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SPECKLE OBSERVATIONS OF MIRA'S COMPANION

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ABSTRACT

We present the first speckle interferometric observations of Mira's hot companion. The companion accretes mass from Mira's wind and provides an excellent opportunity for studying the accretion processes in detached binaries. The separation between the components of the system is crucial for accurate determination of the accretion rate onto the companion. Speckle measurements of the separation made at three epochs since 1983 with much higher precision than previous visual observations show that the companion's distance from Mira is substantially larger than expected.

Subject headings: binaries: visual — stars: individual (*o* Ceti) — techniques: interferometric

1. INTRODUCTION

o Ceti (Mira), the prototype for Mira-type variables—cool stars on the asymptotic giant branch—is one of the few stars in its class known to have a close companion. The companion was discovered by Joy (1926) in 1923 during spectroscopic observations at Mira's light minimum. Joy's spectra showed the presence of a hot continuum, wide H I Balmer lines, and unusual P Cygni profiles in addition to Mira's characteristic spectrum. Mira contributes very little flux in the UV so the spectrum of the companion may be observed at UV wavelengths using the *IUE* satellite. *IUE* spectra show a hot continuum and numerous emission lines (including Mg II, C IV, He II, Lyα) that have been attributed to an accretion disk around a hot star (Deutsch 1958; Reimers & Cassatella 1985). The nature of the star accreting mass from Mira's stellar wind has not been yet determined; it could be a white dwarf (Warner 1972; Reimers & Cassatella 1985) or a main-sequence star (Jura & Helfand 1984).

Soon after Joy's discovery, Aitken visually resolved the companion at a distance of 0″.91 from Mira (Aitken 1923). Since 1923, a number of observers have made measurements of the position angle and separation of the binary components. Due to the large changes in Mira's brightness (m_v = 3–10 mag) over a period of 332 days, observations of the companion were possible only near Mira's light curve minima, when the magnitude difference between the components is small (1–2 mag). Even then the observations are difficult, and errors in the visual measurements are substantial due to the closeness of the pair and the faintness of the companion. The companion itself varies between 10th and 12th mag (Joy 1954).

Mira's companion presents a unique opportunity for studying the accretion processes from the red giant's stellar wind in detached systems, because it is nearby (77 pc, Jenkins 1952), bright, accessible at many wavelengths, and most importantly, it can be spatially resolved from Mira. Speckle interferometry provides a unique resource for observing Mira and its companion during most of Mira's light cycle, and allows measurement of the companion's position angle and separation with much higher precision than has been previously achieved. In this paper we report the first observations of Mira's companion using the PAPA detector (Papaliolios, Nisenson, & Ebstein 1985) and speckle interferometry techniques (Nisenson 1988). The results of these observations are that the real separation of Mira from its companion is at least twice as great as the currently adopted distance, which have important implications on the calculations of the accretion rate from Mira's wind onto Mira's companion.

2. OBSERVATIONS

Observations of Mira were carried out at several epochs from 1983 to 1991 at different phases of Mira's pulsation cycle. Our primary goal was to measure the diameter of Mira in various spectral regions and to obtain high angular resolution (diffraction-limited) images of its extended atmosphere. As a result of these observations, we discovered substantial asymmetries in the Mira's atmosphere (Karovska et al. 1991) and made precise multiwavelength diameter measurements (Karovska 1990). The companion was detected in the observations taken when Mira was not near the maximum brightness, so the magnitude difference between Mira and its companion was not greater than 5 mag. The observations were carried out using the Steward Observatory 2.25 m telescope in 1983 November, the Kitt Peak 4 m telescope in 1986 December, and the Las Campanas 2.5 m telescope in 1990 June, using the CfA PAPA detector, a two-dimensional photon counting camera (Papaliolios et al. 1985) and a set of narrow-band interference filters. A summary of the observations is presented in Table 1.

