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ASYMMETRIES IN THE ATMOSPHERE OF MIRA

M. Karovska, P. Nisenson, and C. Papaliolios
Harvard-Smithsonian Center for Astrophysics, 60 Garden Stree, Cambridge, MA 02138
and
R. P. Boyle
Vatican Observatory, V-00120, Vatican City State

ABSTRACT

A two-dimensional high angular resolution study of *o* Ceti (Mira), carried out at four epochs from 1983 November to 1988 November using speckle interferometry techniques, detected asymmetries in the extended atmosphere of this pulsating star. The reconstructed speckle images show that the strength and the shape of this asymmetry changes as a function of wavelength and time. We determined the position angles of the major axes of the asymmetries at different epochs and measured accurately the axes as a function of wavelength. The origin of the observed asymmetries has not yet been identified. Plausible causes include instabilities in the pulsating atmosphere, nonspherical pulsation, or the interaction with the nearby companion.

Subject headings: interferometry — stars: individual (*o* Ceti)

1. INTRODUCTION

o Ceti, a cool giant on the asymptotic giant branch of the H-R diagram, shows large-amplitude light variations, 3–10 mag in *V*, over a period of about 332 days. *o* Ceti (Mira) is the prototype star for a class of long-period variables with characteristics that are strongly time-dependent; most of the changes in the measured quantities are cyclic with a period equal to that of the light variation. The variability in Mira-type stars is believed to be related to the phenomenon of stellar pulsation. As a result of the stellar pulsation, shock waves form in the vicinity of the photosphere and then propagate outward through the extended atmosphere. During this process, the shock waves lift material to distances of several photospheric radii. Bowen (1988) suggested that the shocks increase the density in the outer cool regions of the extended atmosphere, creating favorable conditions for dust formation and enhanced mass loss. There is substantial observational evidence that the large-amplitude pulsations strongly affect the structure of the extended atmosphere and play a crucial role in the mass-loss process: Mira-type variables lose mass at rates in the range of 10^{-7} to 10^{-6} $M_{\odot}$ yr^{-1} (Morris 1985). The result of this mass loss is the formation of an extended circumstellar shell. Studies of the region from 1 to approximately 5 photospheric radii, using different observational techniques, could provide important insights into the atmospheric structure and processes of mass loss in Mira-type variables.

o Ceti is an ideal object for a detailed study of the structure of the extended atmosphere of the Mira-type variables because it is nearby (84 pc; Celis 1981) and bright, so it is easy to study at many wavelengths. Because of its large angular size, *o* Ceti can be resolved using high–angular resolution interferometric techniques. Pease (1931) first resolved this star using Michelson interferometry and measured a diameter of 47 mas at 575 nm. Speckle interferometric observations carried out at optical wavelengths since 1972 yielded diameters which vary depending on the spectral region and bandpass (Labeyrie et al. 1977; Bonneau et al. 1982; Karovska et al. 1990). Recent 11 μm spatial interferometry observations of *o* Ceti carried out by Bester et al. (1990) resolved a dust shell with an inner radius of 30–35 mas, demonstrating the presence of dust in the upper atmosphere at 1–2 photospheric radii above the photosphere.

Most of the interferometric observations of *o* Ceti obtained to date in optical and infrared wavelengths have been analyzed and interpreted assuming spherical symmetry. The larger angular size of *o* Ceti, however, provides us with a unique opportunity to explore in two dimensions its atmospheric structure and the circumstellar environment. We present in this *Letter* the results of the first two-dimensional study of the extended atmosphere of *o* Ceti, carried out through the high–angular resolution speckle observations at four phases of its pulsation cycle. The principal result of this study is the detection of asymmetries in *o* Ceti's atmosphere.

