HIPPARCOS PERIOD-LUMINOSITY RELATIONS FOR MIRA AND SEMIREGULAR VARIABLES

TIMOTHY R. BEDDING
School of Physics, University of Sydney, A28, Sydney, NSW 2006, Australia; bedding@physics.usyd.edu.au

AND

ALBERT A. ZIJLSTRA
Univesity of Manchester Institute of Science and Technology, Department of Physics, P.O. Box 88, Manchester M60 1QD, England, UK; aaz@iapetus.phy.umist.ac.uk

Received 1998 June 10; accepted 1998 August 13; published 1998 September 9

ABSTRACT

We present period-luminosity (P-L) diagrams for nearby Mira and semiregular variables, selecting stars with parallaxes better than 20% and well-determined periods. Using K-band magnitudes, we find two well-defined P-L sequences, one corresponding to the standard Mira P-L relation and the second shifted to shorter periods by a factor of about 1.9. The second sequence contains only semiregular variables, while the Mira sequence contains both Mira and semiregular variables. Several semiregular stars show double periods that are in agreement with both relations. The Whitelock evolutionary track is shown to fit the data, indicating that the semiregular variables are Mira progenitors. The transition between the two sequences may correspond to a change in the pulsation mode or to a change in the stellar structure. Large-amplitude pulsations that lead to the classical Mira classification occur mainly near the tip of the local asymptotic giant branch luminosity function.

Subject heading: stars: AGB and post-AGB

1. INTRODUCTION

Long-period variables (LPVs) include Mira variables (Miras) and semiregular variables (SRs). Mira variables are located at the tip of the asymptotic giant branch (AGB), where they experience thermal pulses (Iben & Renzini 1983). SRs usually have smaller amplitudes, shorter periods, and more irregular pulsations than Miras, and they often show evidence of multiple periods. The evolutionary relation between the two groups is not clear, but SRs are often considered to be Mira progenitors, in which case they would be located lower on the AGB.

Kerschbaum & Hron (1992, 1994) have argued that some SRs have physical characteristics identical to Miras and are only excluded from the Mira class because of the restrictive classical definition. A good example is the SRb star R Dor, which Bedding et al. (1998) show as alternating between periods of Mira and SR behavior. Such stars could be in a transition phase, but it is also possible that Miras and SRs coexist during the same evolutionary phase rather than forming a sequence in evolution.

Miras in the Large Magellanic Cloud (LMC) are known to follow a well-defined period-luminosity (P-L) relation for both $M_\text{bol}$ and $M_K$ (Feast 1996). This implies that they all pulsate in the same mode, presumably radial, but there is still some controversy over whether this is the fundamental or first overtone. Because of their shorter periods, it is sometimes assumed that SRs pulsate in higher overtones than Miras. Support for this was found by Wood & Sebo (1996), who show that LPVs in the LMC follow two sequences in a K-band P-L diagram. One is the well-known Mira sequence, and the other (a sample of eight stars) corresponds to periods about 2 times shorter. Sequences with shorter periods are seen in MACHO observations of the LMC and the Galactic Bulge (Minniti et al. 1998). The identification of SRs as higher overtone pulsators could mean that Miras and SRs are in a very closely related evolutionary phase.

Results from Hipparcos for 16 of the nearest Mira variables were presented by van Leeuwen et al. (1997), who show that, with two exceptions, the parallaxes are consistent with the same P-L relation as the LMC Miras. They inferred that this P-L relation corresponds to a first-overtone pulsation, with the two stars that fall below the sequence ($\chi$ Cyg and R Cas) being fundamental-mode pulsators (see also Barthès 1998). No stars were found that might correspond to the LMC secondary sequence of Wood & Sebo (1996).

2. SAMPLE SELECTION, PERIODS, AND MAGNITUDES

We selected Miras and SRs from the Hipparcos Catalogue (ESA 1997) using the following criteria:

1. Parallax precision: $\sigma/\pi \leq 0.2$. For the Mira R Leo, we follow van Leeuwen et al. (1997) in adopting the weighted mean of the Hipparcos parallax and a more precise ground-based measurement.

