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Pulsation Modes of Mira Variables Investigated using NIR Interferometry

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Abstract. We have undertaken a program (1999 to present) with the Palomar Testbed Interferometer to measure the angular size variations, with respect to pulsational phase, of a group of about 50 mira variables, approximately 30 of which are M-types. While we have unambiguously detected the pulsation of the miras with phase (Creech-Eakman et al. 1999 and Thompson et al. 2001), our main goal with this study is to determine through direct detection methods whether mira variables pulsate in the fundamental or first-overtone mode. To this end, we use our angular diameter measurements with the best estimates of stellar distances to determine if a particular pulsation mode can be identified for the oxygen-rich stars in our sample.

1. Observations and Data Reduction

All observations were taken at the Palomar Testbed Interferometer (PTI) in the K band as described by Colavita et al. (1999). Most of the data presented herein were taken between June 1999 and August 2001 in the NS baseline configuration of PTI. The data were calibrated using the standard method outlined in Boden et al. (1998). Observations were generally taken for each source and its calibrators every 2-3 weeks during the observing season. A system visibility, the point source response for the interferometer, and angular size for the targets were then estimated from these data. Here a calibration star refers to a singular star within about 10 degrees of the target whose angular size is below the resolution limit of PTI (≤ 0.8 mas). The sizes of the calibrators were initially estimated using a blackbody fit to published photometric data, then iterated until a consistent solution with respect to all the calibrators converged. Error bars on the visibilities of all targets represent the agreement in scatter of the calibrator measurements used to arrive at the system visibility. All apparent angular diameters quoted herein were fitted to the visibility data using a uniform disk model:

$$V^2 = [2J_1(\pi\theta B/\lambda)/(\pi\theta B/\lambda)]^2 \tag{1}$$

where B is the projected baseline, λ is the observational wavelength, θ is the apparent angular diameter, and J_1 is the first-order Bessel function.

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2. Evidence for Pulsation

Detection of pulsation by measuring changes in angular size with respect to phase of the mira variable has been accomplished by a handful of groups (van Belle et al. 1996; Burns et al. 1997; Tuthill et al. 1995; Perrin et al. 1999). In some of these experiments, up to a 35% change in angular diameter has been seen. Below we show estimated angular size with respect to phase for one of the shortest-period miras (148.4 days) in our sample, R Vir (Figure 1). Clear excursions of 11% are seen in its angular size, which is directly related to its linear size via a tangent relation. We also note that R Vir shows a minimum size near visual phase of 0.85. This has been predicted by theory (Beach et al. 1988) and can also be inferred from SiO maser data which traces the motions of the acoustic shocks in these atmospheres (Cho et al. 1996).

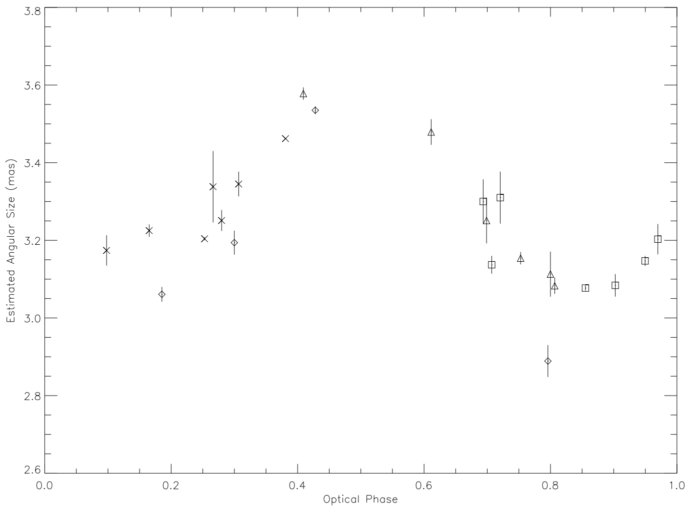

Figure 1. Estimated angular size of the oxygen-rich mira R Vir with respect to visual phase. We use epoch MJD 51261.5 and period 148.4 days. Different symbols indicate data taken in subsequent periods. Error bars are 1σ for the night's observations. We note a size minimum near 0.85 optical phase, which has been predicted for these sources (see text).

For the 25 oxygen-rich miras discussed in this paper, 14 show at least 3σ excursions in their nightly RMS angular size measurements for the data presented here. Examining only those stars with angular sizes ≥ 3 mas, this number increases to 6 out of 9 stars. Therefore, we claim that we have unambiguously detected pulsations in more than 50% of our oxygen-rich sample. The average excursions in size over the nightly RMS for the 14 stars (showing 3σ excursions) in the sample is about 9.6σ, or 0.29 mas over their pulsation cycles. The average size of this sample is about 2.5 mas; this corresponds to a 12% average change in size for those members of the sample which show $\geq 3\ \sigma$ excursions in their measurements with phase. This is not surprising given that the slope of the system visibility function renders PTI most sensitive to size changes for stars between 2.0 and 4.5 mas in angular diameter.

