Mon. Not. R. Astron. Soc. **348,** 1332–1336 (2004) doi:10.1111/j.1365-2966.2004.07454.x

Evidence of asymmetric structure in the atmosphere of Mira variable U Orionis from lunar occultation observations in the near-infrared

Soumen Mondal★ and T. Chandrasekhar★
Physical Research Laboratory, Ahmedabad-380 009, India

Accepted 2003 November 19. Received 2003 October 24; in original form 2003 August 20

ABSTRACT

We present the infrared angular diameter of Mira variable U Ori, obtained from lunar occultation observations at 2.2 μm. The uniform disc (UD) angular diameter is determined to be 11.9 ± 0.3 mas at variability phase 0.28. The source brightness profile derived from a model-independent analysis shows an asymmetric spatial structure. The dispersion in UD angular diameter measurements in comparison with other similar measurements at the same phase in the near-infrared can be explained by a spatial asymmetry of the source, being elongated in the direction northeast – southwest, at position angle of 50°–70°. Several corollary evidences for the spatial asymmetry of the source are presented.

Key words: occultations – stars: individual: U Ori – infrared: general.

1 INTRODUCTION

Due to their relatively large sizes, resolvable angular diameters and high infrared brightnesses, the photosphere and neighbourhood of many Mira variables have been well studied over a wide wavelength range by high angular resolution techniques like lunar occultations (LO), single aperture masking and direct long baseline interferometry (LBI). The picture that emerges is of a complex and very extended Mira atmosphere with generally spherical symmetry, but departures from this symmetry have been reported. These departures could be due to stellar rotation, non-radial pulsation or due to hotspots produced by large-scale convection processes in outer layers of the atmosphere. Repeated occurrences of asymmetries, large chromatic size variations near deep absorptions due to TiO or VO, evidence of clumps and hotspots are all known aspects of the Mira atmospheres (Tuthill, Haniff & Baldwin 1999; Young et al. 2000).

The wavelength-dependent size variations are understandable features evidenced from several high angular resolution measurements. Comparison between continuum and molecular line in narrow filterbands showed the spatial extent of these types of stars. Many such observations have been reported using an aperture masking method (Haniff et al. 1992; Haniff, Scholz & Tuthill 1995; Tuthill et al. 1999) and a direct LBI method (Thompson, Creech-Eakman & van Belle 2002b, and references therein). The angular size variation in the continuum bands are normally attributed to bulk motion of the stellar photosphere while size changes in molecular bands are attributed to opacity variations possibly due to stellar pulsational effects on the extended atmosphere. Chromatic size variations of 7–10 per cent within the *K*-band at the same phase of Mira star S Lac (M4-8IIIe) has been reported by LBI measurements (Thompson et al. 2002b).

★E-mail: soumen@prl.ernet.in (SM); chandra@prl.ernet.in (TC)

Asymmetric spatial structures in Mira variables have been noted earlier and studied by high angular resolution techniques. A few examples of asymmetric structures in Miras can be listed. LBI observations of Mira variable R Tri in the *K* band (Thompson, Creech-Eakman & Akeson 2002a) show phase-dependent significant departures from the spherically symmetric uniform disc (UD) model. An elliptical UD of axial ratio (2b/2a) ∼0.75 or a spherical UD overlaid with a smaller ellipsoidal disc is found to fit the data better than a spherical UD. Furthermore, the position angle of asymmetry is approximately perpendicular to intrinsic polarization position angles which were observed earlier in visible region (McLean 1979). Apart from this model of an overlaid elliptical thin disc, the asymmetric structure in R Tri could also occur due to a grouping of large star-spots about the photospheric equator. In case of O Ceti (Mira) a much greater degree of asymmetry compared to R Tri has been reported. Ground based direct imaging by aperture masking method showed asymmetric structures in the atmosphere of Mira in the optical continuum as well as molecular/atomic line bands (Haniff et al. 1992). These authors have estimated the axial ratios of 0.78–0.85 at postition angle (PA) 105°–158° from the elliptical disc model. *Hubble Space Telescope* (*HST*) imaging using the Faint Object Camera (FOC) in the ultraviolet (UV) and optical wavelengths (Karovska et al. 1997) also detected significant asymmetry in this Mira A atmosphere. The deconvolved image of Mira A shows a strong asymmetry at position angle of 175° prominently at 0.501 μm. Karovska et al. (1997) attribute the asymmetry in Mira A to bright spots on the surface of the star or in its extended atmosphere. They also suggest that the asymmetry could be an indication of non-radial pulsation in the Mira A atmosphere. Yet another example of the spatial asymmetry in Mira variables is R Cas, determined by the speckle imaging techniques in the optical bands using the Russian 6-m Special Astrophysical Observatory (SAO) telescope (Hofmann et al. 2000). The observed data is again better fitted with a elliptical

