LUMINOSITIES OF AGB VARIABLES

Patricia Whitelock
SAAO, PO Box 9, Observatory, 7935, South Africa.
paw@saao.ac.za

Abstract The prevailing evidence suggests that most large-amplitude AGB variables follow the period luminosity (PL) relation that has been established for Miras in the LMC and galactic globular clusters. Hipparcos observations indicate that most Miras in the solar neighbourhood are consistent with such a relation. There are two groups of stars with luminosities that are apparently greater than the PL relation would predict: (1) in the LMC and SMC there are large amplitude variables, with long periods, \( P > 420 \) days, which are probably undergoing hot bottom burning, but which are very clearly more luminous than the PL relation (these are visually bright and are likely to be among the first stars discovered in more distant intermediate age populations); (2) in the solar neighbourhood there are short period, \( P < 235 \) days, red stars which are probably more luminous than the PL relation. Similar short-period red stars, with high luminosities, have not been identified in the Magellanic Clouds.

Keywords: Mira variables, variable stars, carbon stars, LMC, Sagittarius Dwarf Spheroidal, Local Group Galaxies, Solar Neighbourhood, Hipparcos, luminosities, PL relation.

Introduction

This review concentrates on the luminosities of large amplitude Mira-like variables. These are of particular interest because it is during this large-amplitude phase that most of the mass loss occurs. Furthermore, the kinematics of these stars depend upon their pulsation period; thus, if we can measure the period, we can tell a great deal about the star and its parent population (Feast & Whitelock 2000a). I discuss both O- and C-rich variables, but concentrate on the O-rich ones about which we know most. Because of its importance to luminosities, some emphasis is put on the period luminosity (PL) relation, drawing on observations of globular clusters, the Magellanic Clouds, other local group galaxies and last but not least, the solar neighbourhood.
Before examining what we know about luminosities it is worth emphasizing the importance of AGB variables in the understanding of extragalactic populations. The most luminous stars present in old or intermediate age populations are the large-amplitude AGB variables. Thus, as we become able to resolve individual stars in ever more distant stellar populations, those we see first and best will be this type of AGB variable. So, if we are to use such stars as probes of their parent population, it is crucial that we understand how their properties depend on age, metallicity etc.

1. Globular Cluster Miras

The Miras in globular clusters have always been key to calibrating the luminosity of the tip of the AGB. Unfortunately, because of their short lifetimes there are rather few Miras in globular clusters and fewer still that have been well studied. Let me remind you that the Miras are the most luminous stars found in the clusters; in fact they are the only stars with luminosities above the tip of the red giant branch (RGB). They are only found in metal-rich clusters ([Fe/H] > −1), and we presume that the AGB in metal-deficient systems terminates below the tip of the RGB. The pulsation period of a Mira is a function of the metallicity of its parent cluster (e.g. Feast & Whitelock 2000b). In fact it is only for the Miras in clusters, and a very few in binary systems, that we can determine metallicities. The Miras in galactic globular clusters are all O-rich and there is no particular evidence to suggest that they have reached the thermally pulsing part of the AGB.

Feast et al. (2002) recently reexamined the luminosities of the Miras in globular clusters using a new distance calibration based on Hipparcos parallaxes of sub-dwarfs and published photometry for 6 galactic globular clusters, together with new observations of NGC 121 v1, a short period low metallicity Mira in the SMC. They demonstrated that these cluster Miras fit the same PL relation as do the LMC Miras, and derived a zero-point for the PL relation. There are many globular clusters, particularly near the galactic centre, which have not yet been properly surveyed for Miras. We are in the process of rectifying this situation using the Infrared Survey Facility in South Africa in collaboration with astronomers from the University of Tokyo. Any new cluster Miras will obvious improve our statistics, but we are particularly hopeful about finding some longer period stars in the metal-rich bulge clusters.

Once there are theoretical models which deal effectively with mass-loss, and allow us to predict accurately the AGB tip luminosity for different populations, we will be able to use them to calibrate extragalactic
systems. But, until that level of theoretical understanding is reached, those who wish to study extragalactic systems will make deductions based on a comparison with globular clusters or with the galactic bulge. The recent literature contains numerous studies of AGB populations in local group galaxies and beyond and it is interesting to see comparisons being made with galactic globular clusters and very different conclusions being drawn by different authors from essentially the same data. Figure 1 shows a colour magnitude diagram for cluster variables, of the kind typically used for comparison with extragalactic systems. The most luminous cluster star illustrated here is NGC 6553 v4, for which the reddening is uncertain; it is plotted in the figure as two connected open circles for two different reddenings. The lower mean luminosity seems more likely and this is one magnitude fainter than the $K = -8.5$ which some authors use.

