HIGH ANGULAR RESOLUTION OBSERVATIONS OF MIRA

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Abstract

The results of high angular resolution observations of Mira, the prototype star of the class of Mira-type variables, are reviewed, including the detection of substantial asymmetries in its atmosphere. Because of these asymmetries and the effect of the extended atmosphere, it is difficult to determine a photospheric diameter, a crucial parameter for establishing the effective temperature scale and the mode of pulsation. This parameter could be derived using accurate measurements of the diameter and the brightness distribution across the stellar disk as a function of wavelength and pulsation phase, in conjunction with detailed model atmosphere calculations.

1. Introduction

o [omicron] Ceti (Mira) is the prototype of highly variable giant stars on the asymptotic branch of the H-R diagram—the Mira-type variables. This star is a pulsating, cool giant (M2-M7 III), with a diameter of several hundred solar radii and a mass comparable to that of our Sun. It is a primary component of a binary system with a compact companion—possibly a white dwarf (VZ Ceti)—which is accreting mass from Mira's wind. Mira is presently rapidly losing large quantities of its mass, about $5 \times 10^{-7} M_{\odot}$/year, as it heads toward its final state as a planetary nebula or a white dwarf.

At this late stage of its evolutionary path, Mira's tenuous atmosphere extends to several hundred solar radii, and its structure and composition are strongly affected by the propagation of shock waves created as a result of the pulsation process. Because of the effects of the extended atmosphere, it is difficult to determine its diameter, a crucial parameter for establishing the effective temperature scale and the mode of pulsation.

A precisely measured photospheric angular diameter combined with the distance to Mira (e.g., as estimated by Hipparcos) could in principle allow determining the mode of pulsation for Mira variables (Ostlie and Cox 1986). Once the pulsation mode is determined, it should be possible to better define the evolutionary place of Mira variables and their relation to other types of long period variables. Presently, it is still debated whether the pulsation mode is a fundamental or a first overtone (see L. A. Willson's article in this volume).

Accurate determination of Mira's angular diameter and energy distribution is also crucial for establishing its effective temperature scale. The effective temperature can be determined from the relation

$$T_{eff} = 2341 (F_{bol})^{1/4} / \phi^{1/2}, \quad (1)$$

where F_{bol} is in units of 10^{-8} ergs $cm^{-2} s^{-1}$ and ϕ is the true angular diameter in milli-arcseconds (Ridgway and Joyce 1980).

In recent years it has become clear that detailed modeling of Mira's atmospheric structure is necessary for an accurate determination of the photospheric diameter. Key input parameters that must be measured with high accuracy include diameters in selected spectral regions and the brightness distribution across the stellar disk as a function of wavelength and pulsation phase.

2. High angular resolution observations

Some of the earliest diameter measurements of Mira were obtained in the optical wavelengths by Antoine Labeyrie and his group using the speckle interferometric technique and assuming a uniform brightness distribution on the stellar disk (Labeyrie *et al.* 1977). Since then, a plethora of multiwavelength measurements of the size of Mira have been obtained at wavelengths ranging from UV to radio spectral domain, using single and multiple aperture interferometric techniques, and recently, direct imaging using the Hubble Space Telescope (HST).

Angular diameters measured in the optical show a strong wavelength dependence (Labeyrie *et al.* 1977; Bonneau *et al.* 1982; Karovska *et al.* 1989). Measurements obtained in different spectral regions using occultation and speckle interferometry techniques often differ by factors of 2–3. Larger diameters are measured in the absorption minima of the strong TiO molecular bands than in the continuum. The original Labeyrie *et al.* 1977 paper already demonstrated that there is a significant variation in the diameter measurements obtained within the same pulsation phase using filters centered in different spectral regions. The difference was clearly detected using filters with FWHM of 200Å bandpass. This difference increased when filters with narrower bandpasses were used, as shown in Table 1 (from Labeyrie *et al.* 1977).

More recent diameter measurements obtained by interferometric techniques use models ranging from uniform disk and gaussian distribution to brightness distributions calculated from various model atmospheres, in order to estimate the effects of brightness nonuniformity (e.g., Tuthill *et al.* 1994a; van Belle *et al.* 1996).

These models often produce a very simplified and usually incomplete description of the physical characteristics of the extended atmosphere because they do not simultaneously incorporate crucial elements such as pulsation, opacities, dust, and so forth. In addition, these models assume that the atmosphere is spherically symmetric.

Table 1. Diameter measurements of Mira at three different epochs (from Labyerie *et al.* 1977).

