ANGULAR DIAMETER MEASUREMENTS OF EVOLVED VARIABLES BY LUNAR OCCULTATIONS AT 2.2 AND 3.8 MICRONS

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ABSTRACT

We report the angular diameters of two Mira variables (U Ari and Z Sco), three semiregular (SR) and irregular variables (SW Vir, η Gem, and μ Gem), and a supergiant SR variable (TV Gem) by lunar occultation observations in the near-IR broad K band (2.2 μm). Lunar occultations of η Gem and μ Gem were also observed for the first time simultaneously in both the K and L′ bands, yielding angular diameters at 2.2 and 3.8 μm. Effective temperatures and linear radii are also derived for all the observed sources and compared with earlier measurements. The mode of pulsation of both Mira and SR sources in our sample is discussed.

Key words: infrared; stars — stars: atmospheres — stars: fundamental parameters — stars: oscillations — stars: variables: other — techniques: high angular resolution

1. INTRODUCTION

Asymptotic giant branch (AGB) stars are in the last stage of stellar evolution before turning into planetary nebulae and are generally surrounded by circumstellar matter because of their large mass-loss rates (~10^{-6} M_☉ yr^{-1}). AGB stars include classical Mira variables (visual amplitudes >2.5 mag, periods of 100–1000 days), semiregular variables SRa (visual amplitude <2.5 mag, periods of 35–1200 days), semiregular variables SRb (amplitude <2.5 mag, poorly defined periods), and irregular variables SR (small amplitude, no definite periods), as well as supergiant semiregular variables SRc (Smith et al. 2002). The evolutionary connection between the Mira and SR groups is not clear, but SR variables are often considered to be Mira progenitors (Bedding & Zijlstra 1998).

Multiwavelength measurements of the angular sizes of Mira and SR variables at different phases of their pulsation cycle provide a direct means to understanding their atmospheric extension and pulsation properties. The high mass loss and relatively low surface temperature of the evolved stars provide a habitable zone for several molecules such as TiO, VO, H₂O, and CO in their extended atmospheres. The large opacities of these atmospheric molecules in some particular bands mask the dominant photospheric continuum radiation. The emergent observed radiation is thus contaminated by radiation from the relatively cold atmospheric layers. Consequently, photospheric size measurements are affected differently in the different filter bands, which has been known for some time (e.g., Labeyrie et al. 1977; Quirrenbach et al. 1993; Haniff et al. 1995).

Recently, there have been many high-quality interferometric measurements of the angular diameters of Mira variables at near-IR wavelengths (e.g., Mennesson et al. 2002; Thompson et al. 2002; Woodruff et al. 2004; Perrin et al. 2004; Millan-Gabet et al. 2005; Fedele et al. 2005). Mennesson et al. (2002) found that the L′-band diameters of several oxygen-rich Mira variables were much larger (25%–100%) than those measured in the broad K band and proposed as an explanation a simple empirical model of a central stellar disk surrounded by an optically thin gaseous shell. The observed variation of angular size with wavelength can be interpreted in terms of the transparency of the optically thin shell varying with wavelength. Perrin et al. (2004) have observed several Mira variables in narrow bands around 2.2 μm and find systematically larger diameters in bands contaminated by water vapor or CO. Millan-Gabet et al. (2005) report a systematic increase of angular size with wavelength (~25%) from J to H to K′ from a study of 23 Mira variables involving simultaneous measurements in JHK′. The 11 μm interferometric observations of three Mira variables (Weiner et al. 2003a, 2003b) showed the diameters at 11 μm to be larger by a factor of ~2 than those measured in the K band. The increase of apparent diameter from the near-IR toward longer wavelengths seems to be a common phenomenon in Mira and late M-type SR variables. The dispersion in angular sizes from the near-IR to the mid-IR bands are well represented by the modeling of interferometric data by inclusion of a water shell surrounding the Mira variables (Weiner 2004; Ohnaka 2004; Schuller et al. 2004). ISO and ground-based spectroscopy observations also point to a warm molecular shell of H₂O surrounding the Mira variables (Hinkle & Barnes 1979; Tsuji et al. 1997; Yamamura et al. 1999; Matsuura et al. 2002; Tej et al. 2003b).

Several theoretical models have been developed to understand the dynamic atmosphere of Mira and non-Mira M stars (Bessell et al. 1996; Hofmann & Scholz 1998; Hofmann et al. 1998; Höfner et al. 1998, 2003; Woitke et al. 1999). Recent results of interferometric observations have been predicted well by considering molecular contamination effects on theoretical models (Jacob & Scholz 2002; Tej et al. 2003a).

The question of pulsation modes for Mira stars is a complicated one. Theoretical considerations generally suggest a fundamental mode, as it is difficult to reproduce in the first overtone the large velocity amplitude encountered in Mira variables (Bessell et al. 1996). The quantity commonly used in stellar pulsation modeling is the Rosseland radius of the hypothetical parent star of the Mira variable, which does not pulsate. It is not an observed quantity but is related to the intensity distribution on the stellar disk (Scholz 2003 and references therein). It is also a phase- and possibly cycle-dependent value. Jacob & Scholz (2002) showed that transforming a measured diameter into a Rosseland value may be difficult or impossible because of molecular contamination, even in standard near-continuum bandpasses. The variability of diameter with Mira phase and cycle, as well as with wavelength, further complicates the issue. Angular diameters that are reported from observed data are obtained by fitting visibilities (from interferometric data) or occultation light curves (from lunar occultation) to a well-defined artificial center-to-limb variation (CLV),...
such as a uniform disk (UD), a fully darkened disk, or a Gaussian intensity distribution. It is difficult to obtain the actual CLV from the observed data. Another difficulty in determining pulsation modes is the large uncertainty in the distance measurements required to convert angular to linear diameters. While earlier work (Haniff et al. 1995; van Leeuwen et al. 1997; Tej et al. 1999; van Belle et al. 2002) suggested first-overtone pulsations in some Mira variables, recent results based on interferometric diameter measurements (Perrin et al. 2004; Woodruff et al. 2004; Fedele et al. 2005) that take into account molecular contamination in the bandpasses (Jacob & Scholz 2002; Mennesson et al. 2002; Tej et al. 2003a; Ireland et al. 2004a, 2004b, 2004c; Ohnaka 2004) point to a fundamental mode of pulsation in Mira variables.