It is also worth noting that comparing the luminosity of individual stars in extragalactic systems with those of AGB variables in the galactic bulge is even more fraught with uncertainty, because the shape of the bulge and the presence of significant numbers of foreground stars result in many stars having distances less than that of the centre and therefore luminosities that appear to be much brighter than they really are.

Variability is also a factor in comparing one system with another. The short period Miras, found in globular clusters, typically have peak-to-peak $K$ amplitudes of around half a magnitude, so there is a high level of uncertainty associated with single measurements of the luminosity. Longer period stars have larger amplitudes, reaching over two magnitudes for the 1000 day variables discussed below.
Large Magellanic Cloud (LMC)

The PL relation for Mira variables was discovered for stars in the LMC, and Feast et al. (1989) refined earlier results to show that at K the O- and C-rich stars obeyed the same same PL relation. The bolometric luminosities seemed to show slightly different relations for the O- and C-rich stars, although there was always the suspicion that this was an artifact of the way that the bolometric magnitudes were calculated. Feast et al. also noted that O-rich stars with \( P > 420 \) days were significantly more luminous than the PL relation would predict.

Working independently, but at roughly the same time, Hughes & Wood (1990) came to similar conclusions; although they described the PL relation as having two linear parts, with a steeper slope over the long period (\( P > 400 \) days) range. Their derivation of a PL relation had considerable scatter, because their bolometric magnitudes were calculated from single observations rather than from the mean values.

More recently we have been working on much longer period stars in the LMC, which were discovered via their IRAS emission (e.g. Wood et al. 1992; Zijlstra et al. 1996). Most of these are obscured stars with high mass-loss rates. In globular cluster Miras the energy distribution peaks at a wavelength between 1 and 2 \( \mu \)m, while for these IRAS sources the energy peaks at longer wavelengths, \( \lambda > 4 \mu \text{m} \). There has, as yet, been little opportunity for systematic monitoring around the pulsation cycle at long wavelength, although a few repeated ISO observations allow us to estimate the bolometric amplitudes at around one magnitude. There are small systematic differences in the bolometric magnitudes obtained using ISO and IRAS. Furthermore, the way the colour corrections are treated can give rise to systematic differences between O- and C-rich stars. Thus we cannot yet claim to have accurate mean luminosities. Nevertheless, the overall impression given by all the available results is that most of the dusty Miras, with long periods, \( 420 < P < 1300 \) days, fall on an extrapolation of the PL relation derived for O-rich stars with \( P < 420 \) days.

Looking in detail at the stars with bolometric magnitudes brighter than the PL extrapolation, we find that all those which have been studied show evidence for hot bottom burning (HBB), in particular they have very strong lithium lines (but see also Trams et al. 1999). Towards the end of the AGB evolution, in stars with initial masses in the range 4 to 6 \( M_\odot \), the base of the H-rich convective-envelope can dip into the H-burning shell; the introduction of fresh H-rich material into the nuclear-burning shell allows the luminosity to go above the core-mass luminosity predictions (Blöcker & Schönberner 1991). Carbon is burned to nitrogen,
and lithium can reach the surface via the beryllium transport mechanism (Sackmann & Boothroyd 1992). Smith et al. (1995) surveyed luminous AGB stars in the LMC and SMC for lithium - the clearest indication that HBB is taking place. Almost all stars with high lithium abundance lie above the PL relation, and we can now understand the change in slope of the PL, at around 400 to 420 days, as the effect of HBB in LPVs without particularly thick dust shells. Those stars with thick shells, like the ones for which we have ISO observations, are lower mass objects, lie near the PL, and probably never experienced HBB.

An important contribution is provided by the work of Nishida et al. (2000) who monitored 3 C-rich Miras, with thick dust shells, in SMC and LMC clusters, and were thus able to estimate pulsation periods and bolometric magnitudes for stars with known initial mass and metallicity. The periods are all around 500 days and the luminosities are very close to an extrapolation of the Feast et al. (1989) PL for short period O-rich stars. The turnoff masses for these clusters are around $1.5 M_\odot$, and therefore much too low for their AGB stars to have undergone HBB.