3. Pulsation Modes

A considerable volume of literature exists concerning the debate about the pulsational mode of mira variables. Classical methods (before optical and near-infrared (NIR) interferometers became widely used) compared the predictions of theory and observations of miras, depending mainly upon estimates of temperature and luminosity to determine physical characteristics of these stars. When Glass & Lloyd Evans (1981) were able to demonstrate that mira variables in the Large Magellanic Cloud (LMC) fit a period-bolometric magnitude relation it became possible to more reliably estimate distances to these stars. However, it was not until the Hipparcos mission that any but the very closest miras could have reliable distance estimates. Now, with the large variety of spatial scales surveyed by modern optical and NIR ground-based interferometers, and parallax data from missions such as Hipparcos, it may be possible to answer the question of pulsation mode for mira variables unambiguously.

In order to ascertain the pulsation mode for the oxygen-rich miras in our sample, we have taken distance estimates from three sources to apply to the problem of determining the physical size and thus likely pulsation mode for these miras. The first source is the Hipparcos database, for which there are published error estimates. Many of the stars in our sample are far away in order to be resolved within the first null of PTI, thus they are not well-placed for measurements with Hipparcos. The second source is van Leeuwen et al. (1997) where they have calibrated the zero-point of the M_K-P relation for Galactic oxygen-rich Miras by using Hipparcos parallaxes and adopting the slope obtained for the LMC to obtain the relation:

$$M_K = 0.94 - 3.47 log P \tag{2}$$

where M_K is the absolute bolometric magnitude of the mira at K band, and P is the period in days. To use this equation, we obtained archival K band magnitudes or fluxes from the Catalog of Infrared Observations (Gezari et al. 1999) for these stars. Our final source for distance determination was from Alvarez & Mennessier (1997) (A&M) where they determined the effective temperatures (T_{eff}) for 165 oxygen-rich miras using indices related to molecular band strength of TiO and VO computed from narrow-band photometric observations to obtain a period-luminosity (PL) relation and distances for these stars. Because no error estimates are presented with the van Leeuwen et al. or A&M data, error bars of 15% are assumed.

From these distance estimates and our angular diameters, it is straightforward to estimate the physical sizes of the miras. We plot these radii (in units of $R_\odot$) versus the period and superimposing models for the fundamental pulsation solution from Wood (1990):

$$log P = 1.949 log R - 0.9 log M - 2.07 \tag{3}$$

where M is the mass in solar units, R is the radius in solar units and P is the period in days. For the first overtone, we use the standard relation:

$$logP = 1.5logR - 0.5logM + logQ \quad (4)$$

where all constants have the same meaning and $Q = 0.04$ (similar to the values predicted by Fox & Wood (1982)). See Figure 2 for the plots.

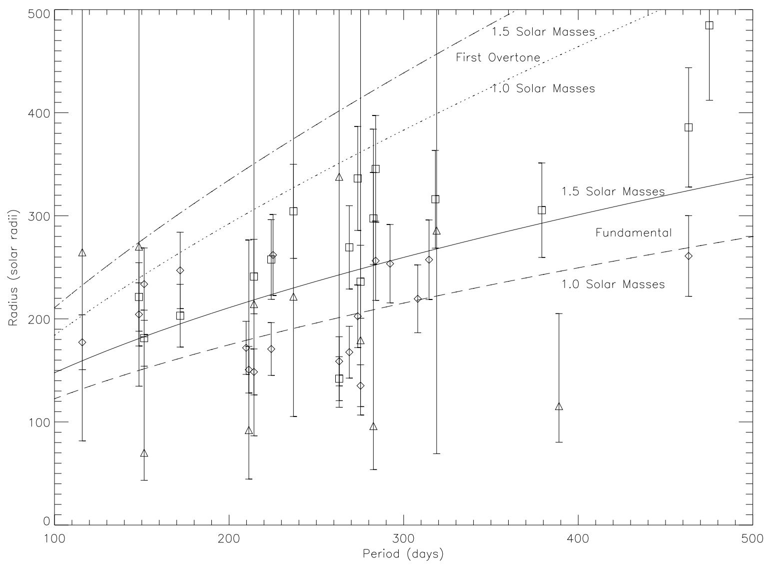

Figure 2. Plot of estimated radial size versus period using three different methods to estimate distance. △ are Hipparcos, □ are van Leeuwen PL relation & ◇ are A&M. Lines are models for fundamental and first overtone pulsators from Wood (see text). We conclude that these oxygen-rich miras are most likely fundamental mode pulsators.

