Asymptotic Giant Branch Stars
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MACHO observations of LMC red giants: Mira and semi-regular pulsators, and contact and semi-detached binaries

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Abstract. The MACHO data base has been used to examine light curves of all red giant stars brighter than $M_{\rm bol} \sim -2$ in a $0.5° \times 0.5°$ area of the LMC bar. Periods, often multiple, have been searched for in all stars found to be variable. Five distinct period-luminosity sequences have been found on the low mass ($M \lesssim 2.25 M_\odot$) giant branch. Comparison of observed periods, luminosities and period ratios with theoretical models identifies Miras unambiguously as radial fundamental mode pulsators, while semi-regular variables can be pulsating in the 1st, 2nd or 3rd overtone, or even the fundamental. All these variables lie on just 3 of the 5 distinct sequences, and they all appear to be on the AGB.

The fourth sequence contains red giants on the first giant branch (FGB) or at the red end of the core-helium burning loops of intermediate mass stars ($M \gtrsim 2.25 M_\odot$). The light curves of these stars strongly suggest that they are contact binaries, and they make up ~0.5% of stars within 1 mag. of the FGB tip. Stars on the fifth sequence show semi-regular, eclipse-like light curves. The light curves and periods of these stars suggest that they are in semi-detached binaries, transfering mass to an invisible companion via a stellar wind or Roche lobe overflow. They make up ~25% of AGB stars. If the existence of these red giant contact and semi-detached binaries is confirmed, then extant theories of binary star evolution will require substantial modification.

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1. Introduction

The MACHO experiment (Alcock et al. 1992) has now accumulated light curve data for LMC stars over an interval of ~2 200 days without any substantial breaks. This is sufficiently long that periods can be derived for essentially all the red, long-period variables (LPVs). Furthermore, the long time span is ideal for picking out secondary periods. In this paper, we examine the light curves of all red variables in a small $0.5°\times0.5°$ area of the LMC bar centred on $5^h28^m14.8^s$, -69°45′42″, J2000.

2. Data calibration and period searches

The MACHO data consists of light curves in non-standard red (R_M) and blue (B_M) bandpasses. Variables were searched for in the area of the (R_M,B_M-R_M) plane redder than the main-sequence and brighter than ~ 1 mag. from the tip of the FGB ($M_{\rm bol} \lesssim -2$). For each variable, up to three significant periods in the range $20 < P(d) < 1\,200$ were determined. A total of 1 431 red stars were identified as variable: 398 had no significant period, 608 had 1, 379 had 2 and 46 had 3. In addition, 107 Cepheids and 22 other blue variables were found in the field. For comparison with theory, B_M and R_M were transformed to V and I (Cousins) using photometry obtained with the 1 m telescope at Siding Spring Observatory (SSO). J and K images of the field were obtained with the 2.3 m telescope at SSO.

3. Results

Fig. 1 shows the period-luminosity (P-L) relation for the red variables, where there is a point in the figure for each period found (i.e. a star with more than 1 significant period will contribute more than 1 point to the figure). The quantity $I_W = I_0 - 1.38*(V-I)_0$ was chosen as the luminosity index as it is almost reddening free and the theoretical period-luminosity-colour relation for LPVs suggests that stars pulsating in a given mode should lie on the same (I_W, log$P$) relation regardless of mass. Stars with $(J-K)_0 > 1.4$ are assumed to be carbon stars and are shown as filled circles. The positions of the FGB tip and the minimum luminosity for thermally-pulsing AGB (TPAGB) stars are indicated.

It is clear that there are 4 parallel sequences (labelled A, B, C and D) above the TPAGB minimum in Fig. 1, and another sequence (E) extending down to the minimum luminosity $I_W \sim 14.25$ of the variable search (most of these sequences are visible in Cook et al. 1997). An examination of the luminosity functions of variable and non-variable stars on the giant branch shows that >80% of definite AGB stars (stars above the FGB tip) are variable. The luminosity function for variable stars below the FGB tip (and above the TPAGB minimum) looks like an extension of the luminosity function for definite AGB stars, suggesting that all the variable stars are on the AGB. A similar conclusion was reached by Alves et al. (1998). Note that the carbon stars are mostly confined to the brighter end of the observed luminosity range, and they lie mainly on sequences B and C.