3. Other Local Group Galaxies

Leaving the Magellanic Clouds, but staying in the local group we look at C-rich Miras in the Sagittarius dwarf spheroidal. This is the galaxy, discovered only in 1994, that is merging with the Milky Way on the far side of the bulge. It contains Miras with periods in the range 230 to 360 days, distinctly shorter than those in Magellanic Cloud clusters, as we might expect from this somewhat older population (Whitelock et al. 1999). The distance modulus derived from the Mira PL, $(m - M)_0 = 17.36 \pm 0.2$ mag, is in good agreement with that from RR Lyrae variables, $(m - M)_0 = 17.18 \pm 0.2$ mag.

There is a Mira in IC 1613 with a period of 641 days, the luminosity of which is considerably brighter than the prediction of the PL relation (Kurtev et al. 2001). With a spectral type of M3e it is clearly O-rich, and from what has been said above we must predict that it is undergoing HBB burning. It would be interesting to look for lithium in its spectrum.

The Leo I dwarf spheroidal contains several large amplitude variables (see Menzies, these proceedings). There is also evidence of very red C-stars from 2MASS observations of Fornax; these will almost certainly turn out to be C-Miras. We can look forward to similar discoveries in other local group galaxies and beyond, during the next few years.
4. Solar Neighbourhood

Returning closer to home I want to finish by looking at what we know about luminosities from Hipparcos parallaxes (Whitelock et al. 2000; Whitelock & Feast 2000; Feast & Whitelock 2000a). It is worth noting that the stars selected for the Hipparcos input-catalogue had to be visually bright throughout their pulsation cycle. Therefore, this selection of stars have, of necessity, low mass-loss rates, $< 10^{-7} M_\odot yr^{-1}$; they are different from the LMC sample discussed above. The selection comprised 213 O-rich Mira-like variables with $K$ magnitudes and pulsation periods.

Before discussing the parallax analysis I outline some of the characteristics of these stars, and their dependence on period and colour. Figure 2 shows the stars in a period-colour plot, where $Hp$ is the Hipparcos broad-band magnitude. At short periods the variables divide into two sequences, a blue one that contains most of the stars and a parallel red one which contains a significant fraction of the shortest period stars; notice that both sequences contain SRs and Miras. The straight line in Fig 2 divides the stars into two groups: those above the line are the short period red (or SP-red) group, while those below, which form part of the sequence seen at longer periods, are the short-period blue (or SP-blue) group (Whitelock et al. 2000).

The pulsation amplitudes of the two groups are very similar, but the colour differences extend to their near-infrared colours - the mean spectral type of the red group, M4.5, is later than that of the SP-blues, M3. Furthermore, the kinematics and scale heights of the two groups are different. The SP-blue stars have larger scale heights, a greater velocity dispersion and a larger asymmetric drift than the SP-red stars. The SP-blue stars have similar characteristics to the Miras found in globular clusters, while the SP-reds seem to be rather different and apparently somewhat younger (see also Feast these proceedings). The differences
Table 1. PL Zero-Point from the Hipparcos Parallax.

| No. Stars | \( \beta \) (mag) | \( \sigma_\beta \) | Stars Included                  |
|-----------|-------------------|-----------------|---------------------------------|
| 180       | 0.84              | 0.14            | not SP-red; \( \Delta H_p > 1.5 \text{ mag} \) |
| 37        | 0.93              | 0.46            | SP-blue only                    |
| 18        | 0.40              | 0.24            | SP-red only                     |
| 38        | 0.90              | 0.31            | Carbon stars                    |

between these two groups justifies treating them differently in the parallax analysis.

Given the high uncertainties on the parallax measurements it is not practical to fit a PL relation to the data. Rather we assume the slope of the PL relation \( M_K = -3.47 \log P + \beta \), derived from the LMC work, and deduce \( \beta \), the zero point, from the parallaxes. The PL relation is solved in the form:

\[
10^{0.2 \beta} = 0.01 \pi 10^{0.2(3.47 \log P + K_0)},
\]

where \( \pi \) is the parallax in mas. This allows us to use all the parallax data, and thus minimize the bias which would be introduced by selection. The right-hand side of the equation is weighted appropriately as described by Whitelock & Feast (2000a).

