Bull. Astr. Soc. India (2005) **33**, 97–102

Evidence of asymmetry in Mira variable U Ori

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Abstract. Near simultaneous, two high angular resolution observations by lunar occultation technique at the same wavelength (2.2 μm) but at different position angles (PA) result in two unique Uniform Disk (UD) angular diameters of Mira variable U Ori. UD angular diameter obtained from observations at Mt. Abu observatory is 11.9±0.3 milliarcsecond (mas) at PA 136^o while from observations at TIRGO observatory UD value obtained is 15.14±0.05 mas at PA 75^o. The source brightness profile derived from a model independent analysis shows an asymmetric spatial structure in both cases. Asymmetric structure of the source at higher spatial scale was also reported by several authors from OH and H_2O maser distribution at radio wavelengths; the source is more extended at PA of 30 - 60^o. Furthermore, moderate level maximum optical intrinsic polarization of $\sim$ 1-2% at PA $\approx 20^o$ - 40^o is also detected. All the evidences bring out the spatial asymmetry in U Ori.

Keywords : Lunar occultation, Mira variables, U Ori, Asymmetry

1. Introduction

Mira stars are in the last stage (asymptotic giant branch phase) of stellar evolution before becoming planetary nebulae. Mira stars are generally surrounded by a circumstellar dust shell because of stellar wind driven heavy mass-loss rate ($\sim 10^{-6}$ $M_\odot$ yr^{-1}).

The transition from spherical symmetric asymptotic giant branch (AGB) winds to non-spherical planetary nebulae (PNe) represents one of the most intriguing questions of stellar astrophysics. The natural question that arises is when and how the stellar wind breaks its spherical symmetry. Further many proto-planetary nebulae (PPne) show distinct large scale asymmetries (IRC+10216: Weigelt et al., 2002; Chandrasekhar and

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Mondal 2001). Their progenitor, late stages of the AGB stars, are conspicuous for breaking the sphericity of their winds. Evidence of asymmetry has become more conclusive for few AGB objects from high spatial resolution observations in recent years (Balick and Frank 2002).

Asymmetric spatial structures in Mira variables have been noted earlier and studied by high angular resolution techniques. Ground based direct imaging by aperture masking method showed asymmetric structures in the atmosphere of O Cet (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 PA 105 -158^o from the elliptical disk model. Hubble Space Telescope (HST) imaging using Faint Object Camera (FOC) in the UV and optical wavelengths, Karovska et al.,(1997) had first directly imaged Mira A and Mira B, and detected also the more significant asymmetry in Mira A atmosphere. These authors suggested that the asymmetry could be an indication of non-radial pulsation in the Mira A atmosphere or interaction with the white dwarf (Mira B) companion. 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 6m Special Astrophysical Observatory telescope (Hofmann et al., 2000). Using Palomar Testbed Interferometer (PTI), Thompson et al., (2002) found asymmetry in R Tri in the K-band visibility measurements over the different position angles. These departures from the spherical symmetric structures could be due to stellar rotation, non-radial pulsation, due to hot spots produced by large scale convection processes in outer layers of the atmosphere or binarity. However, the pinpointing origin of such asymmetries is still in the veil of mystery because of limited observational samples.

U Ori is a Galactic oxygen-rich Mira variable with pulsation period 371 days and spectral type ranges from M6-M9.5 IIIe. The visual amplitude of U Ori in it's variability cycle is 6.5 mag. The distance to the source is 306$\pm$61 pc, estimated from period-luminosity relation for galactic Mira variables of Whitelock and Feast (2000). The reported linear radius of U Ori is 370$\pm$96 R$_\odot$ (van Belle et al., 1996). Using the bolometric flux and distance, the luminosity was calculated to be $\sim$7000 L$_\odot$ (Mondal and Chandrasekhar, 2004)

In this proceedings paper we have reported the angular diameter and brightness distribution of U Ori using lunar occultation technique at K-band (2.2 μm) from 1.2m telescope at Mt. Abu observatory. Our results are compared with observations available in the literature that brings out the asymmetry nature of the source. This work is a part of my Ph.D. thesis and has been published (Mondal 2004; Mondal and Chandrasekhar 2004).

2. Observations and analysis

The lunar occultation observations of U Ori were carried out at the 1.2m Gurushikhar Infrared Telescope (GIRT) (Latitude: 24^o 39$'$ 8.8$''$ N, Longitude: 72^o 46$'$ 47.47$''$ E and

Altitude: 1680m) on 13 March 2000 under clear sky conditions. The visual phase of U Ori on 13 March 2000 was 0.28. The event was a disappearance and was recorded in the K-band using a IR high speed photometer. Details of the instrument can be found elsewhere (Mondal, Chandrasekhar and Kikani 2002a). The sampling time was 2 milliseconds. A good occultation trace was recorded which is shown in Fig.1.