Past studies (Feast et al. 1989; Hughes & Wood 1990) have shown that Mira variables lie on a distinct sequence in the (K, log$P$) plane. The present

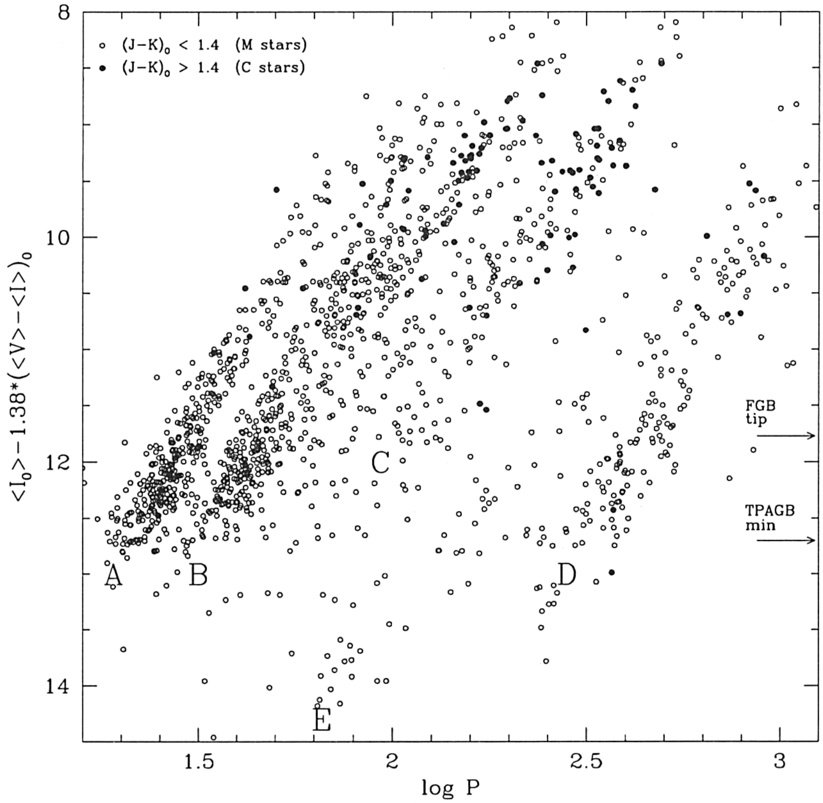

Figure 1. The period-luminosity relation for red variables. $<I>$ and $<V>$ are mean magnitudes, and P is in days. See text for details.

sample of stars has been plotted in the (K, log$P$) plane using single-phase K observations and from this plot we have identified sequence C as the sequence on which the Miras lie (this is also confirmed by the fact that the largest amplitude variables lie on this sequence, although not all stars on the sequence are of large amplitude). Wood & Sebo (1996) have shown that there is a second sequence of small-amplitude LPVs running parallel to the Mira sequence, and from the K observations we can identify sequence B with the second sequence of Wood & Sebo. Using HIPPARCOS data, Bedding & Zijlstra (1998) show that local semi-regular (SR) variables lie on both the Mira sequence and the second sequence of Wood & Sebo.

Examples of light curves of stars on each of the five sequences are shown in Fig. 2. Many of the light curves are semi-regular and multiperiodic. For those stars with two or more periods, the period ratio is plotted against P in Fig. 3.

There is a distinct group of variables in Fig. 3 with a period ratio of ~5-13. In these stars the longer period belongs to sequence D while the shorter period usually belongs to sequence B. A group of local SR variables showing similar period ratios is listed by Houck (1963). A second distinct group of stars in Fig. 3