2. OBSERVATIONS AND DATA PROCESSING

Speckle observations of *o* Ceti were carried out at four epochs between 1983 November and 1988 November. First observations were obtained with the Steward Observatory 2.25 m telescope, and subsequent observations were made with the 4 m telescopes at Kitt Peak and Cerro Tololo. Data were recorded at optical wavelengths with the PAPA two-dimensional photon-counting detector. We used narrow bandpass (10–25 nm) filters centered at several different wavelengths between 530 and 850 nm. The foreoptics package provides magnification of the image so that a telescope diffraction-limited element has greater than 2 pixels sampling. The diffraction limits of the 2.25 and the 4 m telescope are, respectively, 54 and 30 mas at 550 nm. The atmospheric dispersion was compensated using computer-controlled Risley prisms. The output of the PAPA camera (photon addresses) was recorded as a digital data stream. The photon addresses were grouped in 256 × 256 pixel frames by selecting the best correlation time giving the maximum signal-to-noise ratio. Each individual frame was flat-fielded and Fourier-transformed. Integrated frames consisted of power spectra and complex arrays required for the process of image reconstruction with our version of the Knox-Thompson algorithm (Nisenson 1988). The seeing for most of these observations was between 1″ and 2″. Depending on the signal-to-noise ratio in

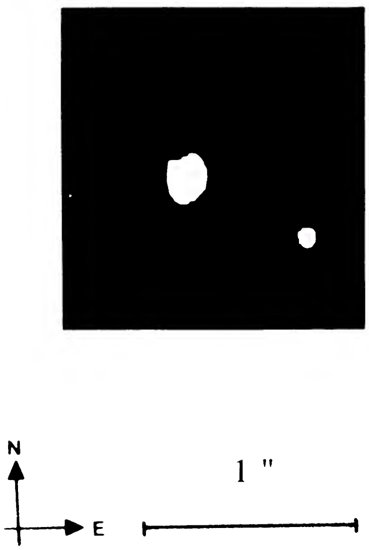

FIG. 1.—Speckle image showing the asymmetry in *o* Ceti and the companion obtained at 620.9 nm using the Steward Observatory 2.25 m telescope in 1983 November.

the data, the number of integrated frames ranged from 20,000 to 100,000 frames. The deconvolution of the object data with the telescope and atmospheric transfer function was performed using the data from an unresolved star, recorded close in time and angular position to the object observations.

The deconvolved integrated power spectra were used to measure the size of *o* Ceti. First, assuming spherical symmetry, the power spectrum of a uniform disk was fitted to the azimuthally averaged observed power spectrum allowing measurement of the diameter of this disk (these results will be presented in a separate article). In order to measure the major and the minor axes of the asymmetry detected in the images of *o* Ceti, we fitted the power spectra brightness ellipses to the observed power spectra. A detailed description of the algorithms and data processing is given in Karovska et al. (1989) and Papaliolios et al. (1989).

3. RESULTS AND ANALYSIS

High–angular resolution speckle observations of *o* Ceti showing strong asymmetry were obtained in several different wavelengths in 1983 November 15–16 (light-curve phase 0.43), 1986 December 9–10 (phase 0.81), 1987 December 30–1988 January 3 (phase 0.97), and 1988 November 28–29 (phase 0.97). The light-curve phases were determined by J. Mattei from the AAVSO observations. Substantial asymmetry was first detected in *o* Ceti's power spectra, autocorrelations and the reconstructed images, obtained from the observations carried out in 1983 at the Steward 2.25 m telescope at 600.6 nm and 620.9 nm. *o* Ceti's hot companion (Joy 1926) with a separation of about 0$''$.6 was also detected in these data. Figure 1 shows the image of *o* Ceti and its companion (about 2.5 mag fainter than *o* Ceti) reconstructed from the data recorded at 620.9 nm. The comparison star (71 Ceti) data, recorded within a few minutes of the observations of *o* Ceti using the same filters, did not show the presence of any asymmetry. We estimate the angular size of the major and the minor axis of the asymmetry at 620.9 nm to be approximately 80 and 60 mas. The degree of asymmetry (the ratio between the axes) appears to be larger at 620.9 nm than at 600.6 nm. The position angle of the major axis of the asymmetry, measured from the power spectra of *o* Ceti, is 30° ± 10°.