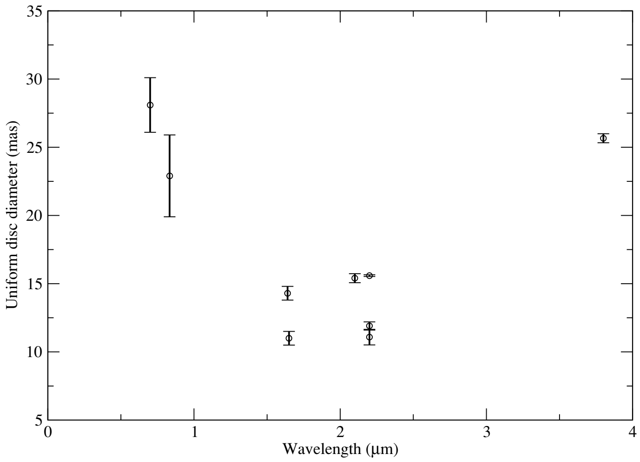

Figure 1. The uniform disc diameter measurements of U Ori from optical to thermal IR are plotted as function of wavelength including the result of present work at 2.2 μm. Reference of the other measurements are given in the text.

uniform disc distribution function having axial ratio ∼0.70–0.87 at different position angles. In this paper we present evidence for the asymmetric nature of U Ori atmosphere from LO observations in the *K* band.

U Ori is a Galactic oxygen-rich Mira variable with pulsation period of 371 d. The spectral type ranges from M6–M9.5 IIIe (Keenan & McNeil 1989), corresponding to the effective temperature changes of approximately 850 K (Richichi et al. 1999). The interstellar visual extinction towards U Ori is $A_v \sim 0.25$ mag (Neckel & Klare 1980). The distance to U Ori ranges from 250 to 310 pc (Wyatt & Cahn 1983; van Belle, Thompson & Creech-Eakman 2002). The photometric light curve is asymmetric in nature with a steep rise and gradual fall during the cycle [Association Francaise des Observateurs d'Etoiles Variables (AFOEV) data base]. The visual amplitude (maximum to minimum) of U Ori is 6.5 mag (Mennesson et al. 2002). At 2.2 μm we measure the photometric variability of U Ori to be 0.3 mag. The reported linear radius of U Ori is 370 ± 96 $R_\odot$ (van Belle et al. 2002). Using the bolometric flux and distance quoted by these authors, the luminosity was calculated to be ∼7000 $L_\odot$. In the case of U Ori, the phase variation of stellar radius may be better represented by the E-series (first overtone) models of Bessell, Scholz & Wood (1996). It has been noted that in this model the predicted variations of radius with phase in the infrared (IR) continuum band are ∼5–6 per cent.

Angular diameter measurements of U Ori (Fig. 1) span the range from optical to thermal IR. Using the aperture masking method on the 4.2 -m William Herschel Telescope (Haniff et al. 1995) derive the photospheric diameter (referring to the layer of unit Rosseland optical depth) of U Ori in the range of 18.5 mas (0.833 μm) to 22.2 mas (0.700 μm) corresponding to their E-series models. In the near-IR one of the earliest measurements of the angular diameter was due to an LO observed by Ridgway, Wells & Joyce (1977) who obtained a value of 15.45 ± 0.33 mas at 2.07 μm with a narrow band filter ($\Delta\lambda = 0.03$ μm) inside the stellar H_2O absorption band. The measurements in the near-IR are summarized and discussed later. In the thermal IR region U Ori shows substantially larger size. Mennesson et al. (2002) measured the angular diameter of 25.66 ± 0.69 mas in the L'-band. Earlier heterodyne interferometry at 11.4 μm by Danchi et al. (1994) measured the inner dust shell size of 80 mas in U Ori.