2. Coarse variability flag (catalogue field H6): $\geq 2$. This flag indicates how much variability was measured from the Hipparcos photometry ([1] $<0.06$ mag; [2] $0.06$–$0.6$ mag; [3] $>0.6$ mag). This constraint allows us to select true variables and to exclude M dwarfs.

3. Spectral type (field H76): M* or S*. We do not consider C stars here. Hipparcos results for carbon LPVs have been discussed recently by Bergeat, Knapik, & Rutily (1998).

A fourth criterium was to select stars with well-defined periods longer than 50 days. The Hipparcos Catalogue gives periods in cases where a solution was found in the photometric data, but the relatively short time span of the observations means that periods for most SRs were not identified. The regular variations in these stars have small amplitudes and are usually superposed on larger and more irregular variations, making a long time sequence necessary to determine the regular period.

We therefore used the General Catalogue of Variable Stars (GCVS; Kholopov et al. 1988) to identify those stars with
periods $\geq 50$ days. For Miras we adopted the GCVS periods, but for all other stars we insisted on confirmation from an independent source. In most cases, we analyzed visual observations supplied by the Association Francaise des Observateurs d'Étoiles Variables (AFOEV) and the Variable Star Observing League of Japan (VSOLJ). For six stars (RX Boo, T Cet, RS Cnc, AF Cyg, TX Dra, and g Her) we used the periods found by Mattel et al. (1997) from the American Association of Variable Star Observers data, while for three others we adopted periods in the literature that we considered reliable: R Dor (Bedding et al. 1998), RX Lep (Cristian et al. 1995), and SW Vir (Armour, Henry, & Baliunas 1990). For many stars we could not locate sufficient observations to confirm the GCVS period, while for others the observations exist but do not reveal definite periodicity. These stars were excluded from the sample.

The final sample (Table 1) contains six Miras and 18 SRs, seven of which have two periods. Note that two stars have been classified in the GCVS as SRc (second column), but this classification is reserved for supergiants, and these stars should be reclassified SRb. One star (W Hya) is classified SRa, reflecting its very regular pulsations.

We have taken $K$ magnitudes for the Miras from van Leeuwen et al. (1997). For most SRs, we used the values in Korschbaum & Hron (1994; reduced to the Carter 1990 system by subtracting 0.031 mag), the IRC Catalogue, and a few other references in the SIMBAD database. For R Dor we used the mean $K$ magnitude from Bedding et al. (1997), and for W Hya we used a mean value from P. A. Whitelock (1997, private communication). For many SRs, these are single-epoch observations. Stellar variability will introduce some additional scatter into the $P$-$L$ diagram, but the $K$-band amplitudes of SRs are small. Even for Miras, single-phase observations produce a scatter about the mean ($K, \log P$)-relation in the LMC of only 0.26 mag (Hughes & Wood 1990), and we expect the spread for SRs to be less than 0.1 mag. For SRs for which we have multiple $K$-band measurements, these generally agree to within 0.1 mag.

### 2.1. Bias

Our sample is selected on the basis of $\sigma_\mu/\pi$, so it will be affected by the Lutz-Kelker bias (Lutz & Kelker 1975; Koen 1992; Oudmaijer, Groenewegen, & Schrijver 1998); on average, distances will tend to be underestimated. This is partially canceled by the decrease of precision at fainter magnitudes, which causes us to select fewer stars at large distances. We can use the calculations by Koen (1992) to estimate the net bias in absolute magnitude, where we select the $p = 2$ case so as to include both effects. The most probable value for the bias is $-0.05$ mag for stars with $\sigma_\mu/\pi = 15\%$ and $-0.1$ mag for $\sigma_\mu/\pi = 20\%$. The mean values for the expected bias are $-0.2$ mag and $-0.4$ mag, respectively, although individual confidence limits are much poorer. The above values give estimates of the most likely and average amounts by which stars have been shifted down in the $P$-$L$ relations (being slightly more luminous than indicated by their parallaxes).