Star	*Date (UT)*	*Phase*	$\lambda/\Delta\lambda$ (Å)	θ_{UD} *(arcsec)*
Mira	1972.479	0.09	4500 /200	0.070 ± 0.010
			5150 /200	0.057 ± 0.005
			7500 /200	0.051 ± 0.005
			10400 /200	0.05
	1972.742	0.38	6700 /200	0.062 ± 0.005
			7000 /200	0.058 ± 0.005
			7500 /200	0.055 ± 0.005
	1977.025	0.11	6080 /80	0.071 ± 0.015
			6200 /80	0.103 ± 0.020
			6470 /30	0.072 ± 0.014
			6720 /175	0.075 ± 0.015
			6960 /80	0.031 ± 0.006
			7120 /80	0.061 ± 0.007
			7400 /50	0.034 ± 0.007

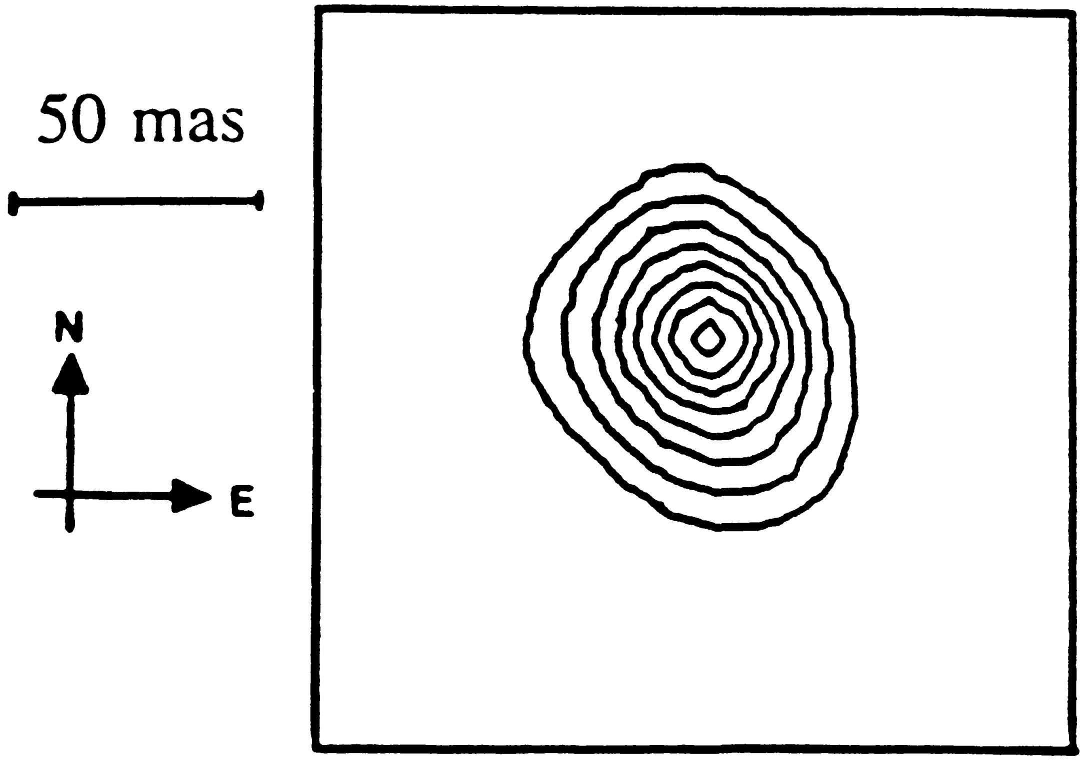

Figure 1. Image of o Ceti showing an asymmetry in the extended atmosphere from the observations carried out in 1988 November at 533nm using the CTIO 4-meter telescope. The image was deconvolved using the Knox-Thompson deconvolution algorithm and a reference unresolved star as a Point Spread Function (see Karovska *et al.* 1991).

However, currently there is substantial evidence that Miras are not symmetric and future models should not ignore this fact.

The asymmetry in the extended atmosphere was first discovered in the prototype of the class, Mira (Karovska *et al.* 1991), Figure 1. The strength of the elongation in Mira's images is strongly dependent on the spectral region in which the observation was made. It appears to be especially prominent when the images are recorded using filters located in the strong TiO absorption bands. Observations of Mira's asymmetry have now been made at several epochs and they show substantial changes in its morphology and characteristics as a function of time (Karovska *et al.* 1991; Haniff *et al.* 1992; Wilson *et al.* 1992; Tuthill *et al.* 1994b).

Recently, we obtained the first HST images of Mira in ultraviolet (UV) and optical. These high angular resolution observations detected elongation in the stellar image similar to that seen in the ground-based observations, Figure 2 (Karovska *et al.* 1997). In addition, the images in the UV show an extension of the star toward the companion, which could be an indication of possible interaction.

Since the discovery of the asymmetries in Mira's atmosphere, interferometric observations of several other Miras, including R Cas (Tuthill *et al.* 1994b), and R Leo and W Hya (Lattanzi *et al.* 1996), show that their extended atmospheres are asymmetric as well.

The causes of these asymmetries are still unknown. The asymmetries could be due to unresolved bright spots on the surface of the star or in the extended atmosphere.

