941219	11.49	1.41
	950514	11.49	1.30
V1402	941219	11.01	1.37
	950514	11.03	1.18
V2056	941219	11.02	1.44
	950514	11.01	1.30
V3094	941219	11.05	1.25
	950514	11.20	1.28

Note: date is in the form year-month-day.

Table 2. Mean magnitudes and colours of LPVs.

Variable	P(days)	$<K>$	$<J>-<K>$	$<V>$	$<V>-<I>$
NGC 1850					
347	109.5	12.26	0.74	16.01	1.80
587	145.6	12.11	1.22	17.80	3.10
670	330.0	10.49	1.83	17.01	2.89
1038	597.0	8.98	1.43	17.70	4.60
1906	230.0	11.15	1.75	17.13	2.73
2093	208.0	11.48	1.31	17.81	3.10
2268	134.5	10.85	1.31	17.46	3.60
NGC 2058/65					
403	47.0	11.44	1.27	16.34	2.27
446	131.0	10.86	1.68	16.36	2.54
523	420.0	10.30	1.37	17.26	3.59
569	238.0	10.90	1.65	16.66	2.49
607	65.0	11.91	1.17	16.60	2.20
627	59.5	11.90	1.23	16.61	2.01
741	286.0	10.69	1.87	16.81	2.76
1111	293.0	11.07	1.99	17.41	2.77
1243	88.0	11.49	1.35	17.10	2.78
1402	135.0	11.02	1.27	17.32	3.35
2056	154.0	11.02	1.37	17.50	3.10
3094	103.0	11.12	1.26	17.91	3.63

Table 1, while the V and I means are magnitude means obtained from least-squares Fourier fits to the time series of V and I magnitudes.

3 THE OBSERVED (K, log$P$) RELATION

The LPVs are plotted in the (K_0, log$P$) plane in Fig. 1. We have assumed reddenings $E(B-V)=0.15$ and 0.21 for the fields of NGC 1850 and NGC 2058/65, respectively, along with absorption $A(K)=0.4E(B-V)$. The line is the (K_0, log$P$) relation for Mira variables of M and C spectral type in the LMC from Feast et al. (1989).

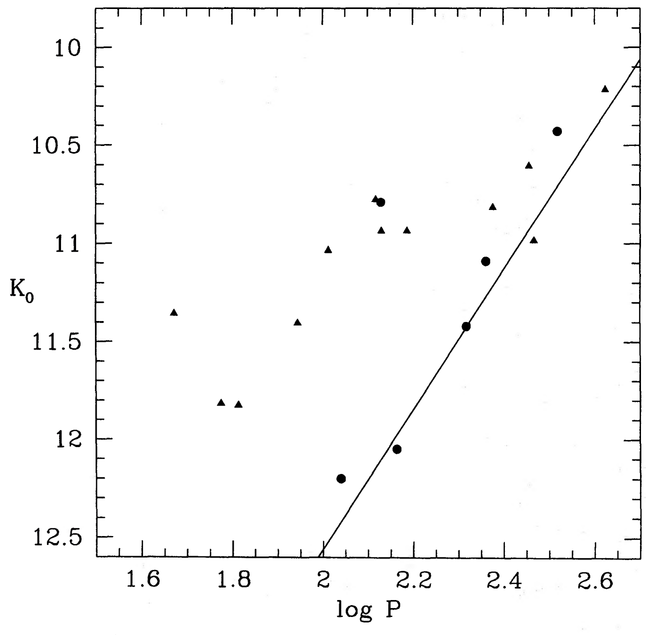

Figure 1. The LPVs in the (K_0, log$P$) plane. Circles are LPVs near NGC 1850 and triangles are LPVs near NGC 2058/65. The line is the LMC Mira relation of Feast et al. (1989).