Observations obtained at several wavelengths in 1986 December at the 4 m Mayall telescope at Kitt Peak confirm the presence of an asymmetry in *o* Ceti's atmosphere. The major axis of the asymmetry at 620.9 nm appears to be the same as in 1983, and the minor axis somewhat larger ($\approx$65 mas). The position angle of the major axis, measured from these data, is 12° ± 10°. Similar results were obtained a year later using the same telescope. The asymmetry was detected in the data recorded in several spectral regions from 533 to 850 nm. Figures 2*b*, 2c, and 2*d* display the power spectra of *o* Ceti obtained, respectively, at 533, 775, and 850 nm. The power spectrum of the comparison star (82 Ceti) at 533 nm is shown in Figure 2*a*. This power spectrum, as well as the power spectra of the comparison star obtained at other wavelengths, does not show departure from spherical symmetry. *o* Ceti's power spectrum is smaller than the power spectrum of the comparison star, due to the fact that the angular size of *o* Ceti is larger than the diffraction limit of the 4 m telescope, and the drop-off in the higher frequencies is clearly apparent. The position angle of the major axis of the elongation in the power spectra of Mira is 115° ± 10° and does not change substantially as a function of spectral region. The asymmetry is also clearly visible in the reconstructed images of *o* Ceti and is not seen in the images of the comparison star. As an example, Figures 3*a* and 3*b* show the reconstructed images of the comparison star and of *o* Ceti at 775 nm. These observations did not detect the companion

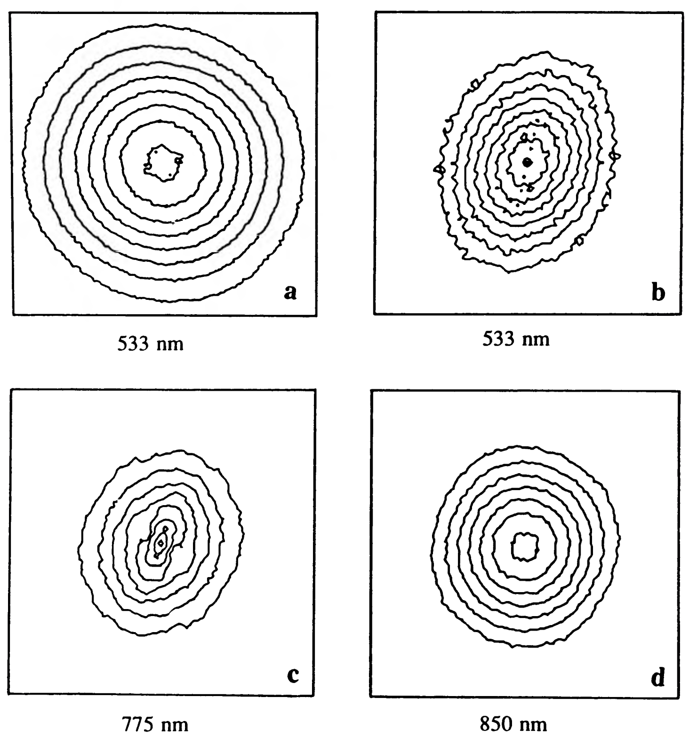

FIG. 2.—Power spectra of the unresolved comparison star and of *o* Ceti obtained in 1987 December using the 4 m Kitt Peak telescope. (*a*) Power spectrum of the comparison star at 533 nm; (*b*), (*c*), and (*d*): Power spectra of *o* Ceti at, respectively, 533 nm, 775 nm, and 850 nm. The first contours are at 12%–14% level from the maximum.

because *o* Ceti was near the maximum light at this epoch and the magnitude difference was too large (≈7 mag).

The reconstructed image of *o* Ceti at 533 nm obtained from the observations carried out in 1988 November at the CTIO 4 m telescope also show an asymmetry (Fig. 3*d*), not seen in the image of the reference (71 Ceti) (Fig. 3*c*). The major axis of the elongated structure has a position angle of 135′ ± 10°, which is similar to the position angle of the asymmetry observed in the same spectral region in 1987 December. The image shows some change in geometry when compared to the 1987 December image, and the degree of asymmetry does appear somewhat smaller. The companion could not be detected at this epoch because of a large magnitude difference of about 7.5.