In summary, even for the least accurate parallax measurements in our sample, the sample bias in $M_K$ is most likely around $-0.1$ mag, which is comparable to the scatter in the photometry. For some individual stars, the effect will be larger but is still not likely to change the conclusions of this Letter, particularly the existence of two separated $P$-$L$ sequences.

### 3. DISCUSSION

#### 3.1. Mira and Semiregular Relations

Figure 1 shows the $K$-band $P$-$L$ diagram for stars in our sample (stars with two periods are plotted twice). The solid diagonal line shows the LMC $P$-$L$ relation of Feast (1996):

$$M_K = -3.47 \log P + 0.91,$$

where $P$ is the period in days, and we adopt a distance modulus for the LMC of 18.56. The crosses show the LMC stars on which the relation is based, and the asterisks show the LMC cluster LPVs of Wood & Sebo (1996). The two sequences defined by the LMC stars agree well with our sample of Galactic LPVs.

Figure 2 shows the histogram of vertical distance from the $P$-$L$ relation for our sample. There is a peak at zero, containing stars in agreement with the relation, and another about 0.9 mag above it (corresponding to a leftward shift in period by a factor of 1.8). This confirms the existence of the secondary relation reported by Wood & Sebo (1996). In addition, several stars clearly fall below the relation by about 1 mag. The six Miras in our sample all fall either on the $P$-$L$ relation or below (for convenience, in Fig. 3 we reproduce the $P$-$L$ diagram of our sample with each point labeled). In contrast, all stars lying above the relation are classified as SR.

Of the seven SRs that have two periods, in five cases, the longer period falls on the standard Mira relation, and the shorter falls on or near the SR relation. (TX Dra and W Cyg do not give such good agreement, but their long periods only differ from the Mira relation by less than 2 $\sigma$. Furthermore, their period ratios agree well with those of the other stars.) The observed period ratios in these stars (1.76–1.90) should provide useful constraints for pulsation models.

### Table 1: Sample of Long-Period Variables

| Name          | GCVS   | Period (days) | $\pi$ (mas) | $\sigma_\pi$ (mas) | $K$ (mag) | Period (days) |
|---------------|--------|---------------|-------------|------------------|----------|---------------|
| RX Boo        | SRb    | 340           | 6.42        | 1.00             | -1.85    | 162, 305      |
| R Car         | Mira   | 308.7         | 7.84        | 0.83             | -1.35    | 309           |
| R Cas         | Mira   | 430.5         | 9.37        | 1.10             | -1.80    | 430           |
| V744 Cen      | SRb    | 90            | 6.00        | 0.76             | -0.75    | 92            |
| T Cep         | Mira   | 388.1         | 4.76        | 0.75             | -1.71    | 388           |
| SS Cep        | SRb    | 90            | 4.04        | 0.64             | -0.56    | 99            |
| T Cet         | SRc    | 158.9         | 4.21        | 0.84             | -0.85    | 162, 299      |
| a Cet         | Mira   | 332.0         | 7.79        | 1.07             | -2.50    | 332           |
| RS Cnc        | SRc    | 120           | 8.21        | 0.98             | -1.65    | 129, 229      |
| RR Cib        | SRb    | 60.8          | 3.67        | 0.73             | 0.94     | 60.0          |
| W Cyg         | SRb    | 131.1         | 5.28        | 0.63             | -1.35    | 131, 236      |
| AF Cyg        | SRb    | 92.5          | 3.30        | 0.58             | 0.29     | 92.5, 163     |
| x Cyg         | Mira   | 480.1         | 9.43        | 1.36             | -1.93    | 408           |
| EU Del        | SRb    | 59.7          | 9.16        | 0.99             | -1.10    | 62.2          |
| R Dor         | SRb    | 338           | 16.02       | 0.69             | -3.91    | 175, 332      |
| TX Dra        | SRb    | 78            | 3.52        | 0.56             | 1.43     | 77, 136       |
| X Her         | SRb    | 95.0          | 7.26        | 0.70             | -1.48    | 101           |
| g Her         | SRb    | 89.2          | 9.03        | 0.61             | -1.99    | 89.5          |
| W Hya         | SRa    | 361           | 8.73        | 1.09             | -3.17    | 383           |
| R Leo         | Mira   | 310.0         | 8.81        | 1.00             | -2.55    | 310           |
| RX Lep        | SRb    | 60            | 7.30        | 0.71             | -1.35    | 98            |
| L1 Pup        | SRb    | 140.6         | 16.46       | 1.27             | -2.65    | 139           |
| e Ser         | SRb    | 100           | 6.27        | 1.00             | -1.06    | 111           |
| SW Vir        | SRb    | 150           | 7.00        | 1.20             | -1.82    | 162           |
3.2. Whitelock Evolutionary Track

