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Asymptotic giant branch variables as extragalactic distance indicators

Patricia A. Whitelock[1,2]

[1]South African Astronomical Observatory, P. O. Box 9, 7935 Observatory, South Africa
[2]Astronomy, Cosmology and Gravity Centre, Astronomy Department, University of Cape Town, 7701 Rondebosch, South Africa

Abstract. Large-amplitude asymptotic giant branch variables potentially rival Cepheid variables as fundamental calibrators of the distance scale, particularly if observations are made in the infrared, or where there is substantial interstellar obscuration. They are particularly useful for probing somewhat older populations, such as those found in dwarf spheroidal galaxies, elliptical galaxies or in the haloes of spirals. Calibration data from the Galaxy and new observations of various Local Group galaxies are described and the outlook for the future, with a calibration from *Gaia* and observations from the next generation of infrared telescopes, is discussed.

Keywords. stars: late-type, stars: distances, stars: carbon, stars: AGB and post-AGB, galaxies: distances and redshifts, galaxies: dwarf, galaxies: individual (NGC 6822, Fornax dSph, Leo I, Sculptor, Phoenix), galaxies: stellar content

1. Introduction

The focus of this paper is on the large-amplitude, or Mira, asymptotic giant branch (AGB) variables. Because of their high luminosity, and particularly their high *infrared* luminosity, stars in this group have huge potential as extragalactic distance indicators. I briefly describe what we know about the Mira period–luminosity (PL) relationship, before going on to review recent work on Miras in Local Group galaxies, contrasting those found in dwarf spheroidals with those in the dwarf irregular galaxy NGC 6822.

Miras are very large-amplitude ($\Delta V > 2.5$, $\Delta K > 0.4$ mag), long-period ($P > 100$ days) variables. They are close to the maximum bolometric luminosity that they will ever achieve and they are cool, with spectra dominated by molecular absorption. Stars with initial masses in the range from 0.8 to 8 $M_\odot$, possibly higher, are thought to go through the Mira evolutionary phase. For most of their AGB lifetime, their nuclear energy comes from burning of the hydrogen shell. However, from time to time stars on the upper AGB experience helium-shell flashes with far-reaching consequences for the stellar atmospheres.

It is following these flashes that dredge-up can occur, bringing material from the core into the convective regime, and the atmospheric abundance can change from oxygen (O)- to carbon (C)-rich. In relatively high-mass AGB stars, hot-bottom burning can also affect abundances, turning carbon to nitrogen and producing lithium, among other things. The relative fraction of O- and C-rich Miras in any population is a function of both age and metallicity.

2. Period–Luminosity Relations

Early work on the Mira PL relation (e.g., at K or $M_{\rm bol}$) in the Large Magellanic Cloud (LMC) was published by Feast *et al.* (1989) and Hughes *et al.* (1990). However, our understanding of this was greatly advanced when Wood (2000) demonstrated that most AGB and upper-giant-branch variables followed various parallel PL sequences. The Mira PL relation, which had been known for some while, was just one of them. Wood showed that the Mira sequence corresponds to fundamental pulsation and includes most of the large-amplitude variables as well as a few of the low-amplitude, or semi-regular, variables. Some of the O-rich large-amplitude, long-period ($P > 400$ days) Miras lay above the fundamental sequence, as had also been known for some while.

The early studies of the multiple sequences used periods determined from microlensing studies, e.g., from MACHO and OGLE at V and I, and these results are now being refined as more systematic observations are made at infrared wavelengths. Among other things, the situation is obviously confused by the fact that many of the Miras have circumstellar shells. In some cases these are so thick that they affect the position of the star on the PL(K) relation (e.g., Ita & Matsunaga 2011). In those cases, it is preferable to work with bolometric magnitudes, if they can be reliably estimated, although it is sometimes possible to correct for circumstellar extinction.

The Miras which lie above the PL relation are an interesting subgroup that may be experiencing hot-bottom burning; there is certainly evidence for lithium and other enrichment (Whitelock *et al.* 2003; Whitelock 2012; and references therein). It also seems possible that they are pulsating in the first overtone (Feast 2009).

From the distance-scale perspective, the multiple PL sequences of the small-amplitude variables are not very useful, since it is unclear which sequence any particular star will be on. It is therefore only the Miras, i.e., the large-amplitude variables, that we consider useful for distance-scale studies and, where possible, Miras with short periods ($P < 400$ days) and thin dust shells are easier to work with.