At radio wavelengths interferometric observations of OH maser have been carried out several occasions since early 1970. The source flared up in the OH maser line at 1612 MHz in 1973 (Pataki & Kolena 1974). The maser shell shows asymmetric geometry and clumpy distribution (Chapman, Cohen & Saikia 1991) which are inconsistent with spherically symmetric mass-loss. The angular extension of OH masers are distributed within a region of 500 × 700 mas^2 in north–south (N–S) by east–west (E–W), measured by these authors. Maser velocity map shows a gradient in the SE to NW direction orthogonal to the maser elongation. Recently Bains et al. (2003), from their subarcsec imaging of U Ori in the H_2O maser line, report an elongation in the direction NE–SW at position angle of 30° while Bowers & Johnson (1994) found similar elongation at position angle ∼60°. Interpolating from their VLBI observations of 1612-MHz OH maser emission, Reid et al. (1979) infer a surface magnetic field in U Ori of about 10 G assuming an angular radius of 8 mas. Chapman & Cohen (1985) suggest that the rotation axis of the source is along PA ∼ 60° and which may be the bipolar axis of the stellar magnetic field. If this is real, the velocity gradient which is almost orthogonal to the axis may be due to the equatorial density enhancement.

There is a also evidence of moderate level maximum intrinsic polarization of ∼1–2 per cent in *V* and *B* bands, respectively, at PA ≈ 20°–40° (Dyck & Sandford 1971; Coyne & Magalhaes 1977). However, it has been noted that the PA of the maximum polarization angle shows variation over phase in the case of long period variables (Dyck & Sandford 1971) and that it cannot be used indiscriminately as the direction of the asymmetry.

In this paper we discuss our LO observations of U Ori in comparison with other high angular resolution observations in the near-IR and related data on the star. We present a case for the existence of phase independent spatial asymmetry in the atmosphere which could be verified by sustained interferometric monitoring of the star.

2 OBSERVATIONS

The LO observations of Mira variables U Ori were carried out at the 1.2-m Gurushikhar Infrared Telescope (GIRT) (latitude: 24°39′8″.8 N, longitude: 72°46″47″.47 E, altitude: 1680 m) on 2000 March 13 under clear sky conditions. The visual phase of observation was 0.28 (the zero-phase reference is JD = 2451510.0 taken from AFOEV data base). The event was a disappearance and was recorded in the *K*-band [2.2/0.33(FWHM) μm] using a IR high-speed photometer which has been regularly used for LO work. The detector used is a single element InSb cooled by liquid nitrogen. Apart from the K filter, the dewar incorporates additional filters J (1.25/0.29 μm) and H (1.65/0.30 μm) for photometric observations. Details of the instrument can be found elsewhere (Mondal,

Table 1. Circumstances of the LO event.

Star	U Ori
IRC No.	20127
Date	2000 March 13
Julian date(0 UT)	2451616.50
Event type	disappearance
Location	Gurushikhar Observatory, Mt. Abu, India
Observed event time (UT)	$18^h19^m25^s.94$
Position angle (NESW)	136°
Contact angle	43°.5
Pred. V_{comp} (km s^{-1})	0.66
Data sampling rate	2 ms
Filter (FWHM) in μm	2.2 (0.4)

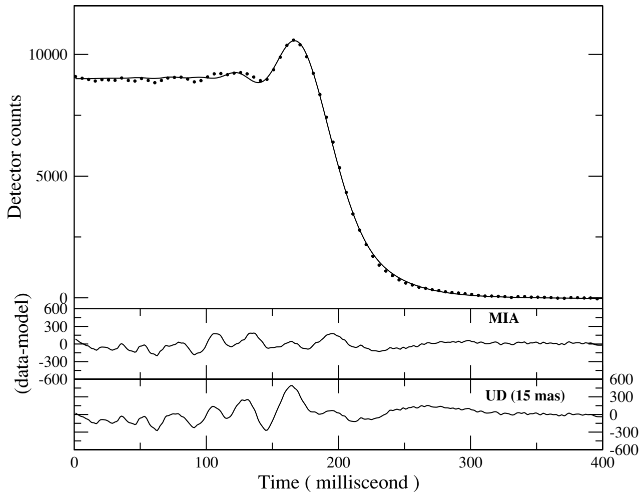

Figure 2. The *filled circles* are the observed data-points of LO light curve of U Ori in the *K*-band (For clarity every fifth point is plotted). The *solid line* is best fit obtained by the MIA analysis. The residual (data – model) of the fits are shown in expanded form at the bottom panels for MIA and UD for a fixed angular size of 15 mas.