It is immediately apparent from Fig. 1 that only about half the LPVs in our sample lie on the Mira sequence in the (K_0, log$P$) plane. We note that Feast et al. (1989) find that the LMC Miras scatter about the mean (K_0, log$P$) relation by only 0.15 mag. Even single-phase observations of Miras in the LMC produce a scatter about the mean (K_0, log$P$) relation of only 0.26 mag (Hughes & Wood 1990). In Fig. 1, there is clearly a second sequence of LPVs parallel to the Mira sequence but separated from it by $\Delta\log P \sim -0.35$, corresponding to periods at a given luminosity that are shorter by a factor of ~2.2. Recalling the discussion in the Introduction, we note that this ratio is remarkably close to the period ratio of fundamental mode to first overtone. We therefore suggest that the Mira variables are fundamental-mode pulsators while the second, shorter period sequence of LPVs in Fig. 1 consists of first-overtone pulsators.

4 AMPLITUDE DISTRIBUTIONS

As a general consideration, overtone pulsators are expected to have amplitudes which are smaller than those of fundamental-mode pulsators. If the two LPV sequences found above correspond to fundamental and overtone pulsation, then different amplitude distributions might be expected for the two sequences. Fig. 2 shows the distribution of I amplitude (ΔI) for stars on the two sequences. Amplitudes of stars on the Mira sequence cover a wide range, $0.1 \lesssim \Delta I \lesssim 2.0$, with most stars having $\Delta I \gtrsim 0.5$, while the overtone pulsators are confined to $\Delta I \lesssim 0.5$. We note that a large number of LMC LPVs with amplitudes $\Delta I \gtrsim 0.5$ mag were studied by Hughes & Wood (1990). All but perhaps eight out of 300 LPVs in this sample lie on the Mira sequence in the (K, log$P$) plane, confirming that larger amplitude LPVs pulsate in the same mode, which we have identified above with the fundamental. [Since there are some uncertainties in period determination for the stars in Hughes & Wood (1990), and given that Hughes & Wood had

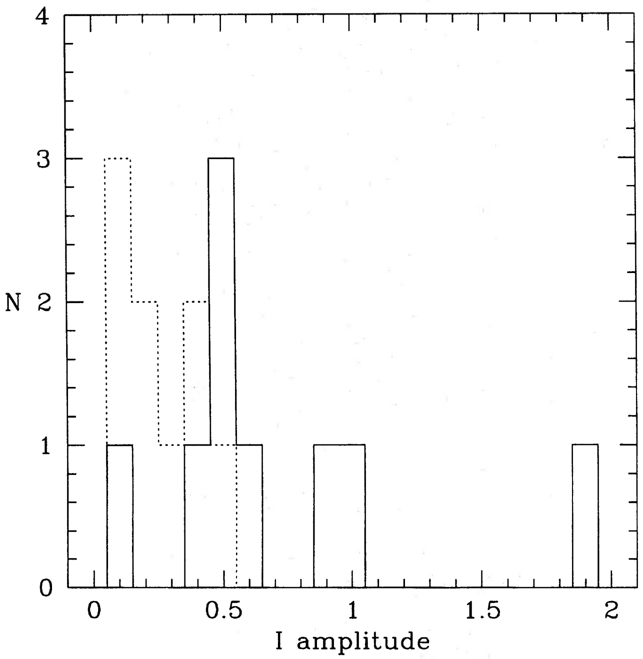

Figure 2. The distribution of total pulsation amplitude in I for LPVs on the Mira sequence (solid curve) and for LPVs on the second, shorter period sequence (dotted curve).

only single-phase K magnitudes rather than mean K magnitudes, it is quite plausible that the small number (~8) of stars in fig. 10 of Hughes & Wood that appear to lie on the overtone sequence are misplaced.]