Whitelock *et al.* (2008) discuss the Galactic calibration of the PL(K) relation and show that it is consistent with the LMC relation. Rejkuba (2004) demonstrated that the PL(K) relation for O-rich Miras in the LMC also fitted similar stars in NGC 5128. This, together with recent work on Miras in dwarf spheroidals and NGC 6822 (see below) is consistent with the same PL relation applying everywhere. It remains possible that there are metallicity effects, but these are unlikely to be significantly greater than 0.1 mag for stars from populations considered so far (see Matsunaga 2012).

3. Which Mira PL relation for distance-scale studies?

For most purposes at the present time it is preferable to work with the PL(K) relation, primarily because the K magnitude is easy to measure, the pulsation amplitude at K is lower than at shorter wavelengths and K is not often severely affected by circumstellar emission or absorption. However, pulsation drives mass loss, and there are Miras with thick shells and severe circumstellar reddening. This is particularly true of the very long-period O-rich Miras, known as OH/IR stars, but it is also the case for a variety of C-rich stars.

In principle using bolometric magnitudes avoids the problem with circumstellar extinction and there are three related ways of deriving such magnitudes, all of which have drawbacks:

(a) Ideally, one obtains bolometric magnitudes derived from multi-epoch measurements across a wide wavelength range extending at least into the mid-infrared regime. Such data are rarely available for many stars.

(b) An alternative approach uses well-calibrated colour-dependent (e.g., $J-K$) bolometric corrections, derived for stars that are similar to those of interest, and for which multi-wavelength observations are available. A potential problem is that the observed

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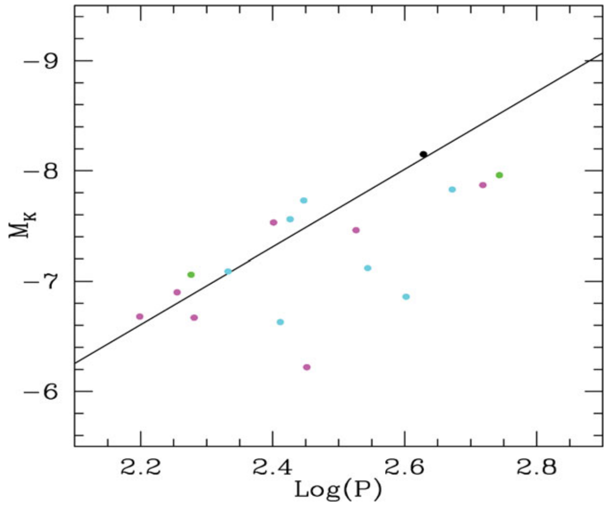

Figure 1. PL(K) relation for the Miras in the dwarf spheroidals, coded as follows: Fornax (cyan), Leo I (magenta), Sculptor (green), Phoenix (black). Periods are given in days. The line is at the slope of the LMC PL relation and assumes a distance modulus to the LMC of 18.39 mag (changing this distance modulus will not alter the loci of the points and the line, only their place relative to the magnitude scale).

colour is a combination of the intrinsic colour of the star and the reddening. The same $(J-K)$ colour can be due to different combinations of these two effects. Thus, $(J-K)$ may not necessarily be uniquely related to the true bolometric correction.

(c) It is sometimes possible to make a correction for the circumstellar reddening (e.g., Matsunaga *et al.* 2009), which is similar to applying a colour-dependent bolometric correction. The weakness of this is that it requires adoption of an intrinsic colour for the star and we have little evidence of the way this colour correlates with period, particularly for long-period stars, almost all of which have shells.

Of course, non-uniform shells, which are the obvious consequence of non-uniform mass loss, present obvious problems to any method for estimating the bolometric magnitude. Different methods of calculating the bolometric magnitude give very significantly different results. For example, Groenewegen *et al.* (2007) and Kamath *et al.* (2010) derive bolometric magnitudes for several pulsating stars in the Small Magellanic Cloud (SMC) cluster NGC 419 using slightly different $JHKL$ values but the same *Spitzer* data. Their bolometric magnitudes differ by amounts that range from −0.1 to 0.4 mag for the same star (see also Kerschbaum *et al.* 2010).

Noting the challenge of determining accurate bolometric magnitudes, estimated values can still provide useful distances, provided a very systematic approach is followed. In practice, this means determining the bolometric magnitude of the star for which the distance is required in *exactly* the same way as for the calibrators used to define the PL relation.