Table 2. JHK photometry.

JD	J	H	K	Phase
2451617	–	–	-0.75 ± 0.10	0.28
2451658	–	–	-0.66 ± 0.08	0.45
2451890	0.44 ± 0.08	-0.22 ± 0.07	-0.95 ± 0.07	0.08

Chandrasekhar & Kikani 2002). The sampling time was 2 ms. Circumstances of event are listed in Table 1. A good occultation trace was recorded and is shown in Fig. 2. We have also carried out limited photometry of the source in *JHK* which are listed in Table 2. A variation of 0.3 mag in *K* can be noted from approximately maximum to minimum in our observations.

3 DATA ANALYSIS

In one sense multiple LO observations are well suited for the determination asymmetry in a source as LO provides a very good angular resolution of ∼1 mas in one dimension only. If the PA of occultation coincides with the asymmetry zone then this could clearly be reflected in the determination of UD diameter. LOs of the same source from different observatories produce different high angular resolution chords across the the source. Earlier studies on the the carbon star TX Psc by LO observers had shown the advantage of sampling different chords across a resolvable source (Richichi et al. 1995). Near-simultaneous LO observations separated by only a few hours in the same wavelength band are particularly valuable as they sample different position angles across the source and can pinpoint the existence of spatial asymmetries which are independent of phase variations.

The model fitting of the LO light curve is based on the standard non-linear least-squares (NLS) method first introduced by Nather & McCants (1970). A uniformly illuminated disc (UD model) is usually assumed. Details of the procedure are discussed elsewhere (Chandrasekhar & Mondal 2001). The resolution limit achieved observationally, as determined by studying occultations of a number of bright point sources, is ∼2 mas (Chandrasekhar 1999). In the case where the UD model fits are not satisfactory, a model-independent

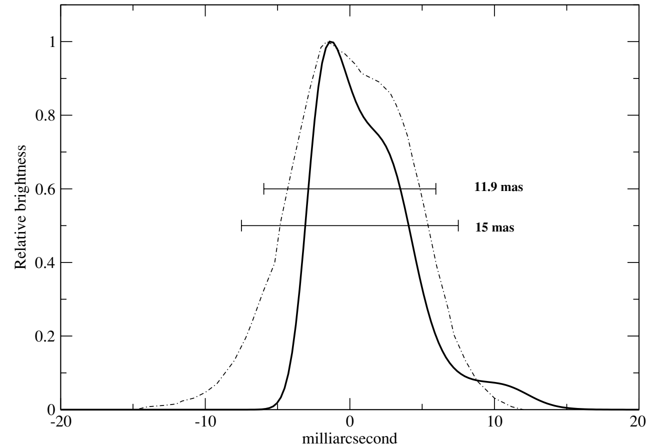

Figure 3. The brightness profile of U Orionis derived from our LO light curve using model-independent algorithm (MIA) is shown by the *solid line* and is compared to that of Richichi et al. (2003) (*dot-dashed line*). The two horizontal lines indicate equivalent UD diameter of 11.9 mas (this work) and 15 mas.

approach (MIA) can be considered if the signal-to-noise ratio of the light curve is good. Such MIAs, first introduced by Richichi (1989), have been applied earlier by us to resolve dust structure of IRC+10216 and WR104 (Chandrasekhar & Mondal 2001; Mondal & Chandrasekhar 2002). MIA is a composite algorithm which makes use of the the NLS method and Lucy deconvolution algorithm, wherein usually the uniform disc profile is assumed as a initial guess profile and is modified iteratively to obtain the best fit of the observed data points.

In the case of U Ori we have first carried out the NLS analysis. We obtain a UD value of 11.9 ± 0.3 mas which is different from the value of 15.14 ± 0.05 mas reported by Richichi & Calamai (2003). Due to the recently reported asymmetry in the source by these authors we have also carried out MIA analysis of our data. In Fig. 2 we show the best fit to the data by MIA analysis. For comparison the residual of a fit to the data by a fixed UD source of 15 mas, close to the value reported by Richichi & Calamai (2003), is also shown. It can be clearly seen that our data fits to a much smaller source size.