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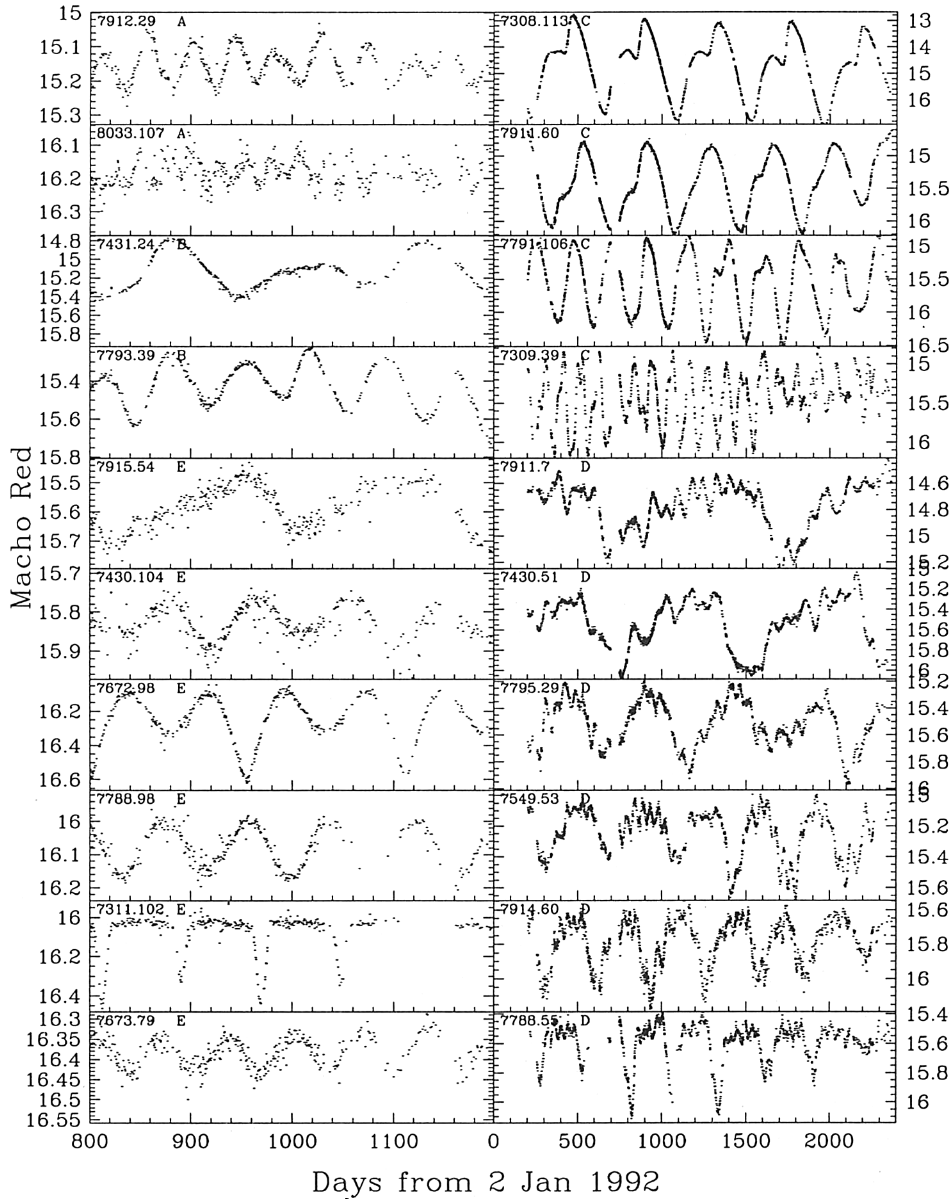

Figure 2. Examples of light curves. The sequence from which each variable comes is noted by one of the letters A...E. The luminosity and period in each sequence increase toward the top of the figure. Note the shorter time interval of the left column.

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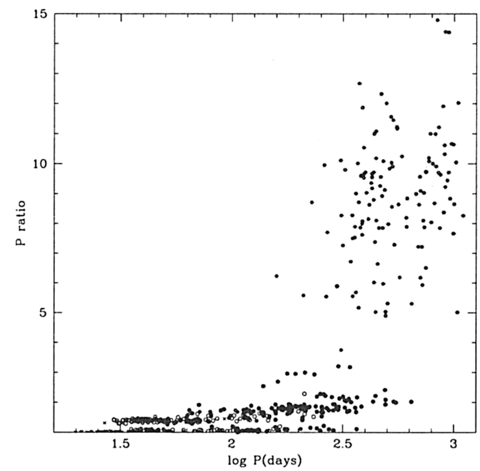

Figure 3. The ratio of the longer to the shorter period in multiperiodic stars plotted against the longer of the two periods.

has a period ratio of 1 to 4, with all periods belonging to sequences A, B or C. These stars are discussed in the next section.

4. The pulsating variables

Successful theoretical pulsation models for LPVs should be able to reproduce the observed P-L relations and the period ratios when the models lie on the observed giant branch. In this section, we try to reproduce the Mira P-L relation as a sequence of stars of different luminosity pulsating in the radial fundamental or first overtone mode. We note that Wood & Sebo (1996) found that they could reproduce the LMC Mira P-L relation assuming fundamental mode pulsation, but here we have the extra constraint of period ratios.