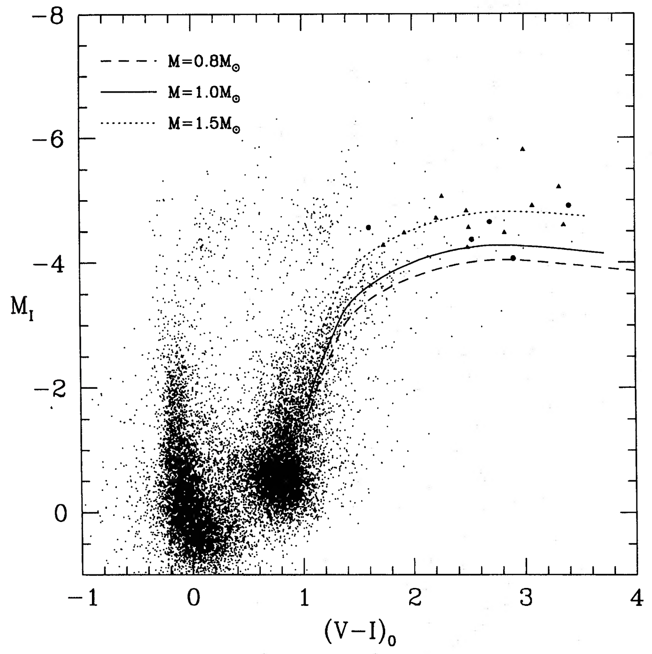

Figure 3. Stars in the 10 × 10 arcmin^2 field around the cluster NGC 1850 plotted in the (I, $V-I$) plane (small dots). The circles and triangles are mean I and $V-I$ values for the LPVs around NGC 1850 and NGC 2058/65, respectively. Theoretical AGB tracks for stars of mass 0.8, 1.0 and 1.5 M$_\odot$ are also shown.

5 THEORETICAL ASYMPTOTIC GIANT BRANCH SEQUENCES

We now make theoretical models for the LMC LPVs in order to confirm the mode identifications suggested above. A theoretical examination of period ratios P_0/P_1 and P_1/P_2 in LPVs shows that these ratios can vary significantly depending on the model used for the LPV (see fig. 3 of Fox & Wood 1982). In order to compare the results in Fig. 1 directly with theory, we construct models appropriate for LPVs in the LMC. Our starting point is the observational ($I,V-I$) diagram (Fig. 3) for stars in the field around NGC 1850. The data for this figure come from Sebo & Wood (1995) and we have assumed a reddening $E(B-V)=0.15$, $E(V-I)=1.3E(B-V)$, $A_V=3.1E(B-V)$ and an LMC distance modulus of 18.5. The LPVs around both NGC 1850 and NCG 2058/65 are plotted on Fig. 3, with a reddening of $E(B-V)=0.21$ assumed for the NCG 2058/65 LPVs. The old giant branch, and presumably the LPV population, for the field around NGC 2058 and NGC 2065 is similar to that around NGC 1850 but with more, and patchy, reddening.

Asymptotic giant branches (AGBs) have been constructed theoretically to fit the observational data in Fig. 3. A series of models was made for masses of 0.8, 1.0 and 1.5 M$_\odot$. This range of masses was chosen to fall within the range defined at the lower end by the core mass for AGB stars of ~0.6 M$_\odot$ and at the upper end by a mass corresponding to that of stars formed in the burst of star formation which began in the LMC ~3×10^9 yr ago (Butcher 1977; Bertelli et al. 1992). For each luminosity and mass, an envelope model was constructed by integrating from surface to core in the manner described in Fox & Wood (1982), with the core mass appropriate for the model luminosity (Wood & Zarro 1981). The mixing length was adjusted so that the AGB sequences had the correct temperature at relatively low luminosities ($M_{\mathrm{bol}} \sim -2$, $M_I \sim -2.5$) where the conversion from T_{eff} to $V-I$ is well calibrated. A value of 2.5 pressure scaleheights was found to fit the observed giant branch T_{eff}. The sequences were extended to higher luminosities assuming a constant mixing length. The $V-I$ colours and bolometric corrections needed to plot the theoretical models in Fig. 3 were derived from the model atmospheres of Kurucz (1993) for $T_{\mathrm{eff}} \geq 4000$ K. At lower temperatures the ($V-I$, logT_{eff}) calibration of Bessell (1979) was used along with the bolometric correction BC$_I$ to I from Bessell & Wood (1984). By this procedure we eliminate the need to adopt a temperature scale for the LPVs themselves. The temperatures and radii of the LPVs are a direct outcome of the assumption that the mixing length is constant up the AGB. Such an assumption generally reproduces giant branches (e.g. in globular clusters) quite well. In constructing the AGB sequences, and in the linear pulsation models described below, the OPAL opacities (Iglesias & Rogers 1993) were used, supplemented by molecular opacities added as described in Chiosi, Wood & Capitanio (1993). Abundances $Y=0.30$ and $Z=0.008$ were adopted.