Fig. 3 shows our brightness profile derived from MIA analysis. The UD values of 11.9 and 15 mas are also marked for comparison. It can be seen that our profile is more asymmetric in both near-central and outer regions ($\sim 2R_*$) compared to the profile of Richichi & Calamai (2003). It may be noted that these authors have also mentioned the presence of fainter wings in their brightness profile extending to 20–30 mas or 1–3 stellar radii which they attribute to extended circumstellar emission. In our case the signal-to-noise ratio in the wings is inadequate to confirm these fainter structures.

4 RESULT AND DISCUSSIONS

In Table 3 all the angular diameter measurements of U Ori in the *H* and *K* bands are listed. It can be seen that the angular diameter of U Ori in these bands shows a large variation from about 11 to 15.6 mas. The variation is much larger (∼25 per cent) than the observational errors involved. We also note that the observed angular diameter variations do not appear to show any phase dependency though data is sparse (Fig. 4). Our derived UD value is in good agreement with earlier LBI measurements in the *K*-band (van Belle et al. 1996) and *H*-band (Berger et al. 2001) though the phases are different. The interferometric measurements were made close to maximum light while our observation was made about midway between maximum

Table 3. Angular diameter measurements of U Ori in the *H* and *K* bands.

Date	Method	Phase	PA[a] deg.	$\lambda/\Delta\lambda$ (μm)	Ang. Dia (UD) (mas)	Ref.
13 Mar 2000	LO	0.28	136	2.20/0.33	11.9 $\pm$ 0.30	Present work
13 Mar 2000	LO	0.28	75	2.20/0.40	15.14 $\pm$ 0.05	Richichi et al. (2003)
15 Jan 1976	LO	0.36	60	2.07/0.03	15.45 $\pm$ 0.33	Ridgway et al. (1977)
08 Oct 1995	LBI	0.97	–	2.20/0.40	11.08 $\pm$ 0.57	van Belle et al. (1996)
26 Nov 2000	LBI	0.04	–	1.60/0.34	11.00 $\pm$ 0.50	Berger et al. (2001)
16 Oct 2000	LBI	0.88	–	2.16/0.32	15.59 $\pm$ 0.06	Mennesson et al. (2002)

Notes. [a]PA is defined as the angle of the event measured from N through E.

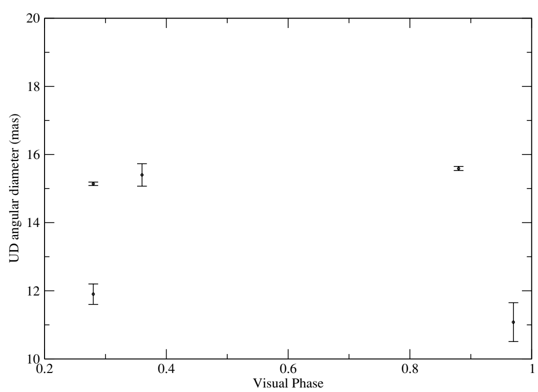

Figure 4. Uniform disc diameters of U Ori at *K*-band are plotted as function of visual phase including the result of present work. Reference of the other measurements are given in the text.

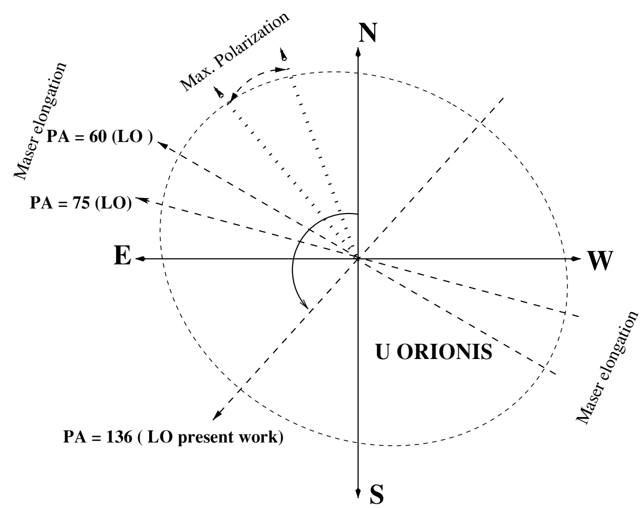

Figure 5. Schematic diagram of asymmetric size of U Orionis is shown and several corollary evidences are depicted. The position angle (PA) of all LOs on U Ori are shown by dashed lines. The direction of OH maser elongation observed at 1665 MHz (Chapman & Cohen 1985) is depicted. Regions of observed PA of maximum intrinsic polarization (Dyck & Sandford 1971; Coyne & Magalhaes 1977) are also shown.