We conclude, based on these 24 stars in our sample of 25 for which at least one of these methods produced an estimated distance, that these oxygen-rich miras are likely pulsating in the fundamental mode. We believe it is important to point out that Hipparcos does not estimate distances well for the stars in our sample, probably because the photocentration errors are on the order of the parallaxes measured for these stars. The A&M distance estimates heavily favor a fundamental pulsator of about 1.0 $M_{\odot}$. Finally, the PL relation from van Leeuwen tends to favor either a considerably more massive fundamental pulsator, closer to 2.5 $M_{\odot}$ or a smaller first-overtone pulsator of about 0.5 $M_{\odot}$. We believe it is important to note that the distance estimates from the van Leeuwen PL relation are utilizing the same equation as Feast et al. (1989) have derived for the LMC, where most miras are concluded to be overtone pulsators.

4. Angular Size vs. Period

One unanticipated result from this data analysis is seen in Figure 3. There appears to be a trend that those stars with the largest angular sizes also have longer pulsation periods. The binning by period for the sample (4, 13, 6, and 2 in 100-200 d, 201-300 d, 301-400 d, and > 400 d bins) has its average period centered around 273 days. While binned by angular size (8, 8, 8, and 1 in 1-2 mas, 2.01-3 mas, 3.01-4 mas and > 4 mas), these stars have an average angular size of 2.61 mas. Performing a simple analysis about these values, stars smaller than 2.61 mas have an ensemble angular diameter of 1.84 mas and ensemble period of 240 days. For stars larger than 2.61 mas, these values are 3.32 mas and 303 days respectively. Similarily, for stars with periods less than 273 days, the ensemble average period and angular size are 203 days and 2.30 mas. For stars with periods larger than 273 days, they are 336 days and 2.90 mas respectively.

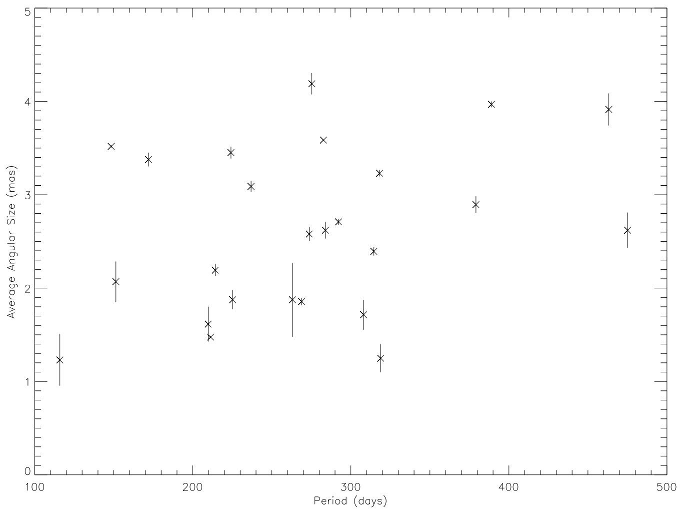

Figure 3. Plot of average angular size for all the nights for each star in the sample versus period. The indicated error bars are 3 σ for the entire data set for each star. We note there appears to be a slight trend toward larger angular sizes for loger period stars in this volume limited sample (see text for discussion). This may indicate that longer period miras loft their atmospheres to a greater extent than short period ones.

It is unclear whether there may be a bias introduced by the target selection for PTI, which includes magnitude limits in the R band (for acquisition) and K band (for tracking), and declination limits for delay line positioning. Assuming, however, that we have a good representation in terms of both periods and angular sizes (measurable by PTI) then we may have found evidence that stars with longer periods appear larger, possibly because they loft their atmospheres to a greater extent than stars with shorter periods. This trend may be part of the same phenomenon that has lead others to conclude that there is a natural break around 400 day periods where O-rich miras change from being first overtone to fundamental pulsators (van Leeuwen et al. 1997), although we must point out that in our data sample there is no indication of such a bimodal distribution (Figure 2). We also note that we see no trend in stellar T_{eff} versus angular size, although estimates of stellar T_{eff} for these stars are problematic at best.

5. Conclusions

We have clearly detected significant pulsations in more than 50% of our sample of O-rich miras with phase. These pulsations appear to be in the fundamental mode, regardless of what method is used to estimate a distance and thus derive an linear size for these sources based on our measured angular diameters. There is further evidence that a trend exists that longer period miras may have more lofted atmospheres, which may be indicative of stronger pulsations.

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