6 THEORETICAL PULSATION MODELS FOR THE LPVs

For the theoretical AGB models shown in Fig. 3, linear, radial, non-adiabatic pulsation periods were computed with the code described in Fox & Wood (1982), updated to include new opacities as described above. The results of these calculations have been compared with the observations of LPVs in the (K, log$P$) plane in two ways. In the first comparison, we made use of the period *ratios* obtained from the models but we did not require the periods

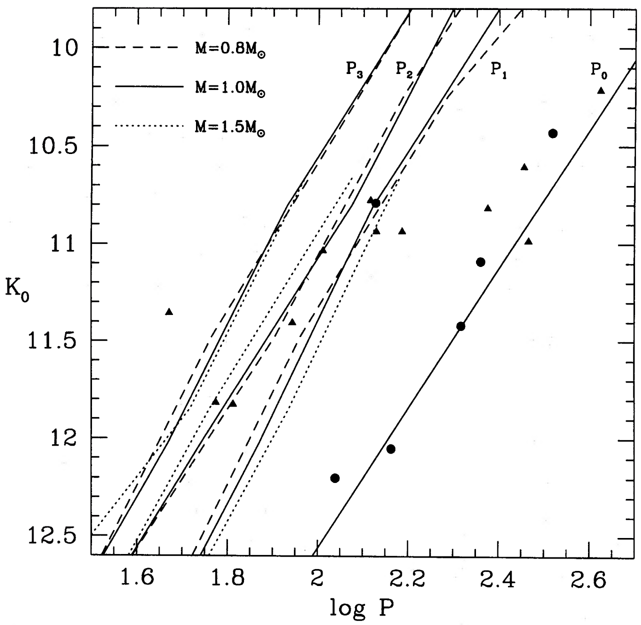

Figure 4. The observations of LPVs compared with theoretical models in the (K_0, log$P$) plane. Points are as in Fig. 1. The theoretical fundamental-mode period has been forced to fit the observed Mira relation of Feast et al. (1989) and period ratios in the models are then used to position the curves corresponding to first, second and third overtones.

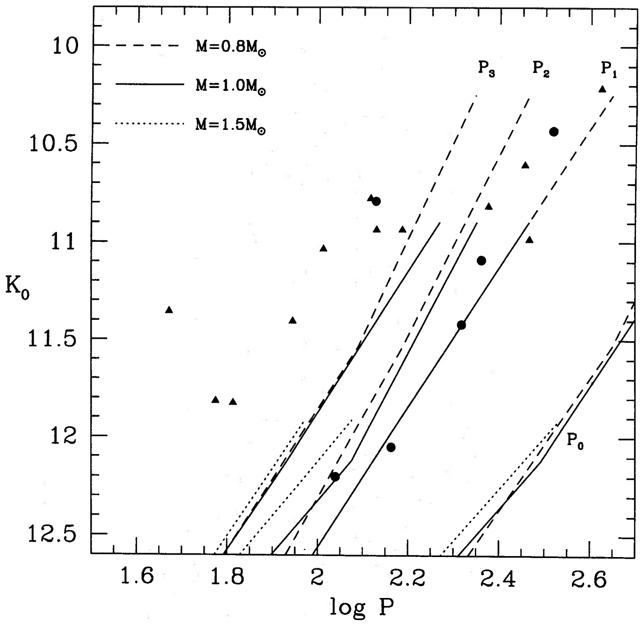

Figure 5. As for Fig. 4 except that the first-overtone period has been forced to fit the observed Mira (K_0, log$P$) relation.

themselves to be very accurate. This method avoids the possibility that the mixing length may vary up the giant branch, giving incorrect values of $T_{\rm eff}$, and hence period, at a given luminosity or K magnitude (period *ratios* are relatively insensitive to changes in stellar parameters).