and minimum. Interestingly our observations and the contemporaneous LO measurement of Richichi et al. (2003) show two well determined but different values of angular diameter. Richichi et al. (2003) obtained a value of 15.14 $\pm$ 0.05 mas at a position angle of 75°. The authors attribute the asymmetry in brightness profile and difference among existing angular diameter measurements of U Ori to the pulsational effects in the atmosphere. We derive a value of 11.9 $\pm$ 0.3 mas at a position angle 136°. An earlier LO measurement in 1976 by Ridgway et al. (1977) gave a value of 15.45 $\pm$ 0.33 mas. Their position angle of 60° is close to that of Richichi et al. (2003). It may be noted from Table 3 that all three LO measurements are nearly at the same phase. The difference between them is only the position angle of the measurement. Our PA of 136° is separated by 60°–75° from PA of the other two measurements. The LBI measurements of Mennesson et al. (2002), Berger et al. (2001) and van Belle et al. (1996) also show a similar dispersion in angular diameter though the PA is not quoted (Table 3). Though these observations were carried out at different epochs, they are nearly at the same photometric phase of U Ori, near its maximum (Fig. 4). We note that there are no high angular resolution observations of U Ori near its minimum phase. Possible explanations for the dispersion in the IR angular diameter measurements could be variation in apparent diameter with position angle, wavelength-dependent size variation (bandwidth effects) and time-dependent variation due to stellar pulsation. Out of these possibilities the two well-determined LO angular diameters at the same wavelength on the same day rule out phase effects and bring out the asymmetric spatial structure in the source.

Based on our observations and other available data on U Ori we have developed a schematic picture of U Ori shown in Fig. 5. The position angles of occultation observations are marked as also the direction of OH maser elongation (NE–SW) and the maximum polarization position angle (Dyck & Sandford 1971).

The picture that emerges is that the IR continuum diameter of U Ori shows large excursion in several measurements much beyond the expected variation with photometric phase. It is possible that that earlier two LOs (Richichi & Ridgway) had shown a bigger value of angular diameter because of these occultation directions were along the asymmetry direction (roughly near the PA of $\sim 70°$) of the source as depicted in the schematic diagram of Fig. 5. The equatorial density enhancement has been reported approximately along this position angle in radio observations of OH maser. Further the maximum of intrinsic polarization has also been also been observed nearby (Dyck & Sandford 1971). It is therefore deduced the source has a asymmetric structure with an ellipsoidal elongation at PA $\sim 70°$. If we consider earlier larger estimation was due to occultation scan along the semi-major axis and lesser value due to scan along the semi-minor axis then the ratio of semi-minor to semi-major axis would be 0.77. The OH maser angular extension also showed such ratio (Chapman et al. 1991) though it is more extended. That the of asymmetric components in the stellar brightness distribution could lead to systematic differences in angular diameter estimations, has been commented upon by Tuthill, Haniff & Baldwin (1995) while studying diameter variation of O Ceti.

Another possibility is that the moderate and even weak magnetic field forms cool spots on surface of U Ori like in AGB stars (Soker 1998). The cool spots facilitate the formation of dust closer to the stellar surface. Such spots can be as big as ≈20–30 per cent of the total surface area found in cool red giants (Neff, O'Neal & Saar 1995; Young et al. 2000). Further star-spots tend to occur near the photospheric equator. The presence of such large spots in the direction of occultation can affect angular diameter measurements. In LO large spots can cause fringe distortions. However distortions of the LO profile are not been noticed in our data. It appears less likely that the dispersion in angular diameter measurements of U Ori is due to starspots.