The equations were solved for various different subsets of the data, some of which are listed in Table 1 (it may be necessary to add a bias correction, \( \sim 0.04 \text{ mag to these values} \)). The best result for the Miras is given by the group of 180 stars which excludes the SP-red group and the small amplitude variables, that should probably never have been considered as Mira-like. The value of the zero-point for that group, \( \beta = 0.84 \pm 0.14 \), corresponds to a distance modulus for the LMC of 18.64, which is comparable to values obtained in other ways. I should also draw your attention to the estimates of the zero point for the SP-red and SP-blue stars listed in the table. Given the large uncertainties the difference between them is not significant, but this difference between the SP-reds and the main Mira group (top row) is significant, and together with other evidence of differences, suggests that the SP-red stars may be brighter than the Mira PL relation would predict.

It is worth making a comparison with the various sequences in the PL diagram for the LMC, as discussed by Wood (2000) on the basis of Macho data. The SP-blue stars are presumably identical to the normal Miras, i.e. sequence C in Wood’s nomenclature. According to Table 1 the SP-reds are about 0.5 mag brighter than the SP-blues, whereas Wood’s B sequence is about 1.3 mag brighter. Note again that there is no difference
in the mean pulsation amplitude of the two groups. It therefore seems that stars like these SP-reds have not yet been identified in the LMC. The kinematic difference between the SP-reds and SP-blues shows that they cannot be similar stars pulsating in different modes. The possibility remains that the SP-reds have a relationship to longer period Miras (\(P > 235\) days) which do have similar kinematics. If that is the case then the SP-reds must be in a slightly earlier evolutionary phase than Miras on the PL relation.

To conclude my comments on the local Miras, it would seem that, with the exception of a small number with short periods and red colours, the large amplitude variables fall on the same PL relation as do Miras in the LMC and in globular clusters.

Finally, space has not permitted a discussion of the numerous OH/IR variables near the galactic centre, which prevailing wisdom suggests are faint, but which are difficult to measure accurately. More work is also needed on C-star luminosities; the evidence points to their also obeying the PL, but dust shells often make luminosity estimates difficult.

Acknowledgments

I wish to thank my various colleagues, particularly Michael Feast, Jacco van Loon, and Albert Zijlstra for their patience in the face of my slow progress towards publication. My thanks also to Michael Feast and John Menzies for advice and critical reading of this manuscript.

References

Blöcker, T. and Schönberner, D. (1991). A&A, 244, L43.
Feast, M.W. and Whitelock, P.A. (2000a). MNRAS, 317, 460.
Feast, M.W. and Whitelock, P.A. (2000b). In: F. Matteucci and F. Giovannelli (eds.), The Evolution of the Milky Way, Kluwer, 229.
Feast, M.W. et al. (1989). MNRAS, 241, 375.
Feast, M.W., Whitelock, P.A. and Menzies, J.W. (2002). MNRAS, 329, L7.
Hughes, S.M.G. and Wood, P.R. (1990). AJ, 99, 784.
Kurtev, R. et al. (2001). A&A, 378, 449.
Nishida, S. et al. (2000). MNRAS, 313, 136.
Sackmann, I.-J. and Boothroyd, A. (1992). ApJ, 392, L71.
Smith, V.V., Plez, B., Lambert, D.L. and Lubowich, D.A. (1995). ApJ, 441, 735.
Trams N.R., et al. (1999). A&A, 344, L17.
Whitelock, P.A. and Feast, M.W. (2000). MNRAS, 319, 759.
Whitelock, P.A., Marang, F. and Feast, M.W. (2000). MNRAS, 319, 728.
Whitelock, P.A. et al. (1999). In: P.A. Whitelock & R. Cannon (eds.), The Stellar Content of Local Group Galaxies, IAU Symp., 192, ASP, 136.
Wood, P.R. (2000). PASA, 17, 18.
Wood, P.R., Whiteoak, J.B., Hughes, S.M.G., et al. (1992). ApJ, 397, 552.
Zijlstra, A.A., Loup, C., Waters, L.B.F.M., et al. (1996). MNRAS, 279, 32.