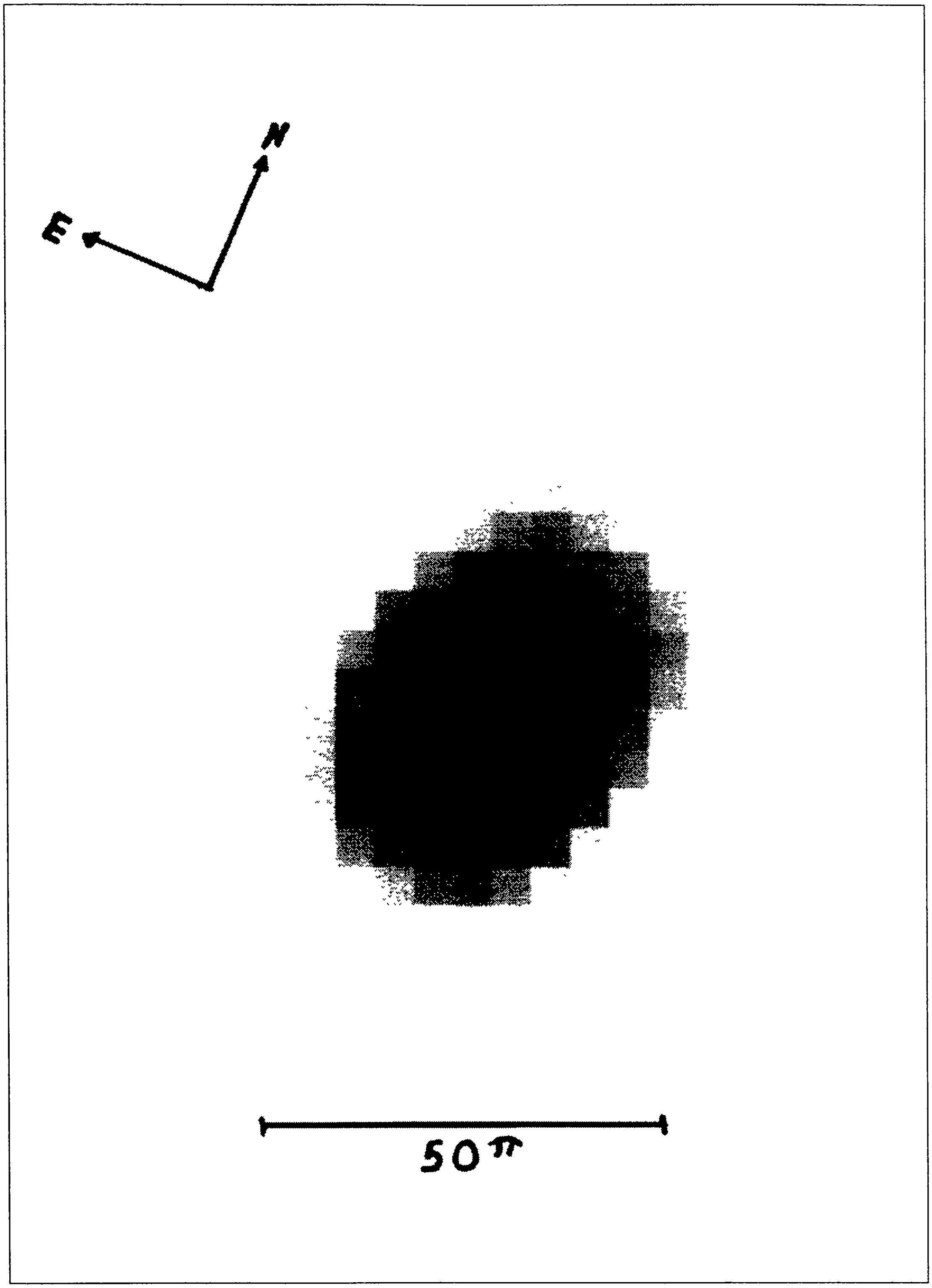

Figure 2. HST image of Mira obtained with the FOC instrument using a 501 nm filter centered in one of the strong TiO absorption bands from the observations carried out in 1995 December. The image showing the asymmetry in Mira's atmosphere was deconvolved using the Richardson-Lucy deconvolution algorithm and the unresolved companion VZ Ceti as a Point Spread Function (see Karovska *et al.* 1997).

They could also be related to the pulsation process: plausible mechanisms include instabilities in the pulsating atmospheres and non-radial pulsation.

3. Conclusion

The "true" photospheric diameter of Mira and of Mira-type variables in general is difficult to measure due to the extended atmosphere. A better understanding of the detailed structure of the atmosphere is required. It is imperative to understand the physics of Miras' atmospheres and to develop realistic models incorporating asymmetries, proper abundance information, and physical processes such as propagation of shock waves and dust formation.

These models should predict the brightness distribution in selected spectral regions important for atmospheric structure diagnostics, such as different TiO bands and selected regions within a given TiO absorption band, the continuum (UV, optical, and especially in the near-IR), and emission lines carrying shock signatures. Observations of high angular resolution of several Miras should be carried out in these spectral regions using adequately chosen filters, and the results of the observations should be used as feedback for models to further improve their prediction accuracy.

Before such models become available, I strongly suggest that observers systematically quote measurements obtained using a uniform brightness distribution assumption, in addition to the results obtained using whichever simplified model they have chosen to use to estimate the "real size" of the star. These uniform brightness estimates can later be corrected using appropriate model atmosphere predictions, and will provide a baseline for monitoring temporal changes in Miras' atmospheres.

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