5 CONCLUSION

From our LO observations we derive a source brightness profile of U Ori which is markedly more asymmetric than the earlier reports. We attribute the asymmetry and dispersion in angular diameter measurements to an extension or asymmetry of the Mira atmosphere approximately in the direction NE–SW at position angle of 50°–70°. The reason for this spatial asymmetry could be pulsational mass loss in a preferred direction.

ACKNOWLEDGMENTS

We are grateful to Dr Sam Ragland for the MIA program. This research has made use of the AFOEV and SIMBAD data bases, operated at CDS, Strasbourg, France. This work was supported by Department of Space, Govt. of India.

REFERENCES

Bains I., Cohen R. J., Louridas A., Richards A. M. S., Rosa-Gonzalez D., Yates J. A., 2003, MNRAS, 342, 8
Berger J. P. et al., 2001, A&A, 376, L31
Bessell M. S., Scholz M., Wood P. R., 1996, A&A, 307, 481
Bowers P. F., Johnson K. J., 1994, ApJS, 92, 189
Chandrasekhar T., 1999, Bull. Astr. Soc. India, 27, 43
Chandrasekhar T., Mondal S., 2001, MNRAS, 322, 356
Chapman J. M., Cohen R. J., 1985, MNRAS, 212, 375
Chapman J. M., Cohen R. J., Saikia D. J., 1991, MNRAS, 249, 227
Coyne G. V., Magalhaes A. M., 1977, AJ, 82, 908
Danchi W. C., Bester M., Degiacomi C. G., Greenhill L. J., Townes C. H., 1994, AJ, 107, 1469
Dyck H. M., Sandford M. T., 1971, AJ, 76, 43
Haniff C. A., Ghez A. M., Gorham P. W., Kulkarni S. R., Matthews K., Neugebauer G., 1992, AJ, 103, 1662
Haniff C. A., Scholz M., Tuthill P. G., 1995, MNRAS, 276, 640
Hofmann K.-H., Balega H., Scholz M., Weigelt G., 2000, A&A, 353, 1016
Karovska M., Hack W., Raymond J., Guinan E., 1997, ApJ, 482, L175
Keenan P. C., McNeil R. C., 1989, ApJS, 71, 245
McLean I. S., 1979, MNRAS, 186, 21
Mennesson B. et al., 2002, ApJ, 579, 446
Mondal S., Chandrasekhar T., 2002, MNRAS, 334, 143
Mondal S., Chandrasekhar T., Kikani P. K., 2002, Bull. Astr. Soc. India, 30, 811
Nather R. E., McCants M. M., 1970, AJ, 75, 963
Neckel T., Klare G., 1980, A&AS, 42, 251
Neff J. E., O'Neal D., Saar S. H., 1995, ApJ, 452, 879
Pataki L., Kolena J., 1974, BAAS, 6, 340
Reid M. J., Moran J. M., Leach R. W., Ball J. A., Johnston K. J., Spencer J. H., Swenson G. W., 1979, ApJ, 227, L89
Richichi A., 1989, A&A, 226, 366
Richichi A., Calamai G., 2003, A&A, 399, 275
Richichi A., Chandrasekhar T., Lisi F., Howell R. R., Meyer C., Rabbia Y., Ragland S., Ashok N. M., 1995, A&A, 301, 439
Richichi A., Fabbroni L., Ragland S., Schloz M., 1999, A&A, 344, 511
Ridgway S. T., Wells D. C., Joyce R. R., 1977, AJ, 82, 414
Soker N., 1998, MNRAS, 299, 1242
Tuthill P. G., Haniff C. A., Baldwin J. E., 1995, MNRAS, 277, 1541
Tuthill P. G., Haniff C. A., Baldwin J. E., 1999, MNRAS, 306, 353
Thompson R. R., Creech-Eakman M. J., Akeson R. L., 2002a, ApJ, 570, 37
Thompson R. R., Creech-Eakman M. J., van Belle G. T., 2002b, ApJ, 577, 447
van Belle G. T., Dyck H. M., Benson J. A., Lacasse M. G., 1996, AJ, 112, 2147
van Belle G. T., Thompson R. R., Creech-Eakman M. J., 2002, AJ, 124, 1706
Wyatt S. P., Cahn J. H., 1983, ApJ, 275, 225
Young J. S. et al., 2000, MNRAS, 315, 635

This paper has been typeset from a TEX/LATEX file prepared by the author.