After correcting the effects of the atmospheric dispersion with a pair of rotating Risley prisms, the digital *x* and *y* photon positions were recorded as a continuous data stream with a specially adapted VCR (Ebstein 1983). The photons were subsequently binned in frames (each 256 × 256 pixels), choosing the frame time which yielded the best signal-to-noise ratio in the high frequencies of the power spectra. Typical frame times ranged from 5 to 10 ms. Each frame was corrected for the camera sensitivity (flat-fielding) and its Fourier transform was calculated. Fourier transforms of as many as 50,000 frames were accumulated into the power spectra and the complex correlation arrays which are required for speckle image reconstruction. Our image reconstruction algorithms, based on the

TABLE 1

SUMMARY OF SPECKLE OBSERVATIONS

Date	Central wavelength (nm)	Bandpass (FWHM) (nm)
1983 Nov 16	600.6	21.7
	620.9	10.4
1986 Dec 9	620.9	10.4
1990 Jul 5	453.5	41.2
	552.3	39.4
	656.3	11.6
	672.3	12.2

Knox-Thompson (K-T) algorithm (Knox 1976), preserve the phase in the object Fourier transform, allowing true image reconstruction as an output of the process. Images are important for studying features on Mira (and its circumstellar environment), but only more conventional speckle interferometry (power spectra and autocorrelations) is needed for measuring the separation, position angle, and magnitude difference of this binary. Observations of various objects have showed that speckle observations carried out with the PAPA detector allow extremely accurate corrections for photon noise biases (Nisenson and Papaliolios 1983) and provide the linearity and dynamic range needed for accurate measurements of source characteristics, in particular the magnitude differences. Details of the observational techniques and the image-reconstruction algorithms are described by Nisenson (1988).

The spatial scale of our images was calibrated in a two-step process. The camera magnification was measured from a reticle placed in the telescope focal plane. This was combined with the known telescope plate scale to give an overall scale calibration. Observations of binaries with known orbit were than used to check the scale. The list of calibration binaries include α Aur, α Psc, ζ Cnc, ε UMa, 4 Aqr, and other binaries with known orbit.

3. RESULTS

Speckle autocorrelations and images yielded measurements of the position angle, separation, and magnitude difference between the components at several wavelengths. We carried out the observations in 1983 November using filters centered at 601 nm and 621 nm. Figure 1 (Plate 1) shows as an example the autocorrelation obtained from the observation at 601 nm and the reconstructed image at 621 nm. The reconstructed images show a source located at 0\".67 ± 0\".03 from Mira at a P.A. 113° ± 1°. The magnitude differences between Mira and its companion are 3.1 ± 0.2 and 2.7 ± 0.2 mag at 601 nm and 621 nm, respectively. At this epoch Mira was at phase 0.4 with $m_v \approx 8$ (AAVSO observations).

The position of the companion did not change significantly in the 1986 December observations, as measured from the autocorrelation and the reconstructed image at 621 nm. The companion's separation in this observation is 0\".63 ± 0\".02, and the position angle 112° ± 1°. The visual magnitude difference between Mira and the companion is 3.5 ± 0.2. This magnitude difference is larger than in 1983 due to the fact that Mira was brighter; Mira's light curve phase was at 0.8 and the visual magnitude was $m_v \approx 7$.

The observations carried out 4.5 yr later (1990 July) at four wavelengths showed the companion at a distance of 0\".61 ± 0\".03 and a position angle of 111° ± 1°. The magnitude differences measured at 450 nm, 535 nm, 656 nm, 670 nm are, respectively, 2.3 ± 0.3, 2.9 ± 0.2, 3.7 ± 0.2, and 3.5 ± 0.2 mag. Mira was close to the minimum at this epoch (phase 0.7) with visual magnitude $m_v \approx 9$.

Our observations provide precise measurements of the magnitude difference between the components. The precision in these measurements was supported by the measurements of the magnitude differences between the components of several standard binaries. Due to the large amplitude variability of Mira, an accurate measure of the brightness of each component cannot be made without contemporaneous precision photometry measurements. Since the primary purpose of our observations was to study details of Mira's atmosphere, accurate photometry was not required. In addition, the precision of the position angle measurements can be substantially improved in the future by better calibration of the north–south direction and by obtaining a larger number of observations of Mira's systems and of binaries with known orbits. McAlister et al. (1989) use an aperture mask to precisely calibrate the north–south direction and the plate scale for speckle binary orbit measurements. We plan to adopt a similar technique for future measurements of the Mira's system.