The signal-to-noise ratio in the data recorded in 1987 December and 1988 November is very high and the effects from the companion are negligible because of the large magnitude difference, allowing precise measurement of the axes of the asymmetries. We determined the axes by least-squares fitting the power spectra of ellipses of uniform brightness to the observed power spectra. Table 1 summarizes our measurements of the major and the minor axes of the asymmetry (approximated with an ellipse with uniform brightness) at different wavelengths. The size of the ellipse and the degree of asymmetry change as a function of wavelength. The degree of asymmetry in the 1987 December observations varies from ≈0.8 at 621 nm to ≈0.9 at 850 nm. The major and the minor axes of the asymmetry measured from the 1988 November data show an increase in the size of *o* Ceti at 533 nm when compared to the size measured in this same spectral region in 1987 December, and the degree of asymmetry is ≈0.9.

The size of *o* Ceti's atmosphere appears smaller at 533 and 850 nm and larger at 621 nm in the 1987 December observations. If this is interpreted in terms of a stratification in the atmosphere of *o* Ceti, then depending on the spectral region in which the observations were made, we effectively probe different layers in the atmosphere. In that case, the layer seen at 533 nm bandpass is much closer to the photosphere than the layer observed in the absorption minimum of the strong TiO band at 621 nm. This is consistent with the measurements of the angular size of *o* Ceti obtained assuming spherical symmetry, showing larger diameters in the absorption minima of the TiO bands (Bonneau et al. 1982; Karovska, Nisenson, & Stachnik 1987). It is difficult to determine directly the "true" photospheric diameter, the crucial parameter for establishing the effective temperature, because of the effects of the extended atmosphere (Willson & Bowen 1988). Our measurements are important for better understanding of the detailed structure of the atmosphere and should provide more solid foundation for development and testing of model atmospheres for Mira-type variables.

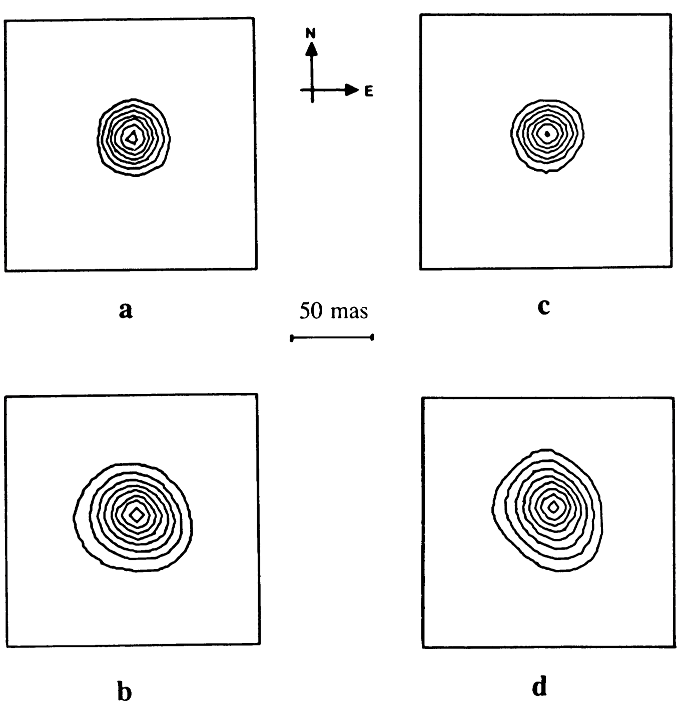

FIG. 3.—Reconstructed images of (*a*) the comparison star, and (*b*) *o* Ceti from 1987 December at 775 nm. Reconstructed images of (*c*) the comparison star and (*d*) *o* Ceti from the observations carried out in 1988 November at 533 nm using the CTIO 4 m telescope. The first contours are at 12%–15% level from the maximum. The size of the image of the comparison star is equivalent to the beam size for the reconstruction process.

TABLE 1

MEASUREMENTS OF THE MAJOR AND THE MINOR AXES OF THE ASYMMETRIES

Wavelength (nm)	Major Axis (mas)	Minor Axis (mas)
1987 December		
533/08	62	48
620/10	77	59
656/10	69	53
775/10	68	58
850/25	60	56
1988 November		
533/08	69	60

NOTE.—(1 σ): ±2 mas.