In this paper we present new angular size measurements of six evolved variables by lunar occultation in the near-IR. These include two Mira variables (U Ari and Z Sco) and four SRs (SW Vir, η Gem, μ Gem, and TV Gem), including the supergiant TV Gem. Our occultation results from another Mira variable, U Ori, are also included for comparison, although its angular diameter has been reported earlier (Mondal & Chandrasekhar 2004). We report the first simultaneous angular diameter measurements at 2.2 and 3.8 μm for two SR variables (η Gem and μ Gem). The source η Gem underwent two occultation events, and in both cases simultaneous K and L′ angular diameters could be determined. UD angular diameters are derived from our occultation data. Bolometric fluxes are estimated from photometry, and effective temperatures are calculated. Distances estimated to the sources are considered, and linear radii are derived. The positions of these evolved variables are plotted in a period–linear radius diagram, and their mode of pulsation is discussed.

2. OBSERVATIONS AND DATA ANALYSIS

Three sources (U Ari, η Gem, and μ Gem) were observed simultaneously in the broad K (2.2/0.40 μm) and L′ (3.8/0.60 μm) filter bands, while Z Sco, SW Vir, TV Gem, and U Ori occultations were recorded in the K band only. All observations were made using the two-channel high-speed photometer installed on the 1.2 m telescope at Mount Abu, India. The details of the instrument can be found elsewhere (Mondal et al. 1999, 2002). The sampling time of the light curves was 2 ms except for SW Vir, which was sampled at 1 ms. The source η Gem was observed twice during an interval of 2 months. All events except Z Sco were recorded under good sky conditions, and the Z Sco event was recorded through thin clouds. The details of the occultation events are listed in Table 1.

The observed light curves containing modified Fresnel diffraction fringes were modeled to get the UD angular diameter of the stellar sources. The model fitting of the lunar occultation light curve involves a χ² minimization technique to obtain the best estimation of the five parameters: (1) the geometric time of occultation, (2) the stellar signal, (3) the sky background, (4) the velocity component of the Moon in the direction of occultation, and (5) the UD angular diameter. The analysis procedures are based on the standard nonlinear least-squares method introduced by Nather & McCants (1970). The point-source Fresnel diffraction pattern modulated by the finite spectral bandwidth of the system, the finite telescope aperture, the instrument time response, and the extended angular size of the source are taken into consideration for fitting of the above-mentioned parameters. The resolution limit of the lunar occultation technique experimentally determined by studying occultations of a number of bright point sources is ~2 mas (Chandrasekhar 1999).

3. RESULTS AND DISCUSSIONS

Individual source parameters are listed in Table 2. Mass-loss rates and outflowing velocities derived generally from CO and SiO line measurements are also listed in Table 2. The difficulty of obtaining good distance estimates is discussed later in § 3.3, and adopted distances to sources are given in Table 2.

3.1. Angular Diameter Measurements

3.1.1. U Ari

U Ari is an oxygen-rich Mira variable of period 371 days and spectral type M4–9.5 IIIe (Keenan & McNeil 1989). Lunar occultation of U Ari was observed simultaneously in the K and L′ bands close to minimum phase (phase 0.57). A good occultation trace has been recorded in the K band (Fig. 1). The signal-to-noise ratio (S/N), limited by atmospheric scintillation noise in the K band, is about 50. The L′-band profile is noisy and has not been considered for analysis.

We obtained a UD angular diameter of 7.3 ± 0.3 mas in the K band. The UD model fit to the K-band light curve is shown in Figure 1. An earlier lunar occultation measurement in the H band gave a UD diameter of 6.11 ± 0.34 mas at phase 0.49 (Ridgway et al. 1979). There is a significant difference of about 20% in the two UD values, which were measured at nearly the same phase near the minimum. From recent simultaneous size measurements of 23 Mira variables in the JHK′ bands, the larger size in the K band compared to in the H band appears to be a common phenomenon in Mira stars (Millan-Gabet et al. 2005). The apparent size variations from the near- to mid-IR wavelengths are reasonably well modeled by the inclusion of a warm (1500–2000 K) H₂O shell within a few stellar radii (Mennesson et al. 2002; Jacob & Scholz 2002; Tej et al. 2003a; Weiner 2004; Ohnaka 2004; Perrin et al. 2004). Furthermore, it is to be noted that as

**TABLE 1**

| Star     | Variability Type | IRC   | Date of Observation | Filter (λ/Δλ) (μm) | P.A. (deg) | t_comp (km s⁻¹) | Event Type¹ |
|----------|-----------------|-------|---------------------|-------------------|------------|-----------------|-------------|
| U Ari    | Mira            | +01040| 2002 Feb 19         | 2.2/0.4, 3.8/0.6   | 18         | 0.475           | D           |
| Z Sco    | Mira            | -20306| 2003 Mar 22         | 2.2/0.4           | 155        | 0.651           | R           |
| U Ori    | Mira            | +20217| 2000 Mar 13         | 2.2/0.4           | 136        | 0.66           | D           |
| SW Vir   | SRb             | +00230| 2001 Jun 1          | 2.2/0.4           | 74         | 0.504           | D           |
| η Gem    | SRa             | +20139| 2001 Jan 8          | 2.2/0.4, 3.8/0.6   | 21         | 0.330           | D           |
| μ Gem    | Lb              | +20144| 2001 Mar 4          | 2.2/0.4, 3.8/0.6   | 68         | 0.645           | D           |
| TV Gem   | SRe             | +20134| 2000 Nov 14         | 2.2/0.4           | 212        | 0.437           | R           |

¹: D: disappearance; R: reappearance.
both observing \((K \text{ and } H \text{ bands})\) phases are close to the minimum, molecular contamination is expected to be more prominent compared to in the maximum phase and is also evident from spectroscopy (Tej et al. 2003b). Hence, our simple fit of the UD diameter may not represent the true continuum size near the minimum of the Mira phase. In the case of interferometric observations, the observed visibilities are compared successfully with the theoretical models of visibilities with the inclusion of a thin surrounding H\(_2\)O shell (Perrin et al. 2004). However, in the case of lunar occultation, such modeling efforts have not yet been carried out.