4. Globular Cluster: Lyngå 7

Matsunaga (2006) discovered a Mira variable, V1, in Lyngå 7 (an old, metal-rich Galactic bulge cluster) with a period of 551 days, a large amplitude, $\Delta K = 1.22$ mag, and red colour, $(J-K) = 4.1$ mag. Sloan *et al.* (2010) showed, based on a *Spitzer* spectrum, that it is carbon-rich and Feast *et al.* (2012a) used a spectrum from the

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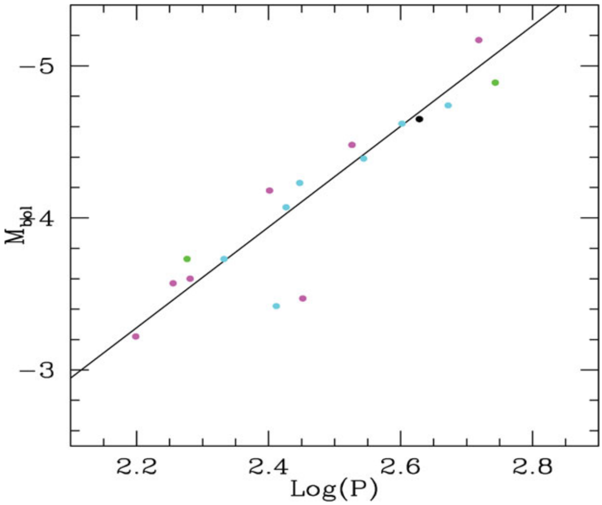

Figure 2. Bolometric PL relation for the Miras in the dwarf spheroidal galaxies, colours as in Fig. 1.

Southern African Large Telescope (*SALT*) to demonstrate that V1 is a radial-velocity member of the cluster.

Assuming a distance modulus of 14.55 mag (Sarajedini *et al.* 2007), this Mira has $M_{\rm bol} = -5.0$ mag, in agreement with the PL-relation value of $M_{\rm bol} = -5.2$ mag. Such a luminous star must have had an initial mass $M_{\rm i} \sim 1.5{\rm M}_{\odot}$ and cannot be a normal member of the cluster. It therefore must have formed from a stellar merger.

To the best of our knowledge, this is the first ever demonstration of a star that was produced by the merger of two others, but that nevertheless obeys a PL relation. It is an interesting result and we might well expect there to be remnants of other mergers in the dense environment of the Galactic bulge.

5. Local Group Galaxies

A group of us from South Africa and Japan have used the Infrared Survey Facility (*IRSF*) at the South African Astronomical Observatory to survey a variety of Local Group galaxies for AGB variables. The several-year survey uses observations made with the *SIRIUS* camera, which simultaneously gives J, H and $K_{\rm s}$ photometry over a 7×7 arcmin^2 field.

5.1. *Dwarf Spheroidal Galaxies*

Results so far have been published for a total of 17 Miras from Fornax, Leo I, Sculptor and Phoenix (Menzies *et al.* 2008, 2010, 2011; Whitelock *et al.* 2009). Where spectral types are available for these stars, they show them to be C-rich and we assume that they are all C-type stars.

Fig. 1 shows the absolute K magnitudes on a PL(K) relation for all the Miras in dwarf spheroidals. The large scatter is very striking and the distance below the LMC's PL(K) relation is a function of the $(J-K)$ colour, indicating that the stars below the line are there because of their thick circumstellar shells.

Bolometric magnitudes can be estimated using a $(J-K)$-dependent bolometric correction (Whitelock *et al.* 2009) and the results are shown in a PL relation in Fig. 2. The scatter is vastly reduced, although there are still two stars which lie well below the mean