4. DISCUSSION

Critical observational parameters for determination of the accretion rate onto the companion include true separation from the mass-losing star and the orbital velocity (cf. Livio & Warner 1984). These two parameters can be determined from the orbit. However, the orbit is presently very uncertain. Several orbits with periods ranging from 14 yr (Parenago 1950) to 842 yr (Hopmann 1964) have been calculated using the visual measurements of the position of Mira's companion. The errors in these measurements often exceed several degrees in position angle and more than a tenth of an arcsecond in separation, leading to large uncertainties in orbital parameters. Figure 2 presents the visual measurements of position angle and separation of Mira's companion made between 1923 and 1976. It also contains the three speckle measurements made in 1983, 1986, and 1990. A fit to the visual data (from 1923 to 1970) by Baize (1980) calculates an orbit with a period of 400 yr (the dashed line in Fig. 2). Despite the fact that Baize's orbit (Table 2) is very uncertain, it has been used to calculate the actual physical separation and orbital velocity of the companion for the purpose of calculating the accretion rate onto the companion (Reimers & Cassatella 1985; Livio & Warner 1984). The speckle data give a separation which is at least twice that used for the accretion calculations. This larger separation will result in lowering the estimated accretion rate from Mira

TABLE 2

ORBITAL PARAMETERS FOR MIRA B (BAIZE 1990)

Parameter	Value
P	400 yr
T	2001.5
e	0.66
a	0.85
i	111.3
ω	106.0
Ω	118.5
n	0.9

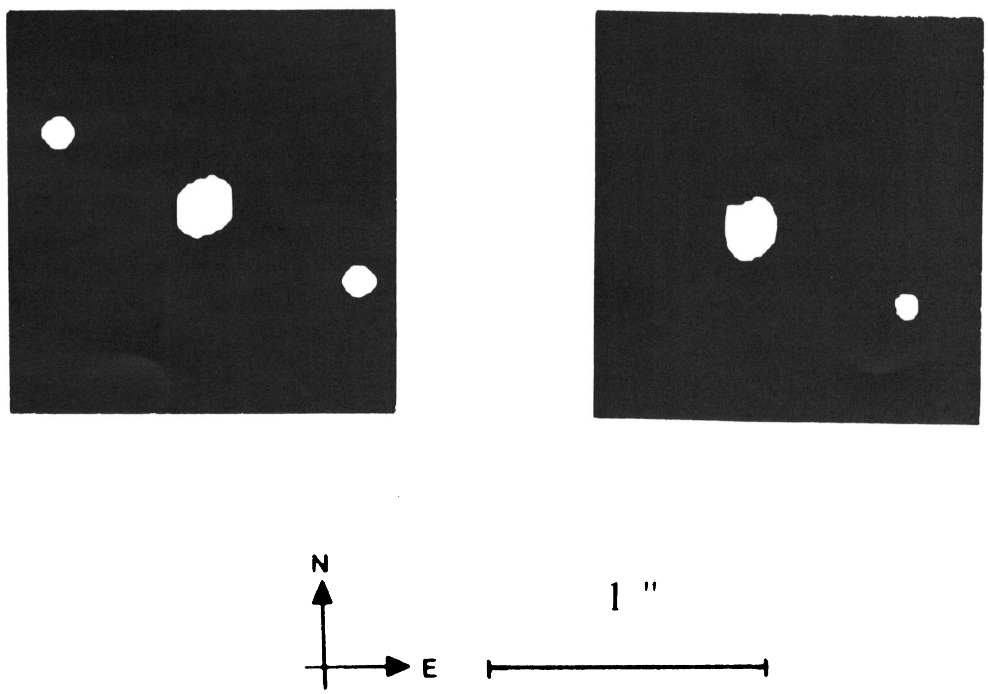

FIG. 1.—Speckle autocorrelation and image of the Mira system obtained in 1983 November using the Steward Observatory 2.2 m telescope. (*a*) The autocorrelation at 601 nm, and (*b*) the reconstructed image at 621 nm.