### 3.1.2. Z Sco

Z Sco is an oxygen-rich Mira variable of period 352 days and spectral type M4–5 IIIe. The maser lines of CO and SiO are not detected in the circumstellar atmosphere of Z Sco (Young 1995; Cho et al. 1996), and hence, there is no mass-loss estimate and outflow velocity of the source. No dust signature is present in \(IRAS\) LRS spectra (Sloan & Price 1998).

The occultation of Z Sco was recorded in the \(K\) band at phase 0.26. The sky condition during observations was poor (thin passing clouds), but it was possible to record the event. Fringe distortion is evident in the occultation trace (Fig. 2), but nevertheless, four fringes are recorded. The light curve is fitted with the UD model and a varying background using a fifth-order Legendre polynomial, shown in Figure 2.

We first derive a UD angular diameter of 3.8 ± 1.0 mas. The error is large because of the poor quality of the light curve. The diameter of Z Sco has never been measured before by a direct technique. Using the empirical relation of van Belle (1999), based on the \((V - K)\) color, we derive an angular diameter of 5.1 ± 1.3 mas using the visual magnitude of 11.6 from the AAVSO database (J. A. Mathieu 2004, private communication). We measure the \(K\) magnitude of the source to be 1.33 ± 0.1 at the time of our occultation observations.

### 3.1.3. U Ori

U Ori is an oxygen-rich Mira variable of pulsation period 371 days, with a spectral type of M6–9.5 IIIe (Keenan & McNeil 1989). The occultation of U Ori was recorded in the \(K\) band at phase 0.33. We obtain a UD diameter of 11.90 ± 0.30 mas. We had earlier studied this source from the point of view of spatial asymmetry. From the comparison of two near-simultaneous lunar occultation observations of U Ori at the same wavelength (\(K\) band) and at different position angles (P.A. 75\(^\circ\) and 136\(^\circ\)), we found evidence of asymmetry in its atmosphere; the source appears to be elongated at a P.A. of about 70\(^\circ\) (Mondal & Chandrasekhar 2004). The asymmetric extension is also found in OH maser observations of U Ori (Chapman et al. 1991).

### 3.1.4. SW Vir

SW Vir is an oxygen-rich SR pulsating variable of SRb type with a pulsation period of 150 days and a spectral type of M7 III (Lebzelter & Hron 1999). Kiss et al. (1999) identified it as a triply

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**TABLE 2**

**INDIVIDUAL SOURCE PARAMETERS**

| Parameters                  | U Ari | Z Sco | U Ori | \(\eta\) Gem | \(\mu\) Gem | SW Vir | TV Gem |
|-----------------------------|-------|-------|-------|-------------|------------|--------|--------|
| Spectral type\(^a\)         | M4–9.5 IIIe | M4/5 IIIe | M6.5–9 IIIe | M3 III | M3 III | M7 III | M1–0 Iab |
| \(V\) Magnitude\(^d\)       | 7.2–15.2 | 8.7–13.4 | 5.3–12.6 | 3.20–3.90 | 3.20 | 8.2–9.4 | 8.7–9.5 |
| \(K\) magnitude\(^b\)       | 1.59 | 1.48 | -0.49 | -1.49 | -1.89 | -1.87 | 0.99 |
| \(L\) magnitude\(^b\)       | 0.28 | 1.50 | -1.41 | -1.59 | -2.01 | -2.28 | 0.62 |
| Variability type            | Mira | Mira | Mira | SRa Lb | SRb | SRc |
| Spectral type\(^c\)         | M4–9.5 IIIe | M4/5 IIIe | M6.5–9 IIIe | M3 III | M3 III | M7 III | M1–0 Iab |
| Distance (pc)               | 371 | 352 | 372 | 233 | 27c | 150 | 182 |
| Period (days)\(^e\)         | 776 ± 155\(^d\) | 778 ± 145\(^d\) | 306 ± 61\(^d\) | 107 ± 22\(^e\) | 71 ± 5\(^e\) | 143 ± 24\(^e\) | 1200 ± 300\(^f\) |
| Luminosity\(^g\) \((10^{5} L_{\odot})\) | 8.4 ± 3.5 | 8.3 ± 3.3 | 9.7 ± 4.0 | 2.3 ± 1.0 | 1.8 ± 0.36 | 4.7 ± 1.7 | 68.5 ± 34.9 |
| Mass loss (10^{-8} \(M_{\odot}\) yr\(^{-1}\)) | 57\(^b\) | ... | 29\(^i\) | 1.4\(^j\) | 0.44\(^j\) | 17\(^i\) | 200\(^b\) |
| Outflow velocity (km s\(^{-1}\)) | 6.0\(^b\) | ... | 7.5\(^j\) | ... | ... | 7.8\(^b\) | 12\(^b\) |

\(^a\) SIMBAD database.
\(^b\) Gezari et al. (1999).
\(^c\) Percy & Wilson (2001).
\(^d\) Whitelock & Feast (2000).
\(^e\) Perryman et al. (1997) (Hipparcos catalog).
\(^f\) Underhill (1984).
\(^g\) Luminosity is estimated using the relation \(L = 4\pi d^2 F_{\text{bol}}\).
\(^h\) Winters et al. (2003).
\(^i\) Knapp et al. (1998).
\(^j\) Drake & Linsky (1986).
\(^k\) Loup et al. (1993).
The spectral type of M2.5 III (Keenan & McNeil 1989). The periodic variable (1700, 164, and 154 days). Here we have adopted the period of 150 days that is widely accepted in the literature.