To test if the observations are consistent with fundamental-mode pulsation in the Mira variables, we assumed that the model fundamental-mode periods corresponded to the observed Mira periods and then derived the K magnitudes for the models from the observed Mira (K_0, log$P$) relation of Feast et al. (1989). Then all models automatically lie on the Mira (K_0, log$P$) relation, while the period *ratios* predict the theoretical positions of the sequences corresponding to first, second and third overtone (Fig. 4). A similar test of the first-overtone hypothesis for Mira pulsation was made by forcing the first-overtone period to coincide with the observed Mira (K_0, log$P$) relation (Fig. 5). Note that the period *ratios* shown in Figs 4 and 5 do not vary greatly with stellar mass or luminosity or mixing length. Therefore uncertainties in the parameters of the models should not lead to errors in mode identification while only period *ratios* are being considered.

The results shown in Figs 4 and 5 confirm the tentative conclusions reached in Section 3. If the Miras in the LMC are assumed to be pulsating in the fundamental mode, then the second sequence of LPVs corresponds well with pulsation in the first or second overtone. In particular, there should be an unpopulated gap between the fundamental and first-overtone sequences, as is indeed observed. On the other hand, if the Miras are pulsating in the first-overtone mode, then the second- and third-overtone pulsators fall in the gap where no LPVs are observed. The second observed sequence of LPVs would have to correspond to ~fifth-overtone pulsation with no unstable modes between the fifth and first overtones. This is a very unlikely situation since the theoretical pulsation models constructed here and by Fox & Wood (1982) are mostly unstable in the second and third overtones, although use of the mixing length theory of convection for energy transport means that the theoretical growth rates are suspect. Finally, we note that, if the Miras are first-overtone pulsators, then the predicted fundamental-mode sequence is unpopulated, in spite of the fact that models exhibit strong instability for the fundamental mode. All these considerations strongly suggest that the Miras are fundamental-mode pulsators.

In the second comparison between theory and observation, we used the AGB models directly to predict the ($M_{\rm bol}$, log$P$) relation expected for fundamental and overtone pulsation and then compared the predictions with the observed Mira relation of Feast et al. (1989). We stress again that estimates of Mira $T_{\rm eff}$ values were not explicitly required here. Our procedure was to adjust the mixing length to get the correct giant branch temperature at relatively low luminosities and to then rely on the assumption that the mixing length does not vary along the AGB to get the $T_{\rm eff}$ values (and radii) of our model AGB stars. Although this assumption may be questioned, we note that evolutionary tracks constructed with constant mixing length in general reproduce red giant sequences well.

The periods of the fundamental mode and first, second and third overtones for 0.8-, 1.0- and 1.5-M$_\odot$ AGB stars obtained in this manner are plotted in the ($M_{\rm bol}$, log$P$) plane in Fig. 6. In this rather crowded diagram, there are four lines for each mass, corresponding to the fundamental and first-, second- and third-overtone modes, respectively. The fundamental mode has the longest period at any luminosity and mass, the first overtone is next longest, and so on. Also shown in Fig. 6 is the mean ($M_{\rm bol}$, log$P$) relation for LMC Mira variables, plotted assuming an LMC distance modulus of 18.5. The LMC LPVs studied in this paper are also shown, where $M_{\rm bol}$ has been derived from $< K >$ using the bolometric correction BC$_K$ to K given in Wood, Bessell & Fox (1983) and a distance modulus of 18.5. Stars with $(J-K)_0 > 1.5$ are assumed to be carbon stars and are shown by solid symbols. The most luminous ($M_{\rm bol} < -4.5$) Mira variables in this study, which are carbon stars, do not closely fit the mean ($M_{\rm bol}$, log$P$) relation, possibly because only two observations were obtained per star and the amplitudes are relatively large.