4. DISCUSSION

Our observations of *o* Ceti show direct evidence that the atmosphere of this star departs substantially from spherical symmetry. It is not yet clear that we have observed the same asymmetry at different epochs since 1983. The position angle of the axis of the asymmetry changed as a function of time; the position angles of the asymmetries measured near maximum light (pulsation phase 0.97) are very similar. However, they are about 90°–100° larger than the position angles measured at pulsation phases 0.43 and 0.81.

Other observations also indicate the presence of asymmetries. For example, an extended bipolar outflow has been detected recently in the CO $J = 2$–1 and $J = 1$–0 emission of the circumstellar envelope of *o* Ceti (Planesas, Kenney, & Bachiller 1990). The observed structure has been interpreted as partial collimation of the stellar wind due to an enhanced density of gas in the equatorial plane of the inner envelope of *o* Ceti. Polarimetric observations of *o* Ceti also indicate departure from spherical symmetry. The position angle of polarization was measured at three of the four epochs in which speckle observations were obtained. The position angles of the polarization measured in the continuum in 1983 (Boyle et al. 1986) (Kemp & Henson 1987) are very close to the position angles of the major axis of the elongation in the reconstructed images from those epochs. The polarization measured at the epoch close to maximum light in 1987 December (Boyle 1991) is in a direction perpendicular to the direction of the major axis of the elongation in the reconstructed images from that epoch. The variation in the position angle of the polarization could be related to the change in the size of the scattering particles in the asymmetric atmosphere in the course of the pulsation process (e.g., Coyne 1988). If the polarization in *o* Ceti is related to the observed asymmetry, then it is conceivable that the presence of polarization in other Mira variables (e.g., Boyle et al. 1986) also indicates departure from spherical symmetry. Presence of substantial asymmetries in the atmosphere of the Mira-type variables would have an important effect on the measured quantities and the model atmospheres for these stars.

The cause of the observed asymmetries in *o* Ceti has not yet been determined. Thermal, density, or dynamic instabilities could create asymmetries in brightness distribution on the surface of *o* Ceti, or geometric asymmetries with orientation that changes with time. For example, dynamic instabilities apparent in some atmospheric models can produce "shock pairing" which in turn could produce departures from spherical symmetry (Willson & Bowen 1988, Fig. 8). Convective instabilities (Schwarzschild 1975) could result in a formation of large supergranules or spots on the photosphere which if partially resolved could create asymmetries in the diffraction limited images obtained using the 2.25 or the 4 m telescopes.

Rapid roatation, or the presence of the companion and its orbital motion, could affect the upper atmosphere of *o* Ceti and create an asymmetry. The existing (rather uncertain) orbit for the companion indicates period of about 400 yr (Baize & Petit 1982). The position angles of the companion measured in 1983 and 1986, respectively 120° and 116°, are almost perpendicular to the orientation of the major axis of the asymmetry as measured in 1983 and 1986, and close to the position angle of the major axis of the asymmetry as measured in 1987 December and in 1988 November. If the companion or the stellar rotation is causing the asymmetry, the orientation of the asymmetry should not vary significantly as a function of time.

Nonradial pulsations can create departures from spherical symmetry similar to the asymmetries observed in *o* Ceti. In fact, Shawl (1974) has already suggested that *o* Ceti could be a nonspherical pulsator, in order to explain the observed variations in the position angle of the polarization and the light maxima. To determine if the cause of the asymmetry is related to the phenomenon of nonradial pulsation, the changes in the geometry of the images of *o* Ceti need to be monitored over several pulsation cycles.

Further speckle observations, coordinated with observations carried out using other techniques, should result in a better understanding of the atmospheric structure and could allow determination of the origin of the asymmetry. Speckle observations obtained in the continuum, emission lines, and the molecular spectral features will probe different layers of the atmosphere at different phases of the pulsation cycle and could show whether the asymmetry or asymmetries are confined to the upper atmosphere or originate near the photosphere. To determine the cause of the departure from spherical symmetry, it is necessary to find out if there is a preferred orientation of the axes of asymmetry. This will allow distinguishing processes that would create erratic changes, such as convection, thermal or dynamical instabilities, and processes that would create a preferred orientation of the asymmetry, such as orbital motion, rotation, or nonspherical pulsation.

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