The lunar occultation of SW Vir (M7 III) was recorded in the K band only. The S/N of the data is limited by atmospheric scintillation. We derive a UD diameter of 15.9 ± 0.6 mas at a P.A. of 261° from the primary at a P.A. of 29° that there is no detectable variation of angular size with phase in the case of

| Star    | Date       | Phase | λ/Δλ (μm) | Angular Diameter (UD) (mas) |
|---------|------------|-------|-----------|-----------------------------|
| U Ari   | 2002 Feb 19| 0.57  | 2.2/0.4   | 7.3 ± 0.3                   |
| Z Sco   | 2003 Mar 22| 0.26  | 2.2/0.4   | 3.8 ± 1.0                   |
| U Ori   | 2000 Mar 13| 0.33  | 2.2/0.4   | 11.9 ± 0.3                  |
| SW Vir  | 2001 Jun 1 | 0.56  | 2.2/0.4   | 15.9 ± 0.6                  |
| η Gem   | 2001 Jan 8 | 2.2/0.4| 12.7 ± 0.3|                             |
|         | 2001 Jan 8 | 3.8/0.6| 12.7 ± 1.0|                             |
|         | 2001 Mar 4 | 2.2/0.4| 12.8 ± 0.3|                             |
|         | 2001 Mar 4 | 3.6/0.6| 12.8 ± 2.0|                             |
| μ Gem   | 2001 Mar 4 | 2.2/0.4| 13.7 ± 0.5|                             |
|         | 2001 Mar 4 | 3.6/0.6| 14.8 ± 1.0|                             |
| TV Gem  | 2000 Nov 14| 2.2/0.4| 4.8 ± 0.2  |                             |

variability is classified as SRa with a small visual amplitude of 0.75 mag. Two periods, 233 and 20 days, are found from photometric observations (Percy & Wilson 2001). Most of the earlier observations report the longer period, 233 days.

Two lunar occultations of η Gem (M2.5 III) were observed on 2001 January 8 and 2001 March 4 simultaneously in the K and L’ bands. The best-fit UD model curves and the observed data points are shown in Figure 3. We derive UD angular diameters of 12.7 ± 0.3 mas at K and 12.7 ± 1.0 mas at L’ for 2001 January 8 and 12.8 ± 0.3 mas at K and 12.8 ± 2.0 mas at L’ for 2001 March 4 (Table 3).

We thus have two good sets of observations in both the K and L’ bands separated by a 2 month interval. In this period, a good K-band measurement of angular diameter was made (Richichi & Calamai 2003) that is in good agreement with our value. From our two-epoch, two-wavelength observations we can conclude that there is no detectable variation of angular size with phase in the case of η Gem.

Previous angular diameter measurements of η Gem are listed in Table 4. The source has a well-determined angular diameter over the wavelength range 0.55–2.2 μm. The optical (0.55–0.80 μm) UD diameters are 11.43 ± 0.55 and 10.91 ± 0.11 mas, respectively (Mozurkewich et al. 2003). At 0.712 μm (in the strong TiO band) and at 0.754 μm (in the adjacent continuum), the UD diameters are 11.75 ± 0.27 and 10.70 ± 0.15 mas, respectively (Quirrenbach et al. 1993). These optical diameters are not different from the continuum diameters and are slightly lower than our measured IR diameters.

The source η Gem is also identified as a spectroscopic binary. The spectral type of the companion is identified as G0 III, with a visual magnitude of 11.3 and a separation of 0.9–108 from the primary at a P.A. of 29° (Phillips et al. 1980; Baize 1980). The Hipparcos catalog shows a binary separation of 177 at a P.A. of 261° (Perryman et al. 1997). The variation of separation in several observations is attributed to the ellipticity of the orbit. No binarity signature is detected in any of our lunar occultation light curves, and it was also undetected from previous lunar occultation observations. The brightness ratio between the primary and secondary component is estimated to be ∼1:1600 in the visual band. The K magnitude of the
companion would be ~13 mag, which is well below the limit of our detection.

3.1.6. \( \mu \) Gem

The source \( \mu \) Gem is an oxygen-rich SR variable of Lb type. The source has a spectral type of M3 III (Keenan & McNeil 1989) and a period of 27 days (Percy & Wilson 2001).

The lunar occultation of \( \mu \) Gem (M3 III) was also observed simultaneously in the \( K \) and \( L' \) bands. We derive UD angular diameters of \( 13.7 \pm 0.5 \) and \( 14.8 \pm 1.0 \) mas in the \( K \) and \( L' \) bands, respectively (Table 3). The model-fitted light curves along with the observed data points are shown in Figure 5.

There are 13 observations of lunar occultation in the wavelength range 0.4–0.82 \( \mu \)m listed in the catalog of White & Feierman (1987), and the mean UD value in that wavelength range is \( 13.06 \pm 0.42 \) mas. The UD angular sizes in the optical bands from recent interferometric observations are \( 13.98 \pm 0.14 \) mas (at 0.80 \( \mu \)m) and \( 13.48 \pm 0.19 \) mas (at 0.55 \( \mu \)m) (Mozurkewich et al. 2003). The UD sizes at the TiO absorption band (0.712 \( \mu \)m) and the nearby continuum (0.754 \( \mu \)m) are \( 13.97 \pm 0.28 \) and \( 13.50 \pm 0.13 \) mas, respectively (Quirrenbach et al. 1993). The UD value at the \( K \) band is \( 13.50 \pm 0.15 \) mas (Di Benedetto & Rabbia 1987). Mira-like enlargement (a factor of \( \sim 2 \)) at the TiO band compared to the adjacent continuum has not been noted in \( \mu \) Gem. Some of the previous measurements are listed in Table 4.

Considering all available measurements including our own, it appears that the UD diameter of \( \mu \) Gem has not shown any substantial variation from optical to near-IR over many years. Our UD angular diameters also show no significant variation between the \( K \) and \( L' \) bands within the errors of measurement.