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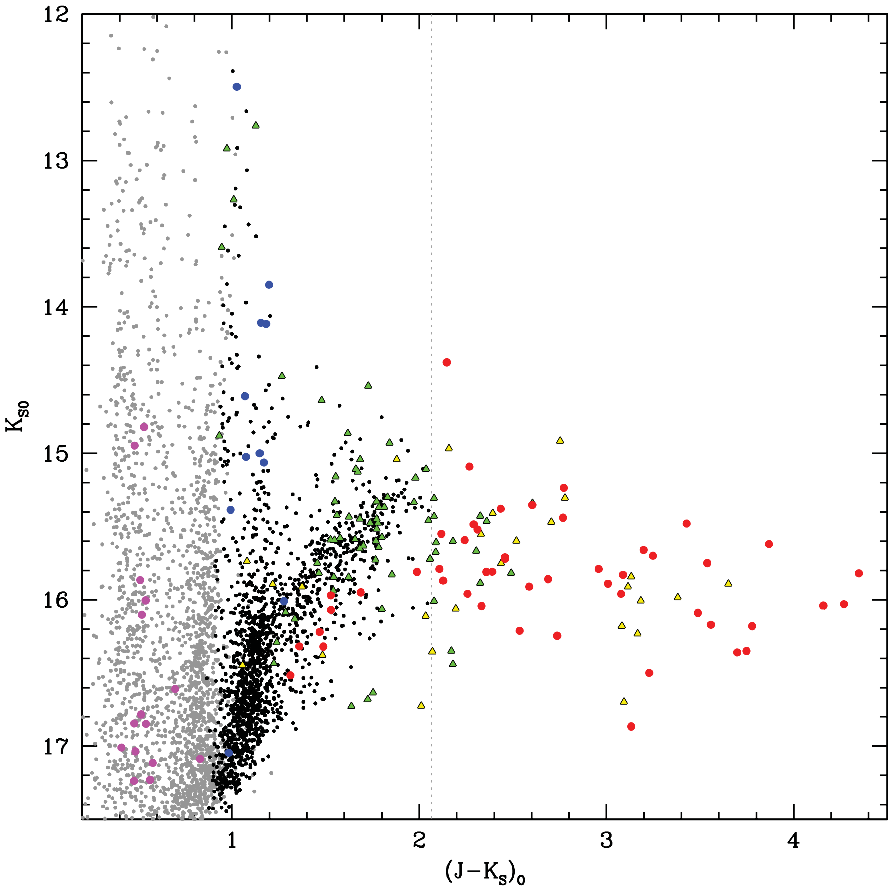

Figure 3. Colour–magnitude diagram for the variables in NGC 6822, showing Cepheids (magenta), large-amplitude variables with measured periods, which are presumed O-rich (blue) or C-rich (red), and variables without measured periods that have large (yellow) or small (green) amplitudes.

relation. Two possible explanations have been offered for these faint points. It may be that the bolometric correction does not apply to these intrinsically relatively blue, short-period, stars (see point [*b*] in Sect. 3), since it was derived for significantly longer-period stars. Alternatively, they are undergoing obscuration events of the type that are common among C-rich Miras in the Galaxy and the LMC (e.g., Whitelock *et al.* 2006) and have non-uniform shells.

5.2. *NGC 6822*

NGC 6822 is an isolated barred dwarf galaxy, similar to the SMC, but with slightly higher metallicity. It has been examined for AGB variables in the same way as the dwarf spheroidals over 3.5 years and has had numerous Miras catalogued (Whitelock *et al.* 2012; see also Battinelli & Demers 2011). Fig. 3 shows the variables in a colour–magnitude diagram. Spectral types are available for only very few stars and the split into O- and C-rich assumes that all very red stars are C-rich. Several of the large-amplitude stars without measured periods are probably also Miras and all very red stars are variable.

Fig. 4 shows the NGC 6822 Miras on a PL(K) relation. Most of the longer-period O-rich stars fall above the PL relation and are probably similar to the stars in the LMC

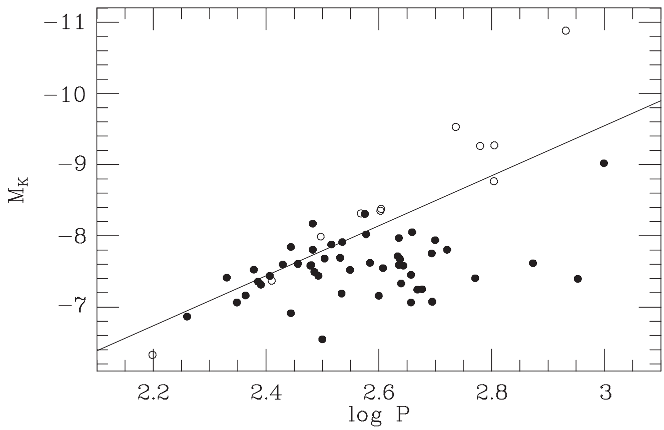

Figure 4. PL(K) relation for NGC 6822 showing O-rich (open circles) and C-rich Miras. The line has the slope of the LMC PL(K) relation and has been fit to the four short-period O-rich Miras.