The Mira $P$-$L$ relation cannot be an evolutionary sequence (see, e.g., Whitelock, Feast, & Catchpole 1991). Instead, Whitelock (1986) has shown that Miras and SRs within a globular cluster define a sequence in the $P$-$L$ diagram that is shallower than the Mira $P$-$L$ relation. Within each cluster, Miras are located at the intersection of this sequence with the $P$-$L$ relation. This sequence, the Whitelock track, is therefore the most probable evolutionary track. The slope of the Whitelock track agrees with the evolutionary calculations of Vassiliadis & Wood (1993).

The Whitelock track has been defined only for $M_{bol}$. To convert it to $M_K$, we used data from Whitelock (1986) for 47 Tuc and NGC 5927, two clusters with similar high metallicity and Mira populations with the same period distribution. For these stars, we find that the Whitelock track is fitted by

$$M_K = -(1.67 \pm 0.12) \log P - (3.05 \pm 0.25),$$

where the zero point depends on the distance scale used. The slope of this Whitelock track varies little for stars with initial masses up to $2.5 M_\odot$ (Vassiliadis & Wood 1993), while the end point (lying on the Mira $P$-$L$ relation) shifts to brighter magnitudes for younger populations.

The dotted line in Figure 1 shows the Whitelock track shifted up by 0.8 mag so as to pass through the SRs. The track fits reasonably well and connects the highest density of points on the $P$-$L$ relation with the same for the SR sequence, confirming its importance as an evolutionary track. The SRs in our sample thus can be considered progenitors of Miras having periods above 300 days. This agrees with the kinematical studies of...
SRs (Feast, Woolley, & Yilmaz 1972), which show a relatively low velocity dispersion, independent of period and similar to the velocity dispersion of long-period Miras. Shorter period Miras show higher velocity dispersions, indicating an older population. Hipparcos proper motions for our sample also agree with these findings.

Although the shifted Whitelock track fits the SR data quite well, it does not explain the clustering into two separate sequences. The clustering shows that the evolution along the Whitelock track is not continuous: instead, stars spend more time near the location of the sequences. This, together with the double-mode stars that may fit both sequences, can be interpreted as a difference in the pulsation mode between the two sequences. In this interpretation, the luminosity of the star increases during the SR phase, followed by a sudden increase in period due to a mode change, after which evolution continues on the Mira relation. However, this interpretation is by no means proved. An alternative possibility is that the period changes because of an adjustment in the stellar structure. In this case, the fact that the shorter periods of double-mode LPVs fitted the SR sequence would be coincidental.

4. CONCLUSIONS

We have identified period-luminosity sequences for Miras and SRs by selecting stars with precise Hipparcos parallaxes. Our main conclusions are as follows:

1. A significant number of SRs fall on the standard Mira P-L relation, implying that they pulsate in the same mode as most Miras and are closely related in evolution.