For non-Mira stars of up to at least spectral type M4, it has been shown that observed and model-predicted visibility curvatures do not differ significantly from the UD profile (Wittkowski et al. 2001, 2004). This is also realized from theoretical models of non-Mira M giants (Hofmann & Scholz 1998), as opposed to the Mira model (Hofmann et al. 1998). In the case of non-Mira stars (\( \eta \) Gem, \( \mu \) Gem, and TV Gem but not SW Vir) in our sample, the UD size in the \( K \) band may be close to the true continuum diameter, consistent with previous observations (Table 4). Although warm H\(_2\)O is detected in the spectra of K and early M giants (Tsui 2001), for \( \eta \) Gem and \( \mu \) Gem we find that there is no change between the \( K \) and \( L' \) diameters, unlike in Mira variables or SW Vir (M7 III). Molecular layers, if at all present in the atmospheres of \( \eta \) Gem and \( \mu \) Gem, must have column densities too low to affect the \( L' \)-band diameters, unlike in Mira variables.

3.1.7. TV Gem

TV Gem is an oxygen-rich supergiant SR variable (SRc). The spectral type is M1–0 Iab (Keenan & McNeil 1989). The visual magnitude varies from 7.0 to 7.8 over a pulsation period of 182 days (Kukarkin et al. 1969). The distance we have adopted here is \( 1200 \pm 300 \) pc based on interstellar extinction toward the Gem OB1 association (Underhill 1984).

The lunar occultation of supergiant TV Gem was recorded on 2000 November 14 in the \( K \) band under clear sky conditions. The S/N is high (~100) and is limited by atmospheric scintillation. The UD model fit to the light curve with the usual five free parameters (in \( \xi^2 \)) was not completely satisfactory. A better fit to the data was obtained by including a star plus shell model rather than a single-star model, both of which are shown in the residuals.

### Table 4

| Star       | Variability Type | Date of Observation | Method* | Phase | \( \lambda/\Delta\lambda \) (\( \mu \)m) | Angular Diameter (UD) (mas) | References |
|------------|------------------|---------------------|---------|-------|--------------------------------------|----------------------------|------------|
| U Ari .............. | Mira             | 1977 Sep 3          | LO      | 0.49  | 1.62/0.42                           | 6.11 ± 0.34                | 1          |
| U Ori .............. | Mira             | 2000 Oct 15         | LBI     | 0.88  | 2.20/0.40                           | 15.59 ± 0.06               | 2          |
|              |                  | 2000 Nov 15         | LBI     | 0.96  | 3.75/0.70                           | 25.66 ± 0.69               | 2          |
|              |                  | 2000 Oct            | LBI     | 0.83  | 2.20/0.1                            | 10.6                       | 3          |
|              |                  | 2001 Nov            | LBI     | 0.91  | 2.20/0.1                            | 9.66 ± 0.12                | 3          |
| SW Vir .......... | SRb               | 1981 Jan 26         | LO      | 0.02  | 1.62/0.04                           | 16.82 ± 0.34               | 4          |
|              |                  | 1981 Sep 1          | LO      | 0.48  | 2.17/0.03                           | 16.11 ± 0.13               | 5          |
|              |                  | 1982 Jun 29         | LO      | 0.48  | 2.28/0.40                           | 16.77 ± 0.23               | 4          |
|              |                  | 2000 Feb 9          | LBI     | 0.51  | 2.20/0.40                           | 16.24 ± 0.06               | 2          |
|              |                  | 2000 Mar 12         | LBI     | 0.56  | 3.75/0.70                           | 22.88 ± 0.33               | 2          |
| \( \eta \) Gem ... | SRa               | 1988–1990           | LBI     |       | 0.55/0.02                           | 11.43 ± 0.55               | 6          |
|              |                  | 1988–1990           | LBI     |       | 0.80/0.02                           | 10.91 ± 0.11               | 6          |
|              |                  | 1993                | LBI     |       | 0.712/0.012                         | 11.75 ± 0.27               | 7          |
|              |                  | 1993                | LBI     |       | 0.754/0.005                         | 10.70 ± 0.15               | 7          |
|              |                  | 2001 Mar 31         | LO      |       | 2.20/0.40                           | 12.57 ± 0.04               | 8          |
| \( \mu \) Gem ..... | Lb                | 1988–1990           | LBI     |       | 0.55/0.02                           | 13.48 ± 0.19               | 6          |
|              |                  | 1988–1990           | LBI     |       | 0.80/0.02                           | 13.99 ± 0.14               | 6          |
|              |                  | 1993                | LBI     |       | 0.754/0.005                         | 13.50 ± 0.13               | 7          |
|              |                  | 1993                | LBI     |       | 0.712/0.012                         | 13.97 ± 0.28               | 7          |
|              |                  | 1987                | LBI     |       | 2.20/0.40                           | 13.50 ± 0.15               | 9          |
| TV Gem ........... | SRc               | 1982 Aug 15         | LO      | 0.55  | 5.31 ± 0.91                         | 10                       |            |
|              |                  | 1993 Mar 30         | LO      | 2.20/0.40 | 4.9 ± 0.30 | 11                       |            |
|              |                  | 1993 Feb 3          | LO      | 2.20/0.40 | 4.46 ± 0.07 | 12                       |            |

* LO: lunar occultation; LBI: long-baseline interferometry.

References—(1) Ridgway et al. 1979; (2) Mennesson et al. 2002; (3) Perrin et al. 2004; (4) Ridgway et al. 1982; (5) Schmidtke et al. 1986; (6) Mozurkiewich et al. 2003; (7) Quirrenbach et al. 1993; (8) Richichi & Calamai 2003; (9) Di Benedetto & Rabbia 1987; (10) Radick et al. 1984; (11) Ragland et al. 1997; (12) Richichi et al. 1998.
The JHK photometric observations on 2000 November 16 yielded the magnitudes $m_J = 2.31 \pm 0.05$, $m_H = 1.39 \pm 0.05$, and $m_K = 1.16 \pm 0.06$ in $J$, $H$, and $K$, respectively.

