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Miras and Mass Loss in the Local Group

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Abstract. Evolved AGB stars pass through a phase of heavy mass loss during which they become optically obscured. We describe an observational program to find and study such stars in the Magellanic Clouds. Many of the obscured stars are found to be luminous carbon stars, a population previously missing. We discuss the Mira PL relation, valid before the onset of the heaviest mass loss. We find that a number of semi-regulars fit this relation, based on Hipparcos parallaxes. No evidence is seen for a Z-dependence, giving a powerful potential distance indicator. We derive a distance modulus to the LMC of $m - M = 18.63 \pm 0.09$ as well as a bright calibration for the Horizontal Branch in globular clusters.

1. Introduction

The final phase of stellar evolution on the Asymptotic Giant Branch (AGB) is dominated by heavy mass loss. The mass-loss rates reach values around $10^{-5}\, M_\odot\, yr^{-1}$, exceeding the nuclear burning rate and causing the star to lose almost its entire hydrogen envelope. The cause of the mass-loss process is not well understood. It is generally believed to be a two-step process, involving pulsation-driven atmospheric shock waves, followed by radiation pressure on the dust driving the outflow. Observationally, dust formed in the wind obscures the star during the mass loss phase. Infrared observations to detect and study such stars have been limited to Galactic stars. To understand the dependence on metallicity and initial mass on the mass-loss process, observations of obscured stars in different stellar populations are crucial. The lack of observational data is mainly due to the difficulty to detect dust at any large distance, and the paucity of 'dusty' AGB stars due to the short life time of the superwind phase.

2. Obscured AGB Stars in the Magellanic Clouds

Although AGB stars can be detected with near-infrared observations to distances of several Mpc (e.g. Alonso et al. 1998), evidence for mass loss requires mid-infrared observations which greatly limits the sensitivity. So far, extra-galactic observations have been limited to the Magellanic Clouds.

A group of IRAS sources in the MCs was found to have colours consistent with AGB stars. Subsequent near-infrared observations uncovered a num-

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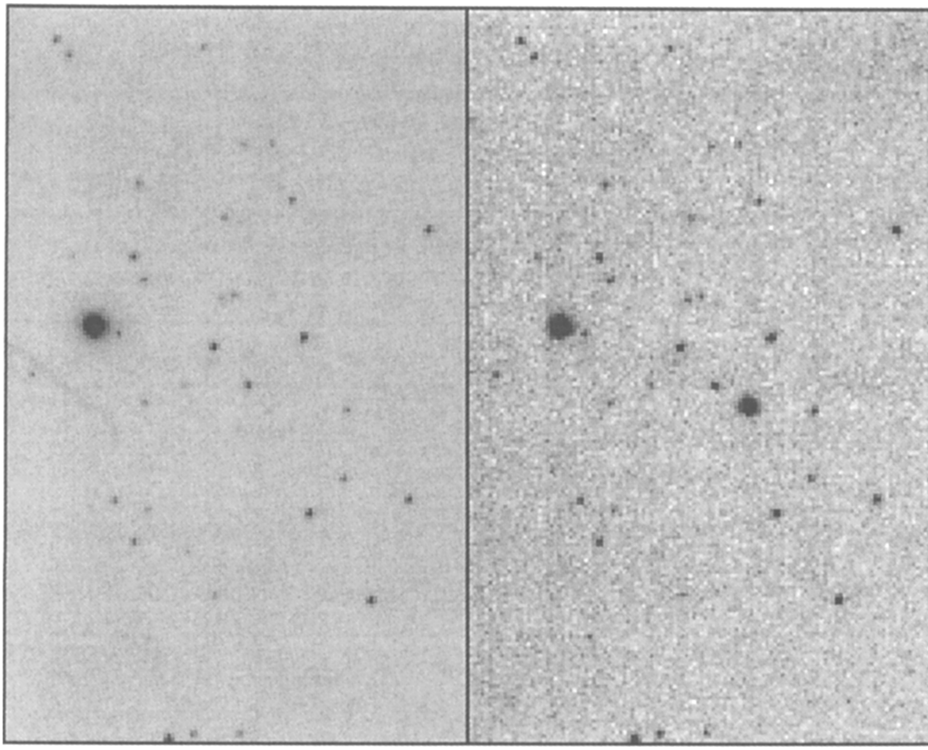