(mentioned above) that may be hot-bottom burning (Whitelock *et al.* 2003). Feast (2009) suggested that these stars may be pulsating in the first overtone. Many of the C-rich Miras fall well below the line as the result of thick circumstellar shells. Fig. 5 shows the same stars on a bolometric PL relation, and we see that the C stars scatter around a relation that is very similar to the one obeyed by LMC Miras. The slope is almost identical to the slope of the LMC line, within the uncertainties.

Using an LMC distance modulus of 18.5 mag, we determine from the C-rich Miras that $(m - M)_0 = 23.56 \pm 0.03$ mag for NGC 6822. This may be compared to 23.40 ± 0.05 mag derived from Cepheid variables (Feast *et al.* 2012b) and 23.49 ± 0.03 mag from RR Lyrae variables (Clementini *et al.* 2003). Note that all errors quoted here are internal, but there are systematic uncertainties in all of the measurements. The agreement is reasonable and certainly shows that Miras offer a viable alternative to the more conventional distance indicators.

5.3. *Challenges*

However, I should note that there remain challenges in using Miras as distance indicators. One of the most serious of these is ensuring that measurements made with different photometric systems give the same result. Battinelli & Demers (2011) have 16 large-amplitude variables in common with Whitelock *et al.* (2012) in NGC 6822. The periods determined for these agree well, but the mean magnitudes differ by $\Delta K = 0.25$ mag. Both groups know that their photometry of normal stars, i.e., those with $(J - K) < 1.0$ mag, is on the 2MASS system. Dealing with very red stars, of which there are no non-variable examples, will require considerably more effort.

It also remains possible that we will find metallicity effects as the PL relationships become better defined.

6. Cepheids and/or Miras?

Cepheids have long provided a vital step on the distance-scale ladder linking the Galaxy to distant supernovae. However, Mira variables offer a viable alternative which may well be preferable for the following reasons:

• Miras are of comparable brightness to Cepheids at K and brighter at longer wavelengths (see Table 1 and Whitelock 2012).

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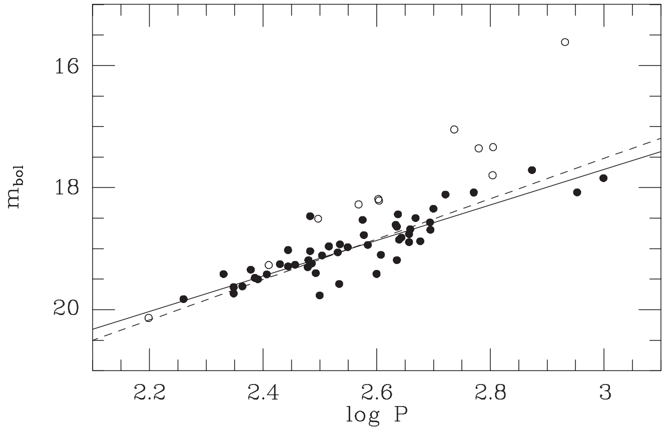

Figure 5. Bolometric PL relation for NGC 6822, showing the same stars as in Fig. 5. The dashed line is the LMC PL relation, while the solid line is the relation fitted to these data.

Table 1. Comparison of the absolute magnitudes of Cepheid and Mira variables at 2.2 and 8 μm (Whitelock 2012 and Feast 2010, unpublished).

Wavelength	Variable type	Period (days)	Absolute mag
K(2.2 μm)	Cep	50	−7.9
	M	380	−7.9
8 μm	Cep	50	−8.3
	M	230	−8.3
	M	380	−9.2

• Miras are found in galaxies which do not host Cepheids, such as dwarf spheroidals, and will be found in ellipticals.

• Miras are found in the haloes of spiral galaxies, where they may be less confused, and therefore more easily observable at large distances, than stars in the spiral arms.

• Miras are best observed in the infrared and are therefore not severely affected by interstellar extinction.

• The next generation of space telescopes, as well as large ground-based telescopes equipped with adaptive optics, will primarily work in the infrared. They will be ideally suited to observing distant Mira variables.

7. Conclusion

Large-amplitude AGB variables offer a viable alternative to Cepheids for distance-scale studies, which will be particularly valuable when infrared observations are available. There remain, however, calibration issues that must be resolved if observations from different instruments are to be combined reliably. The *Gaia* satellite will provide a vital Galactic calibration that will put the Mira absolute-magnitude scale on a new footing (see Whitelock 2012).

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