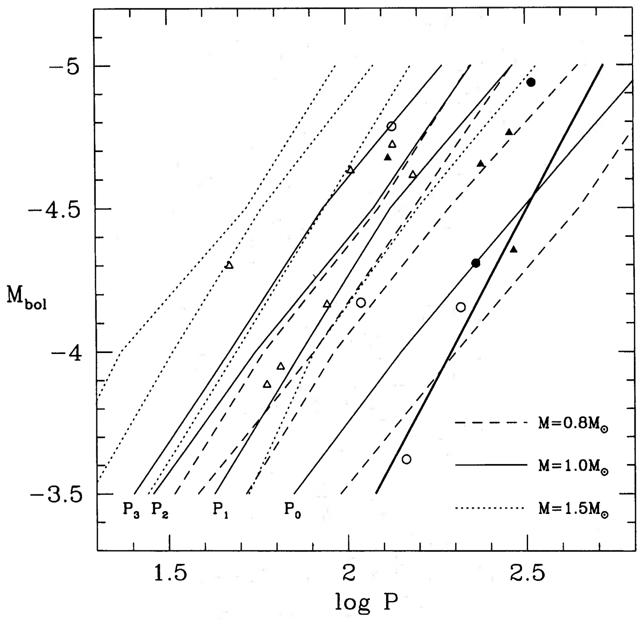

Figure 6. Periods of the fundamental, first- second- and third-overtone modes of model AGB stars of mass 0.8, 1.0 and 1.5 M$_\odot$ (thin lines). The thick line is the mean (M_{bol}, log$P$) relation for Mira variables in the LMC from Feast et al. (1989). Circles are LPVs near NGC 1850 and triangles are LPVs near NGC 2058/65, where carbon stars [defined as objects with $(J-K)_0 > 1.5$] are shown as solid symbols and M stars are shown as open symbols.

It is clear from Fig. 6 that the observed Mira (M_{bol}, log$P$) sequence in the LMC is readily explained in terms of fundamental-mode pulsation in stars of increasing mass as the luminosity increases. We note that kinematic studies of Mira variables in the Galaxy show just such an increase in mass with pulsation period (Feast 1963; Jura & Kleinmann 1992). The LPVs observed here, and lying on the short-period sequence parallel to the Mira sequence, are well explained as overtone pulsators. On the other hand, the predicted first-overtone periods are much too short to be consistent with LMC Mira pulsation.

7 SUMMARY

We have obtained infrared observations of a set of small- and large-amplitude LPVs in the LMC and shown that the LPVs fall on two distinct sequences in the (K, log$P$) plane. One sequence is the well-known Mira sequence while the second sequence runs parallel to the Mira sequence but has periods smaller by a factor of ~2.2. Theoretical models have been made for AGB stars on the prominent LMC old giant branch and pulsation periods have been derived for the fundamental, first-, second- and third-overtone mode. Using period *ratios* only, we showed that if the Miras are fundamental-mode pulsators then the second sequence of stars can be readily explained by first- or second-overtone pulsation. However, if the Miras were first-overtone pulsators, then the smaller amplitude LPVs would need to be pulsating in a high (~fifth) overtone and we would not expect to see the distinct gap which is observed between the two sequences unless all modes between the first and fifth overtones were stable. Similarly, the absence of a sequence of LPVs corresponding to fundamental-mode pulsation would require this mode to be stable, in disagreement with theoretical models. Observations presented here and by Hughes & Wood (1990) show that LPVs of relatively large amplitude ($\Delta I \gtrsim 0.5$) all lie on the Mira sequence while all LPVs on the second sequence have small amplitudes ($\Delta I \lesssim 0.5$). This result is consistent with expectations if the LPVs on the Mira sequence are fundamental-mode pulsators and the LPVs on the second sequence are overtone pulsators. Finally, comparison of the actual model periods with the observed Mira periods shows good agreement between fundamental-mode periods and observed Mira periods. Taken together, we believe these results present strong evidence in favour of the Miras being fundamental-mode pulsators. Although the current sample of stars is relatively small, we are beginning a study of a larger sample of stars using the MACHO data base in order to provide a better sample for comparison with the theory.

If we accept the conclusions above, then some explanation is required for the large radii that have been derived for Miras from angular diameter or T_{eff} measurements. Possible explanations include overestimation of Mira distances, and underestimation of the atmospheric opacity and/or extension caused by pulsation in the models of Bessell et al. (1996), which were used by Tuthill et al. and Haniff et al. to interpret their observations. A better understanding of the large observed radii in Miras is clearly needed.

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