Figure 1. Identifying an obscured AGB star in the LMC. Invisible in the J-band image (at left), it rivals the brightest star in the K-band image (at right). The images were obtained using the IRAC2b near-IR camera at the ESO/MPI 2.2m telescope at ESO La Silla, Chile. South is up, and East is to the right. The frames shown here measure one arcminute along the short (E-W) axis.

ber of stars without optical counterparts (e.g. Reid 1991; Wood et al. 1992, Zijlstra et al. 1996). As an example, Fig. 1 shows J and K-band images of IRAS 06025−6712 obtained with the IRAC2b camera on the 2.2m ESO/MPI telescope at ESO La Silla, Chile. Invisible at J down to 18^{th} magnitude, it is very bright in the K-band image at $K = 11.52$ mag. It is located in a small, anonymous open cluster.

At the moment about 50 obscured AGB stars have been found in the LMC (van Loon et al. 1998a) and about 20 in the SMC (Groenewegen & Blommaert 1998). In contrast, existing optical studies of AGB stars in the MCs identified very few obscured objects. An ISO central program (P.I. Trams) study was made of these stars, involving photometry and spectroscopy. Two representative ISO spectra are shown in Fig. 2. The spectrum shows one object to be oxygen rich but the other carbon rich. Previously, no carbon stars in the MCs were known at luminosities higher than 2×10^4 $L_{\odot}$ (Iben 1981; Costa & Frogel 1996). The lack of luminous carbon stars was explained by Hot Bottom Burning (HBB),