The results of the modelling, using the programs described in Wood & Sebo, are shown in Fig. 4. It is clear that fundamental mode pulsation is able to accurately reproduce the P-L relation of the Miras while simultaneously reproducing the observed period ratios reasonably well (considering the uncertainties in structure resulting from use of mixing-length theory). It is important to note that the solid circles in the period-ratio plot arise from stars in which the longer period lies on sequence C (the Mira sequence). Since the Miras are fundamental mode pulsators in these models, period ratios P_0/P_n, with n $>$ 0, should match these points. Indeed, stars with period ratios $>$2.5 are explained by the ratios P_0/P_2 or P_0/P_3, and the sequence of stars with period ratios of 1.7-2.5 is explained by the ratio P_0/P_1. The SR variables become 1st, 2nd or 3rd overtone pulsators in these models, although some could be low-amplitude fundamental mode pulsators. Finally, we note that short P Miras require a smaller mass than long P Miras if the models are to simultaneously fit the P-L relation and the giant branch. This is consistent with masses estimated from the kinematics of Galactic Miras (Feast 1963).

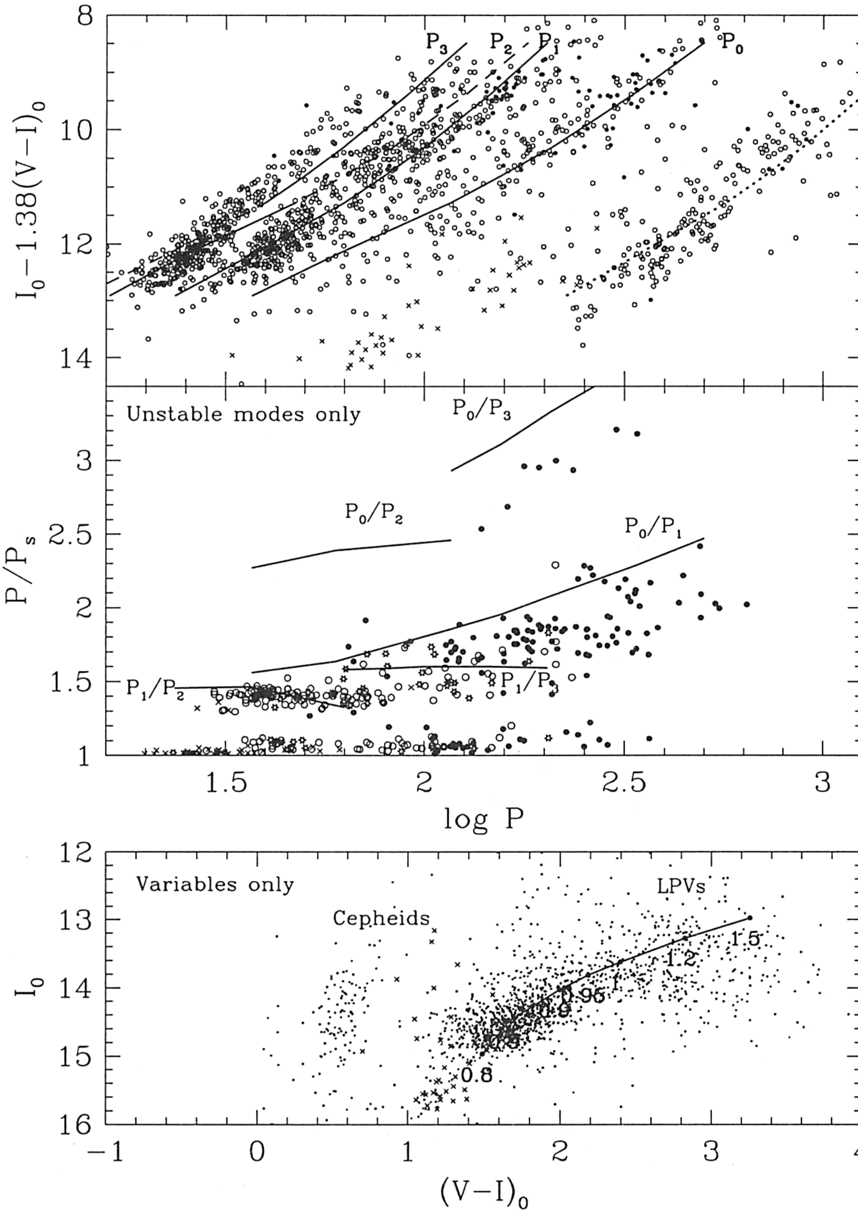

Figure 4. *Top panels*: the luminosity index I_W and the period ratio plotted against P. The solid (dashed) lines correspond to the unstable (stable) radial pulsation modes P_0, P_1, P_2 and P_3, as indicated. In the P-ratio plot, a line is shown only if both modes are unstable. The dotted line is the orbital period expected for an AGB star in a semi-detached binary (see text). *Bottom panel*: the theoretical AGB in the I_0, $(V-I)_0$ diagram. The mass ($M_\odot$) used at each luminosity is displayed. Crosses are stars with light curves like contact binaries.