Angular diameter measurements of TV Gem by lunar occultation have been reported several times and are listed in Table 4. Earlier lunar occultations reported UD values of $5.31 \pm 0.91$ mas in the optical region (Radick et al. 1984), $4.9 \pm 0.3$ mas in the $K$ band (Ragland et al. 1997), and $4.46 \pm 0.07$ mas again in the $K$ band (Richichi et al. 1998). From lunar occultation observations in the $K$ band, Ragland et al. (1997) had reported a double-shell structure for TV Gem, as for another supergiant, $\alpha$ Ori (Danchi et al. 1994). The inner dust shell was estimated to be at $20 \pm 5 R_\odot$. The outer shell was estimated to be at $\sim 500 R_\odot$, based on IRAS LRS spectra and IRAS photometry (12, 25, and 60 $\mu$m). They found the shell contribution in the $K$ band to be $\sim 3\%$. We measure the UD angular diameter of the source to be $4.8 \pm 0.2$ mas. We estimate the dust shell to be at $(13 \pm 5) R_\odot$. The shell contribution to the $K$-band flux is $\sim 5\%$. These results are consistent with earlier measurements by Ragland et al. (1997).

We estimate the effective temperature to be $3750 \pm 120 K$, again in good agreement with earlier values of Richichi et al. (1998).

3.2. Bolometric Flux and Effective Temperatures

The bolometric fluxes are estimated by fitting a blackbody curve to the available broadband IR photometry measurements ($JHKLM$) compiled in the IR catalog of Gezari et al. (1999) and to 12, 25, and 60 $\mu$m IRAS PSC measurements, including our $JHK$ measurements in some cases. In some cases (U Ari, U Ori, and Z Sco) a two-temperature blackbody is required to best fit all observed points (1.25–60 $\mu$m). Specifically, an additional blackbody curve with a cooler temperature ($\sim 500 K$) fits the excess in IRAS flux. Such fits are shown in Figure 7. For $\eta$ Gem a single-temperature blackbody curve is adequate for all observed fluxes (Fig. 7). The observed broadband photometric magnitudes ($JHKLM'$) are converted to flux densities using the zero magnitude to flux density calibration established by Bessell et al. (1998). The blackbody flux is normalized with the observed flux in the $K$ band. In the case of a two-temperature blackbody fit to the photometric data, the star flux is fitted with a relatively hotter blackbody curve that is normalized with the observed $K$-band flux. An additional, relatively cooler blackbody curve fits the excess in the observed IR fluxes, which is further normalized.
with the star continuum–subtracted IRAS flux at 25 μm. By numerically integrating the single (or the result of the two temperatures) blackbody curve in the wavelength range 0.4–100 μm, the bolometric flux is calculated. No reddening corrections were applied to estimate the bolometric fluxes. These were deemed unnecessary, since the typical magnitudes of the corrections of our sample are less than 0.05 mag in the K band. For example, the largest visual extinction was found in U Ori, A_v = 0.25 mag (Whitelock et al. 2000) and, correspondingly, A_k = 0.03 mag using the wavelength-dependent extinction relation A_k = 0.11A_v established by Bessell et al. (1998). Our own IR JHK photometric measurements of U Ari are used to estimate the bolometric flux at that particular phase (near minimum), while others are taken from Catchpole et al. (1979) at a similar phase. In the case of SW Vir and TV Gem, the bolometric fluxes were taken from the literature (Perrin et al. 1998; Ragland et al. 1997). For other sources (U Ari, U Ori, Z Sco, μ Gem, and η Gem) we used our estimated bolometric fluxes from blackbody fits to calculate the effective temperature using the relation given below:

$$ T_{\text{eff}} = 2341 \left( \frac{F_{\text{bol}}}{\phi^2} \right)^{1/4}, $$

where the bolometric flux $F_{\text{bol}}$ is in units of $10^{-8}$ ergs cm$^{-2}$ s$^{-1}$, the UD angular diameter $\phi$ is in milliarcseconds, and the effective temperature $T_{\text{eff}}$ is in kelvins. The typical error in bolometric flux is estimated to be about 15%. The effective temperatures of the sources using our derived K-band UD diameters are listed in Table 5. For Mira variables, which are sources with extended atmospheres, $T_{\text{eff}}$ refers to a specific layer. The characteristic reference level seems to be near optical depth unity in the near-IR continuum (Perrin et al. 2004). The effective temperature $2280 \pm 80$ K of U Ari at phase 0.57 is substantially lower than the expected value of Mira stars ($\sim 3000$ K), while the values $2905 \pm 80$ K of U Ori at phase 0.33 and $3120 \pm 420$ K for Z Sco at phase 0.26 are consistent.

We estimated effective temperatures of $3450 \pm 125$ K for η Gem and $3675 \pm 140$ K for μ Gem, consistent with their spectral type. For SW Vir we estimate the effective temperature to be $3060 \pm 130$ K, consistent with earlier measurements.

### 3.3. Linear Radii and Mode of Pulsation

From interferometric observations and theoretical models it appears that a true continuum size estimate is difficult or impossible for Mira variables in the presence of molecular contamination effects and phase cycle effects. Fedele et al. (2005) draw similar conclusions for R Leo. Other than wavelength and phase effects, determination of the mode for pulsation in Mira stars from the period-radius relation is also constrained by the large uncertainty in the distance to most of the sources, as noted earlier in § 3 (Whitelock & Feast 2000; van Leeuwen et al. 1997). Theoretical models (Bessell et al. 1996; Hofmann et al. 1998) indicated the fundamental mode for these stars because it is difficult to produce the observed large velocity amplitude (Hinkle et al. 1997; Scholz & Wood 2000) with the first-overtone model.

![Fig. 5.—Occultation light curves of μ Gem in the K band (left) and L' band (right): model fit, residuals of fit (lower plots), and convergence of fit (insets). The dotted and solid lines are the observed data and model-fitted curves, respectively. The best-fit UD angular diameter is 13.7 ± 0.5 mas at K band and 14.8 ± 1.0 mas at L' band.](image)

![Fig. 6.—Occultation light curves of TV Gem in the K band: model fit and convergence of fit (inset). The dotted and solid lines are the observed data and model-fitted curve, respectively. The best-fit UD angular diameter is 4.8 ± 0.2 mas. The bottom panel of the graph shows the enlarged residuals, particularly the first and second fringe positions, which are marked by arrows for the star+shell model fit (solid line) and single-star model fit (dashed line).](image)
The comparison of theoretical pulsation models with MACHO observations of long-period variables in the LMC (Wood et al. 1999), with pulsation velocities derived from Doppler line profiles (Scholz & Wood 2000), also strongly indicates that Mira stars are fundamental-mode pulsators. Earlier observed UD diameters for Mira stars at optical and near-IR wavelengths without considering molecular contamination pointed to the first-overtone mode (Haniff et al. 1995; van Belle et al. 2002). More recently, considering molecular contamination in observed visibilities, Perrin et al. (2004) arrived at a lower size compared to the earlier UD-fitted size of six Mira variables and concluded that these are pulsating in the fundamental mode. Woodruff et al. (2004) found that the interferometric visibilities curve of o Cet differs from the UD profile, and the data are better fitted with the fundamental model.