The model fitting of the lunar occultation light curve is based on the standard non-linear least- square (NLS) method first introduced by Nather and McCants (1970). A uniformly illuminated disk (UD model) is usually assumed. Details of the procedure are discussed elsewhere (Chandrasekhar and Mondal 2001). In case UD model fits are not satisfactory a Model Independent Approach (MIA) can be considered if the SNR of the light curve is good. Such MIA, first introduced by Richichi (1989), have been applied earlier by us to resolve disk structure of IRC+10216 and WR104 (Chandrasekhar and Mondal 2001; Mondal and Chandrasekhar 2002b).

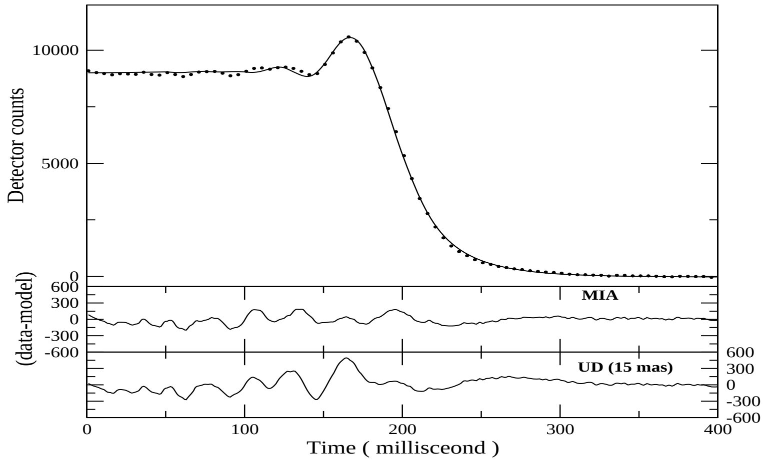

Figure 1. The MIA model fit (solid line) to the observed data-points (*filled circles*) of lunar occultation light curve of U Ori in the K-band. The residual (data - model) of the fits are shown in expanded form at the bottom panels for MIA and UD for a fixed angular size of 15 mas.

3. Result and discussion

We have first carried out the NLS analysis on the observed light curve of U Ori. 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 and 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.1 we show the best-fit to the data by MIA analysis. For comparison the residual of a fit

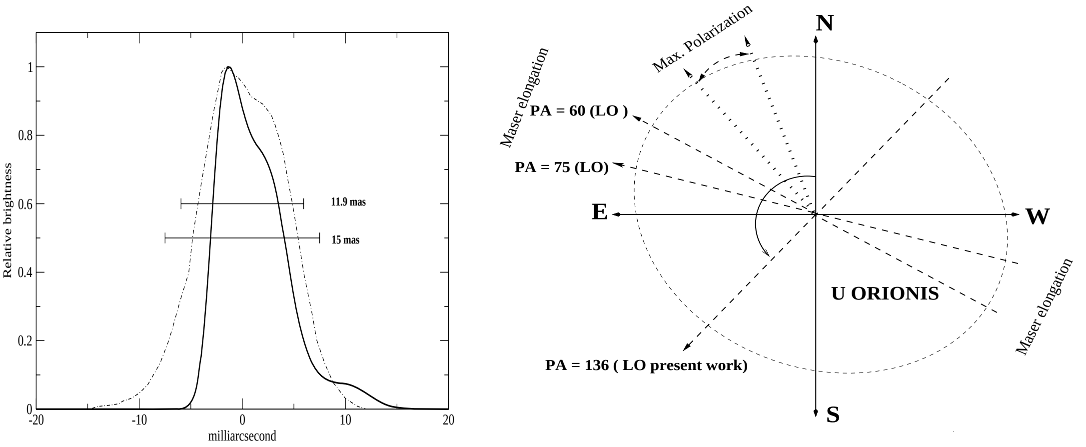

Figure 2. In the **left** figure, the brightness profile of U Ori derived from lunar occultation light curve is shown and compared to that of Richichi et al., (2003) (*dot-dashed line*). The two horizontal lines indicate equivalent UD diameter of 11.9 mas (this work) and 15 mas. In the **right** figure, schematic diagram of asymmetric size of U Ori is shown and several corollary evidences are depicted. The position angle (PA) of all lunar occultations on U Ori are shown by dashed lines. The direction of OH maser elongation (Chapman et al., 1991) is depicted. Regions of observed PA of maximum intrinsic polarization (Dyck et al. 1971; Coyne at al. 1977) are also marked.

to the data by a fixed UD source of 15 mas, close to the value reported by Richichi and Calamai (2003) is also shown. It can be clearly seen that our data fits to a much smaller source size.