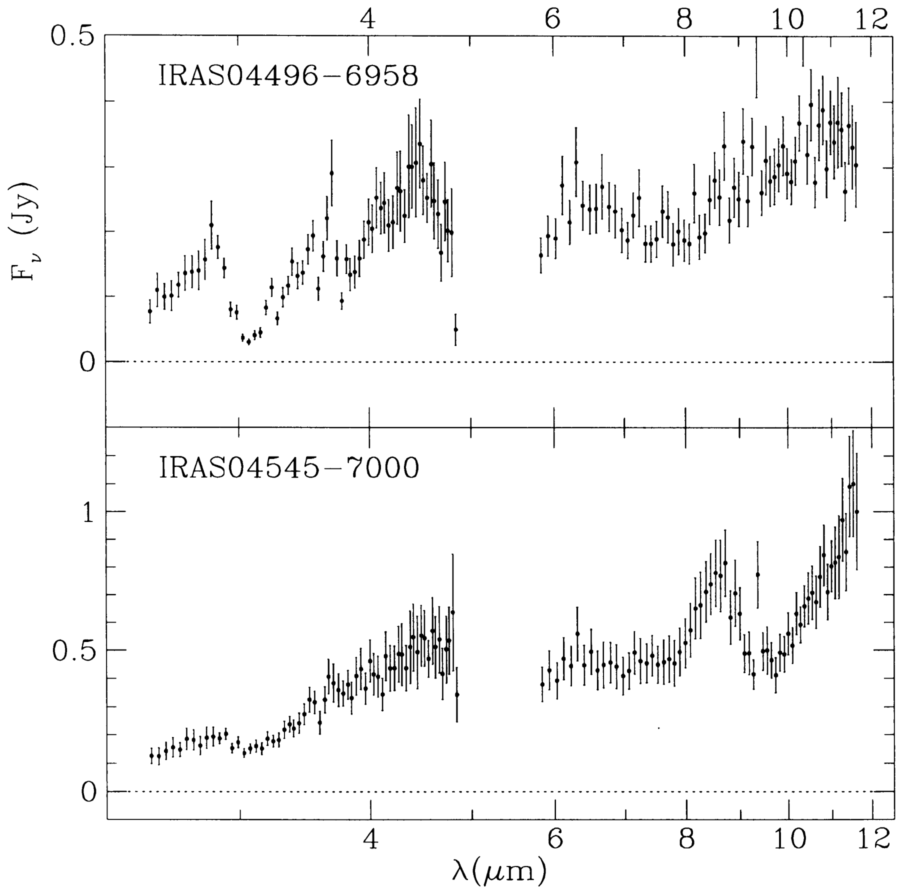

Figure 2. Phot-S spectra of two obscured AGB stars in the LMC, one carbon-rich and one oxygen-rich.

but it was also possible that all luminous carbon stars were dust-enshrouded. The ISO spectrum now shows evidence for the latter.

The majority of the luminous obscured AGB stars now appear to be carbon rich (van Loon et al. 1998b). Obscured carbon stars reach up to the highest luminosity at the AGB, $M_{bol} \approx -7$, in sharp contrast to the previous lack of luminous carbon stars.

Other Galactic satellites would also be feasible for observations of obscured AGB stars, and they would extend the range in Z and in age, but they have much smaller numbers of stars. Further discovery of obscured AGB stars may be expected for Sgr, Leo I and Fornax, all of which have a population of intermediate-age stars.

3. The Mira Period-Luminosity Relation

Mira variables in the LMC show a well-defined period–luminosity relation, originally discovered by Glass & Lloyd Evans (1981). Feast et al. (1989) showed that the relation is especially narrow (1-σ = 0.13 mag) when using the K-band. The Mira phase of the AGB is too short for appreciable evolution in luminosity: instead the relation traces a range of initial mass and metallicity. That the relation is so narrow is surprising since it indicates that the period of the star remains constant in spite of its mass being constantly reduced due to the mass loss. It suggests a feedback mechanism between mass loss and stellar pulsation.