SRs are separated from Mira stars by having a shorter period and smaller amplitude, and they often show evidence of multiple periods (Bedding et al. 1998; Kiss et al. 1999). The modes of pulsation of Galactic Mira variables are well studied, while little attention has been given to the pulsation studies of SRs. Feast (1996) found that SRs in globular clusters are pulsating in the first overtone. From MACHO observations of LMC red variables, Wood et al. (1999) concluded that SRs can be pulsating in the first, second, or third overtone or the fundamental mode. Comparing observational and theoretical $Q$-values of 13 Galactic SRs, Percy & Parkes (1998) found that the majority are pulsating in the first or second overtone, while some are pulsating in the fundamental mode.

Wood (1990) had suggested that, in principle, one combined equation for the position of low-mass AGB stars (both Mira and

### Table 5

**Derived angular diameters, bolometric fluxes, and effective temperatures**

| Star       | Spectral Type | $m_L$ | $m_s$ | UD (K band) (mas) | $F_{bol}$ ($10^6$ ergs cm$^{-2}$ s$^{-1}$) | $T_{eff}$ (K) |
|------------|---------------|-------|-------|-------------------|------------------------------------------|---------------|
| U Ari      | M9 IIIe       | 1.26  | 14.50 | 7.3 $\pm$ 0.3    | 45 $\pm$ 5                              | 2250 $\pm$ 80 |
| Z Sco      | M4/S IIIe     | 1.33  | 11.6  | 3.8 $\pm$ 1.0    | 46 $\pm$ 5                              | 3120 $\pm$ 420|
| U Ori      | M8 IIIe       | $-0.88$ | 10.89 | 11.9 $\pm$ 0.3*  | 336 $\pm$ 33                            | 2905 $\pm$ 80 |
| SW Vir      | M7 III        | $-1.74$ | 7.90  | 15.9 $\pm$ 0.6   | 735 $\pm$ 110                           | 3060 $\pm$ 130|
| η Gem      | M2.5 III      | $-1.49$ | 3.70  | 12.8 $\pm$ 0.3   | 760 $\pm$ 105                           | 3450 $\pm$ 125|
| μ Gem      | M3 III        | $-1.89$ | 3.20  | 13.7 $\pm$ 0.5   | 1140 $\pm$ 170                          | 3675 $\pm$ 140|
| TV Gem     | M1 Ia         | 1.16  | 6.83  | 4.8 $\pm$ 0.2    | 153 $\pm$ 15                            | 3750 $\pm$ 120|

* The angular diameter of U Ori is taken from Mondal & Chandrasekhar (2004).
SR variables) could be used for comparing the observational results. The standard pulsation equation is written as

\[ Q = P \left( \frac{M}{M_\odot} \right)^{1/2} \left( \frac{R}{R_\odot} \right)^{-3/2}, \]

where \( Q \) is a constant quantity (units of days) that has a distinct value for each mode of pulsation. Here \( R \) is actually the Rosseland radius of the nonpulsating star. Theoretical model–predicted \( Q \)-values vary with period, mass, and luminosity (Fox & Wood 1982). Typically, the \( Q \)-values are \( \approx 0.105 \) (fundamental) and \( \approx 0.04 \) (first overtone), estimated from the theoretical models by Fox & Wood (1982). The \( Q \)-values used by Percy & Parkes (1998) for the study of Galactic SR variables are 0.04 (first overtone), 0.022 (second), 0.017 (third), and 0.012 (fourth) from the models of Xiong et al. (1998).

We have estimated \( Q \)-values for the samples considering a mass of 1 \( M_\odot \) (Table 6). Furthermore, following Ostlie & Cox (1986), we have considered the following expressions for fundamental and overtone modes, respectively,

\[
\log P = 1.86 \log \left( \frac{R}{R_\odot} \right) - 0.73 \log \left( \frac{M}{M_\odot} \right) - 1.92, \\
\log P = 1.59 \log \left( \frac{R}{R_\odot} \right) - 0.51 \log \left( \frac{M}{M_\odot} \right) - 1.60,
\]

where \( P \) is the period in days.

Masses of Mira variables of moderate period (\( \leq 400 \) days) are reasonably well constrained at \( \approx 1 \) \( M_\odot \). Wyatt & Cahn (1983) estimated the main-sequence masses of 124 Mira variables considering the available data on radial velocity measurements. The main-sequence mass of the progenitor of one Mira (U Ari) in our sample has been determined by Wyatt & Cahn (1983) to be 1.3 \( M_\odot \). Jura & Kleinmann (1992) suggested that the main-sequence masses of Mira progenitors are in the range 0.8–2.0 \( M_\odot \) for Mira variables with a period less than 400 days. Theoretical models of Mira stars for masses of 1 and 1.2 \( M_\odot \) have predicted that geometric pulsation of continuum-forming layers is little affected by the mass difference (Ireland et al. 2004b). As SR variables are progenitors of Mira variables, such mass considerations may also be applicable for them. In this mode analysis we have considered the mass range 1.0–2.0 \( M_\odot \).

The linear radius is obtained from our \( K \)-band UD angular diameters and the adopted distance (Table 6) and is superposed on the theoretical model curves (Fig. 8). The errors shown on linear radii are mainly due to errors on distance estimates.