Fig.2 (left) shows our brightness profile derived from MIA analysis. The UD values of 11.9 mas 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 et al., (2003).

Previous angular diameters observed by lunar occultation (LO) and long baseline interferometric (LBI) observations of U Ori is listed in Table 1. The value we determined is significantly (27%) smaller than other two UD sizes by LO (Richichi and Calmai 2003; Ridgway et al., 1979) and by LBI (K' size of Mennession et al., 2002) but consistent with LBI sizes (van Belle et al., 1996; Berger et al., 2001). The observations of Richichi and Calmai (2003) differ only the PA while band-pass and phase are same. Perrin et al., (2004) has determined so far smaller stellar size of U Ori in several narrow bands falling in the region of continuum and molecular absorption bands (2.03 (H_2O), 2.15 (cont.), 2.22 (cont.) and 2.39 (CO + H_2O) μm) inside broad K-band and it was only possible through the interferometric visibility modeling considering thin H_2O shell within few stellar radii. This is a subject of investigation about molecular contamination effects (act

Table 1. Infrared Angular diameter measurements of U Ori.

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 ±0.30	Present work
13 Mar 2000	LO	0.28	75	2.20/0.40	15.14±0.05	Richichi et al.,(2003)
15 Jan 1976	LO	0.36	60	2.07/0.03	15.45±0.33	Ridgway et al.,(1977)
08 Oct 1995	LBI	0.97	-	2.20/0.40	11.08±0.57	van Belle et al.,(1996)
26 Nov 2000	LBI	0.04	-	1.60/0.34	11.00±0.50	Berger et al.,(2001)
16 Oct 2000	LBI	0.88	-	2.16/0.32	15.59±0.06	Mennesson et al.,(2002)
	LBI	0.88	-	3.80/0.70	25.66±0.69	Mennesson et al.(2002)
Oct 2000	LBI	0.83	-	2.22/0.10	10.60	Perrin et al., (2004)
Nov 2000	LBI	0.91	-	2.22/0.10	9.66±0.12	Perrin et al., (2004)

[a] PA is defined as the angle of the event measured from North through East.

as a pseudo-continuum in the upper layers) on the observed UD sizes in the near-infrared band-passes (Ohnaka 2004; Weiner 2004). L′ measurement in Table 1 is a good example of such effects and the larger UD value of Ridgway et al., (1979) may be affected by the combined effects of spatial asymmetry and molecular contaminations.

Based on our observations and other available data on U Ori we have developed a schematic picture of U Ori shown in Fig.2 (right). The maser shell shows asymmetric geometry and clumpy distribution (Chapman, Cohen and 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 by east-west, measured by these authors. Recently Bains et al., (2003), from their subarcsec imaging of U Ori in the H_2O maser line , report an elongation in the direction northeast-southwest at PA of 30^o while Bower and Johnson (1994) found similar elongation at PA $\sim 60^o$.

There is also an evidence of moderate level maximum intrinsic polarization of $\sim$ 1-2% in V and B bands respectively at PA $\approx 20^o$ - 40^o (Dyck and Sandford 1971; Coyne and Magalhaes 1977). The significance of detailed polarimetry studies in continuum and atomic/molecular line bands of Mira variables lies in its ability to probe gross departure from spherical symmetry which allows a net polarization to appear in the integrated starlight (Boyle et al. 1986). For example, VY CMa (M5 Ib) is an irregular variable which shows high polarization (10 -15 %) in optical bands at position angle between 150^o - 180^o. Recent Keck high angular resolution images in the IR bands revealed the asymmetric structures of the source at position angle $\sim 170^o$ (Monnier et al., 1999). However it has been noted that the PA of maximum polarization angle shows variation over phase in case of long period variables (Dyck et al., 1971) and the PA of maximum polarization cannot be used indiscriminately as the direction of asymmetry.

4. Conclusion

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), time dependent variation due to geometric pulsation. Out of these possibilities the two well determined lunar occultation angular diameters at the same wavelength on the same day rule out phase and bandwidth effect and strongly favour the asymmetric spatial structure in the source.

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