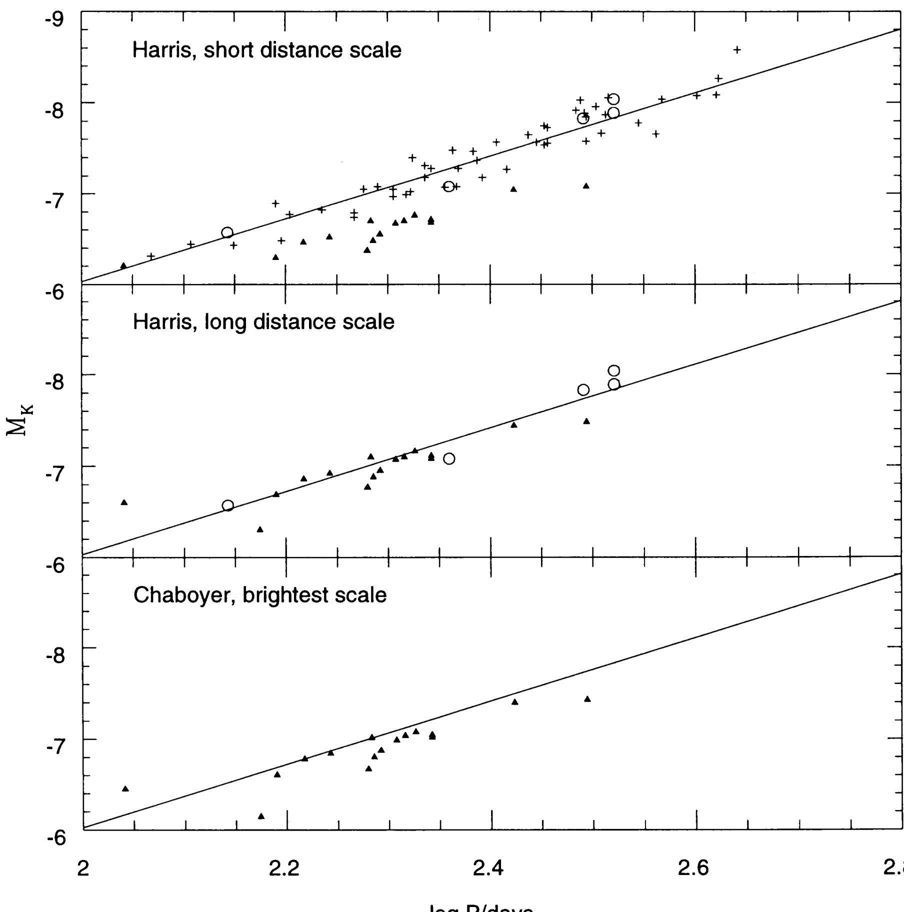

Figure 3. The Mira *PL* relations. Plus signs indicate LMC Miras (Feast et al. 1989) for a distance modulus of 18.57. Circles are Galactic Hipparcos Miras (Bedding & Zijlstra 1998) and triangles Miras in globular clusters (Whitelock 1986), for three different calibrations for the horizontal branch magnitude.

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Not all Miras follow the *PL* relation. LMC Miras with periods longer than 400 days tend to be overluminous (e.g. Zijlstra et al. 1996). In contrast, high-mass-loss OH/IR stars near the Galactic Centre appear underluminous (Blommaert et al. 1998, Wood et al. 1998). The *PL* relation thus may break down at high luminosities and/or high mass-loss rates. Wood (1990) predicts that the Mira *PL* relation depends on Z, with Galactic Miras being 0.25 mag fainter at K than LMC Miras. Such a large shift is not presently confirmed by observations of Galactic disk stars (e.g. van Leeuwen et al. 1997, Feast 1996). The underluminous Galactic Centre OH/IR stars may present a case.

Galactic Miras and semi-regulars (SR) with accurate Hipparcos parallaxes define three sequences (Bedding & Zijlstra 1998), one of which coincides with the LMC Mira *PL* relation. Especially R Doradus and L2 Puppis, with parallaxes accurate to 5%, very closely agree with the LMC *PL* relation. A secondary, broader sequence is seen in the Hipparcos data, shifted by about a factor of two towards shorter periods, containing only semiregulars (see also Wood & Sebo 1996). Several semiregulars in the Hipparcos sample show two periods, one of which agrees with the Mira relation and the other with the SR sequence. The two classes of variables appear closely related. The luminosity difference between SRs and Miras is consistent with the Whitelock (1986) evolutionary track. The few stars which fall well below the *PL* relation (see also van Leeuwen et al. 1997) have luminosities similar to the semiregulars (although having much longer periods) and may be evolutionarily related to this group.

From the Hipparcos data, lifetimes of the order of $5 \cdot 10^5$ yr can be estimated for the Mira phase and similar or larger for the SRs. The lifetimes indicate that the SR/Mira phase covers a large fraction of the Thermal-Pulsing AGB.

Figure 3 compares the LMC Miras with Hipparcos Miras. The Hipparcos Miras (open circles) were selected on having parallax uncertainties less than 15%: the resulting Lutz-Kelker bias is less than 0.05 mag (Koen 1992). A direct fit between the LMC and Hipparcos Miras (applying a bias correction according to Koen 1992) gives an LMC distance modulus of 18.63 ± 0.09, consistent with Cepheid-based determinations. (A shift of 0.25 mag would put the LMC at an unlikely distance of 18.9: at this distance the luminosity of the brightest carbon star in the LMC would yield a core mass above the Chandresekhar limit).

Hipparcos thus suggests that any metallicity effect in the Mira *PL* relation using the K-band is small. A Z-effect on the *PL* relation is seen in the infrared colors (Feast et al. 1989), possibly related to molecular absorption features in the J and H spectra. Miras show their smallest angular diameters at K, indicating the smallest optical depth through their extended atmospheres occurs at this wavelength.