There has been a great deal of discussion on \( Hipparcos \) parallax measurements of Mira variables in the literature (van Leeuwen et al. 1997; Whitelock & Feast 2000; Knapp et al. 2003). The revised \( Hipparcos \) parallaxes for U Ori and Z Sco have large errors (Table 6), and so we have not adopted them for distance estimation. \( Hipparcos \) parallaxes are excellent for \( \mu \) Gem, \( \eta \) Gem, and SW Vir, and we have adopted those parallaxes (Table 6). The adopted distances to all Mira variables in our sample have been estimated using the period-luminosity (PL) relationship given in Whitelock & Feast (2000; U Ori and Z Sco) and Feast (1996; U Ari). The PL relations for Mira variables have been developed by several other authors (Feast 1996; van Leeuwen et al. 1997; Knapp et al. 2003), and those are consistent with the adopted relation. Considering the uncertainties in the apparent magnitudes (because of variability amplitude) and the dispersion in PL relations, we have considered errors in the Mira distances to be about 20%.

From Figure 8 and the \( Q \)-value in Table 6, it appears that the Mira star U Ari is pulsating in the first-overtone mode, from both \( K \)- and \( H \)-band measurements. However, as noted in § 3.1.1, observations in both the \( K \) and \( H \) bands were near the minimum

### Table 6

| Star     | \( K \) band UD (mas) | Period (days) | PL Distance \( (\text{pc}) \) | \( Hipparcos \) Distance \( (\text{pc}) \) | Adopted Distance \( (\text{pc}) \) | Linear Radii \( (R_\odot) \) | \( Q \)-Value for \( 1 \) \( M_\odot \) |
|----------|-----------------------|--------------|-----------------------------|---------------------------------|---------------------------------|-----------------------------|-----------------------------|
| U Ari    | 7.3 \pm 0.3           | 371          | 776 \pm 155\( ^a \)         | \ldots                          | \ldots                          | \ldots                      | 0.025                       |
| Z Sco    | 3.8 \pm 1.0           | 352          | 778 \pm 145\( ^a \)         | \ldots                          | \ldots                          | \ldots                      | 0.062                       |
| U Ori    | 11.9 \pm 0.3          | 372          | 306 \pm 61\( ^a \)          | 585 \pm 875\( ^b \)             | 778 \pm 145                     | 320 \pm 100                  | 0.048                       |
| SW Vir   | 15.9 \pm 0.6          | 150          | 98 \pm 19\( ^a \)           | 143 \pm 24                      | 143 \pm 24                      | 244 \pm 42                  | 0.039                       |
| \( \eta \) Gem | 12.8 \pm 0.3        | 233, 20\( ^c \) | 150 \pm 30\( ^c \)       | 107 \pm 22                      | 107 \pm 22                      | 146 \pm 30                  | 0.130, 0.012                |
| \( \mu \) Gem | 13.7 \pm 0.5         | 27           | \ldots                      | 71 \pm 5                        | 71 \pm 5                        | 104 \pm 8                   | 0.025                       |
| TV Gem   | 4.8 \pm 0.2           | 182          | \ldots                      | 1492 \pm 2340                   | 1200 \pm 300\( ^d \)            | 623 \pm 158                 | 0.012                       |

\( ^a \) From the PL relation of Whitelock & Feast (2000).
\( ^b \) Revised \( Hipparcos \) parallax from Knapp et al. (2003).
\( ^c \) This secondary period is determined from visual photometric observations by Percy & Wilson (2001).
\( ^d \) Adopted from Underhill (1984).
phase, when molecular contamination effects are at a peak. Converting the measured lunar occultation UD diameter directly to a linear diameter would tend to overestimate the linear size. Until further measurements at other phases are available, the result of overtone pulsation in U Ari must be treated with caution.

The Mira star Z Sco is probably a fundamental-mode pulsator, but precise angular diameter determination was not possible because of noisy data. The mode of pulsation for U Ori appears to be a borderline case. We note that similar conclusions were drawn from earlier $K$-band interferometric observations of van Belle et al. (2002). The minimum diameter for U Ori from recent interferometric observations in several narrow bands inside the broad $K$ band (Perrin et al. 2004), however, favors the fundamental mode.

It is difficult to draw any conclusion on the SR variables SW Vir and $\mu$ Gem from their position in Figure 8. However, comparing observational (Table 6) and theoretical $Q$-values of Percy & Wilson (2001), both SW Vir and $\mu$ Gem may be overtone candidates. The SRs $\eta$ Gem could be a fundamental-mode pulsator of low mass, but it has a second period of 20 days, which complicates the issue.

4. SUMMARY AND CONCLUSIONS

Our UD angular diameter of U Ari in the $K$ band shows a substantially larger value (~20%) than in the earlier $H$ band observation at nearly the same variability phase. Such an enhancement is consistent with a hot extended molecular layer close to the photosphere, as suggested by Perrin et al. (2004).

The supergiant TV Gem yields an angular size of 4.80 ± 0.20 mas in the $K$ band, consistent with previous measurements. The dust shell around TV Gem is reconfirmed. We measure the dust shell size to be (13 ± 5)R$_s$. The effective temperature derived is 3750 ± 120 K, consistent with the earlier value.

We estimate the linear radii of three Mira variables (U Ari, U Ori, and Z Sco) from the $K$-band lunar occultation UD angular diameters and distances derived from the PL relation. Comparing theoretical period-radius plots (Fig. 8), we find that U Ari is a first-overtone pulsator, Z Sco is probably a fundamental-mode pulsator, and U Ori is a borderline case between fundamental and first-overtone modes. A stronger conclusion regarding the pulsation mode of Mira variables from occultation observations could probably be reached by modeling lunar occultation light curves for molecular contamination effects.

The two SR variables $\eta$ Gem and $\mu$ Gem clearly do not show any variation in their angular diameter in the $K$ and $L^\prime$ bands, unlike the Mira variables. SW Vir and $\mu$ Gem appear to be candidates for the overtone mode from their $Q$-values. However, as we are using occultation UD radii that are greater than the Rosseland radii, our $Q$-values may be lesser than the theoretical values. The case of $\eta$ Gem is complicated by the presence of two periods in its optical light curve. Further high angular resolution studies of SR variables are clearly warranted.

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