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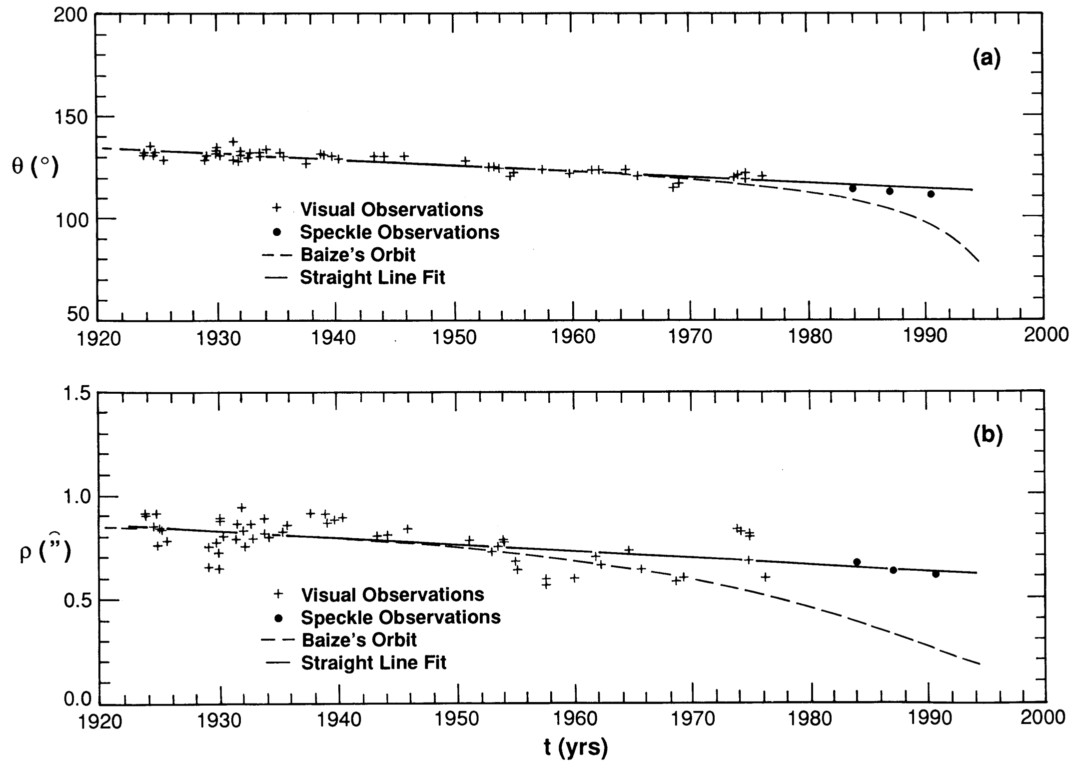

FIG. 2.—Visual and speckle measurements of (*a*) position angle, and (*b*) separation of Mira's companion from 1923 to 1990. The errors in the speckle measurements of the position angle and the separation are, respectively, 1° and 0".02–0".03. The errors of the individual visual observations can be as high as 5° in the position angle measurements, and 0".2 in the separation measurements. Baize's apparent orbit and a straight line least-square fit to the data are also shown.

onto the companion, and it may be too low to account for the observed accretion luminosity (Reimers & Cassatella 1985).

The speckle measurements show slight deviation from a straight line best fit to the whole data set that might indicate orbital motion of the companion. This suggest an orbital period much longer than 400 yr. The deviation from the straight line may be due to a third body in the system as suspected by Baize (1980). In fact, the residuals of the speckle data from the straight line best fit appear to be consistent with the perturbations of the orbit suggested by Baize (detailed analysis will be presented in a separate article).

We expect that high-precision speckle measurements of the position of the companion in the next few years will show either sufficient deviation from a straight line to allow fitting of an orbit or will at least set a lower limit on the separation of the components. Future observations will also answer the question of the existence of a third body in the system. In addition, simultaneous multiwavelength speckle interferometry and photometric observations of Mira's system will permit a determination of the spectral distribution of each component at optical wavelengths and allow a better estimate of the accretion luminosity of the companion.

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