Attempts were made to model the Miras as first overtone pulsators since this mode is suggested by direct radius measures of Miras (Haniff et al. 1995). However, first overtone models that fit the P-L relation are far too cool to fit the observed giant branch and, most importantly, it is not possible to produce Mira-to-secondary period ratios $\gtrsim$1.7 (as observed) from period ratios P_1/P_n, where n $= 2$ or 3 (such ratios are always $\lesssim$1.5, as in Fig. 4). The above results provide very strong evidence that Miras are fundamental mode pulsators.

5. Contact and semi-detached binaries

Six light curves from sequence E are shown in Fig. 2. Two of these light curves are immediately identifiable as binaries: 7311.102 is a detached, but relatively close, binary while 7672.98 is a contact binary. It is suggested here that all the other stars in this sequence are contact binaries. Most have quite symmetric light curves, like those shown by 7430.104, 7788.98 and 7673.79. These light curves are readily recognised among the other LPVs by their regularity and they are indicated by crosses in Fig. 4. These contact binaries lie on the FGB, where they make up ~0.5% of all stars in the search region (the brightest 1 mag. of the FGB); they also lie in the region occupied by intermediate mass stars ($M \gtrsim 2.25\ M_\odot$) at the red end of their core He burning loops.

Six light curves for stars on sequence D are shown in Fig. 2. These stars all have two distinct periods with a period ratio of 9±4 (Fig. 3). The higher frequency variation usually belongs to sequence B (1st overtone pulsation). The long secondary period (hereinafter LSP) belongs to sequence D. Some possible explanations for the LSPs are:

• Nonradial modes. The p-mode periods are shorter than those of the corresponding radial mode and they can not explain the LSPs. The g^- modes are dynamically unstable and lead to convection (rotation may stabilize some g^- modes, but it seems unlikely that such modes would fall on a well-defined P-L sequence). The oscillatory g^+ modes are evanescent in convective regions so it is unlikely they would be seen.

• Strange modes. Strange modes with roughly the correct period exist in these stars but all modes found were extremely damped and they should not be seen.

• The dust κ-mechanism (Winters et al. 1994; Höfner et al. 1995), a modulation caused by dust formation in the stellar wind. However, this mechanism seems to work only in the dense winds of (carbon) stars with $L \gtrsim 10^4 L_\odot$ whereas the LSPs are seen at all luminosities down to ~2 000 $L_\odot$.

The mechanisms above seem unable to explain the observed LSPs. The model proposed here is that the LSPs are due to an eclipse of the AGB star by a cloud of dusty accreted matter surrounding an orbiting, invisible companion star. The pulsating AGB star almost fills its Roche lobe and loses matter to the companion star via an enhanced stellar wind or Roche lobe overflow. The properties of the sequence D light curves, and their interpretation in terms of this model, are now given:

• The amplitudes range from the limit of detectability up to 0.8 mag.: the amplitude variations result from orbital inclination variation, as well as variations in the spatial extent and optical thickness of the cloud.

• The decline in the light curve is generally faster than the rise: this is consis-

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tent with the comet-like appearance of the cloud of accreted wind material in the SPH simulations of Theuns & Jorissen (1993).

- The 1st overtone pulsation is visible at all phases of the LSP: this is consistent with the semi-detached model where only the AGB star is seen.
- The 1st overtone period does not appear to vary with phase: this indicates that the LSP does not cause significant changes in the radius of the AGB star, as would happen with an intrinsic pulsation (e.g. a strange mode).
- The LSPs are seen only after the onset of intrinsic pulsation: this indicates that the enhanced mass loss induced by pulsation is needed to build up a significant cloud of accreted material.
- Most importantly, the LSPs lie on a distinct P-L sequence (Fig. 1).

The last point allows a quantitative test of the semi-detached binary hypothesis. Assuming the binary system is made up of two stars each of mass equal to the Mira mass derived above from pulsation theory, and assuming that the AGB star fills its Roche lobe, it is possible to calculate the orbital period of the system. The orbital period derived in this way is shown in Fig. 4 by the dotted line. There is remarkably good agreement between the predicted and observed periods, providing strong support for the hypothesis.

The ultimate test of the reality of the existence of semi-detached and contact binary systems on the AGB and FGB will come from observations of radial velocity variations. If the semi-detached binary nature of ~25% of AGB stars is confirmed, then these binaries provide a natural explanation for the formation of bipolar planetary nebulae, but their existence in such large numbers will require a substantial modification to binary star evolution theory.

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