2. The remaining SRs define a second P-L sequence with the same slope but shifted to shorter periods by a factor of about 1.9. Most of the SRs that fall on the standard Mira P-L relation have a secondary period that falls on or near the SR relation. The period ratios are in the range 1.76–1.9.

3. Large-amplitude pulsations seen in classical Miras occur mainly near the tip of the local AGB luminosity function.

4. The slope of the Whitelock evolutionary track agrees with the data, implying that the SRs are progenitors of long-period Miras. The separation into two sequences may be due to either a difference in pulsation mode or an adjustment in the stellar structure.

We are grateful to the Hipparcos team and to the hundreds of amateur observers whose measurements were critical to this Letter. Visual data for many stars were obtained from the AFOEV database, operated at CDS, France, and the VSOLJ database in Japan. We also made extensive use of the SIMBAD and ADS data services. We thank the referee, Mike Feast, for valuable suggestions that led to significant improvements in the Letter. For financial support, T. R. B. is grateful to the Australian Research Council, and A. A. Z. thanks the European Southern Observatory.

REFERENCES

Armour, J. E., Henry, G. W., & Baliunas, S. L. 1990, Inf. Bull. Variable Stars, 3521, 1
Barthès, D. 1998, A&A, 333, 647
Bedding, T. R., Zijlstra, A. A., Jones, A., & Foster, G. 1998, MNRAS, submitted
Bedding, T. R., Zijlstra, A. A., von der Lühe, O., Robertson, J. G., Marson, R. G., Barton, J. R., & Carter, B. S. 1997, MNRAS, 286, 957
Bergeat, J., Knapik, A., & Rutily, B. 1998, A&A, 332, L53
Carter, B. S. 1990, MNRAS, 242, 1
Cristian, V. C., Donahue, R. A., Soon, W. H., Baliunas, S. L., & Henry, G. W. 1995, PASP, 107, 411
ESA. 1997, The Hipparcos and Tycho Catalogues (ESA SP-1200; Noordwijk: ESA)
Feast, M. W. 1996, MNRAS, 278, 11
Feast, M. W., Glass, I. S., Whitelock, P. A., &Catchpole, R. M. 1989, MNRAS, 241, 375
Feast, M. W., Woolley, R., & Yilmaz, N. 1972, MNRAS, 158, 23
Hughes, S. M. G., & Wood, P. R. 1990, AJ, 99, 784
Iben, I., Jr., & Renzini, A. 1983, ARA&A, 21, 271
Kerschbaum, F., & Hron, J. 1992, A&A, 263, 97
Kerschbaum, F., & Hron, J. 1994, A&AS, 106, 397
Kholopov, P. N., et al., eds. 1988, General Catalogue of Variable Stars (4th ed.; Moscow: Nauka)
Koen, C. 1992, MNRAS, 256, 65
Lutz, T. E., & Kelker, D. H. 1975, PASP, 87, 617
Mattei, J. A., Foster, G., Hurwitz, L. A., Malatesta, K. H., Willson, L. A., & Mennessier, M.-O. 1997, in Proc. Hipparcos Venice ‘97 Symp., ed. B. Battrick (ESA SP-402; Noordwijk: ESA), 269
Minniti, D., et al. 1998, in Pulsating Stars—Recent Developments in Theory and Observation, ed. M. Takeuti & D. Sasselov (Tokyo: Universal Academy Press), 5 (MACHO Collaboration)
Oudmaijer, R. D., Groenewegen, M. A. T., & Schrijver, H. 1998, MNRAS, 294, L41
van Leeuwen, F., Feast, M. W., Whitelock, P. A., &Yudin, B. 1997, MNRAS, 287, 955
Vassiliadis, E., & Wood, P. R. 1993, ApJ, 413, 641
Whitelock, P. A. 1986, MNRAS, 219, 525
Whitelock, P. A., Feast, M. W., & Catchpole, R. 1991, MNRAS, 248, 276
Wood, P. R., & Sebo, K. M. 1996, MNRAS, 282, 958