The only other group of Miras at 'known' distances are globular cluster Miras, found in clusters with [Fe/H] > 0.1 (Whitelock 1986). They are included in Fig. 3 as triangles. Two different Horizontal Branch distance scales of Harris (1996) are used, a short scale (derived from RR Lyrae statistical parallaxes) and a long one (field subdwarfs). The average scale corresponds to $M_V(\mathrm{HB}) = 0.15[Fe/H] + 0.85$. The bottom panel uses the alternative Chaboyer (1998) relation $M_V(\mathrm{HB}) = 0.23([\mathrm{Fe/H}] + 1.6) + 0.46$ which again is 0.1 mag brighter than an average including the statistical parallax.

It is clear that only the brightest scale gives good agreement for the globular cluster Miras with the LMC and Hipparcos PL relation. A formal direct fit to the LMC data using the Harris scale gives $M_V(\mathrm{HB}) = 0.15[\mathrm{Fe/H}] + 0.60$. This favours a bright RR Lyrae scale.

In conclusion, under the assumption of metallicity-invariance, the Mira distance scale is found to be in good agreement with the Cepheid distance scale. To confirm this, observations of Miras in other extra-galactic systems would be required. If confirmed, Mira variables would be the only distance indicator for which individual stars are calibrated by Hipparcos to better than 10%.

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Discussion

Whitelock: It is not clear that intermediate age populations of all metallicities form Miras, e.g. Fornax has none and Sagittarius has lots. This fact may relate to what happens in the LMC.

Zijlstra: Miras are not seen in globular clusters with [Fe/H] < -1.0. Old, metal-poor stars may spend relatively more - or all - of their TP-AGB on the semi-regular sequence. Miras are found in the younger, metal-poor stellar population of the SMC. How many one would expect in Fornax depends on the size of its intermediate-age population and the time AGB stars spent as Miras at its metallicity. It would be worthwhile to search for Miras in Fornax.

Whitelock: What distance would you need the Galactic Centre to be at if you want its LPVs to fit on the Mira PL extrapolation?

Zijlstra: I don't remember which distance for the Galactic centre was used by Blommaert. One would need to shift by about 0.4 mag towards larger distance modulus.

Feast: Three points: (1) The Galactic kinematics of OH/IR stars of long period fit them on an extension of the PL relation. (2) As regards possible metallicity effects on the PL relation we know that the period-colour relations in the LMC and Galaxy are different so the PL distance derived for the LMC from a Galactic calibration depends on wavelength. The most likely reason for this is a difference in metallicity between the LMC and Galactic Miras at the same period (at least for the longer period stars). (3) However, at a given period there seems no good reason to expect a wide range of abundances amongst LMC Miras.

Zijlstra: The only disk OH/IR star with a reasonable distance, OH231.8+4.2, is overluminous with respect to the PL relation, similar to LMC stars of similar period and in agreement with your result. This appears quite different from the OH/IR stars and the Galactic Centre. (2) The PL relation is best defined at K which is also the band where Miras show the smallest angular diameters - least affected by molecular bands. There is no convincing evidence yet that the P-K relation depends on Z, depending on distance scales used. Other bands than K would be expected to show a Z dependence. (3) Either higher Z or lower age will cause higher luminosities at the tip of the AGB, giving an age-metallicity degeneracy. A dispersion in Z at a given age would broaden the PL relation if this relation depends on Z. The existence of mass-losing C and O stars at the same luminosity may indicate such a spread, although there are other interpretations.

Lloyd Evans: Are the few stars with periods much too long for the Mira P-L relation semi-regulars which also have a normal short period?

Zijlstra: They are χ Cyg, R Car and R Cas. They seem to have stable, single periods and are also not known to be binaries. Their luminosity agrees with

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those of the semi-regulars and they may be more closely related to these stars than to the Miras.