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Further speckle interferometric studies of α OrionisM. Susan Wilkerson¹⁾ and Simon P. WordenSacramento Peak Observatory,²⁾ Air Force Geophysics Lab, Sunspot, New Mexico 88349

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Speckle interferometry was conducted on α Orionis (Betelgeuse) to check and extend the observations of Lynds, Worden, and Harvey (1976). Digital reduction of the data indicated the diameter had not changed significantly from the value derived in the previous study. In addition it was found that α Ori is very highly limb darkened. No significant surface structure was revealed. All other results of the Lynds *et al.* study are confirmed.

INTRODUCTION

THE M2 Ia supergiant star α Orionis (Betelgeuse) has a large enough angular diameter ($\sim 1/20$ arcsec) to be resolved using large optical telescopes. As such it is an ideal candidate for diameter measurements and image reconstruction. The first stellar-diameter measurements of α Ori were performed by Michelson and Pease (1921) using the Michelson stellar interferometer on the Mt. Wilson 100-in. telescope. Since then many methods have been used to obtain stellar-diameter information, including a more sophisticated form of Michelson interferometry (Currie *et al.* 1974), intensity interferometry (Hanbury Brown 1968), and lunar occultations (Evans 1955). One of the newest techniques for obtaining stellar diameters is speckle interferometry. (Table I summarizes the various techniques and results as applied to α Ori.) Speckle interferometry has been shown to provide information from which images may be reconstructed (Knox and Thompson 1974; Lynds *et al.* 1976); it is therefore especially suited for studies of the largest-angular-diameter stars such as α Ori.

The use of speckle interferometry to obtain large-telescope diffraction-limited information was first demonstrated by Labeyrie (1970). In his technique, photographs are exposed on a time scale less than that of the variations of the optical transfer function of the Earth's atmosphere. The resulting images yield information near the diffraction limit of the telescope. Labeyrie's technique has been used not only to obtain angular diameters but to determine binary- and multiple-star separations (Gezari *et al.* 1972; Bonneau and Labeyrie 1973; Labeyrie *et al.* 1974) and to study small-scale solar features (Harvey and Breckinridge 1973; Harvey and Schwarzschild 1975).

In Labeyrie's method, power spectrum analysis is used

to determine the spatial harmonics of the original brightness distribution. However, by so doing, the spatial phase information is lost and two-dimensional image reconstruction is impossible. A speckle data-processing technique that preserves the phase information has been demonstrated by Lynds, Worden, and Harvey (1976, henceforth referred to as LWH). Using this technique, the radius of α Ori was determined and possible surface structure was detected. Subsequent in-depth analysis of the LWH results by McDonnell and Bates (1976) have confirmed these results and outlined methods whereby the maximum information with regards to limb darkening and surface structure may be extracted from speckle data. It is the purpose of this study to repeat the LWH observations on more extensive data obtained several years after the LWH results. In particular, we are investigating the possibility of time changes in stellar diameters, as well as the reported dependence of diameter on wavelength and the possible surface structure reported by LWH.

1. THE DATA AND REDUCTION PROCEDURE

Observations of α Ori, β Ori, and γ Ori were made on the nights of 14/15 and 15/16 January 1976 with the Kitt Peak National Observatory 4-m Mayall telescope. The complete optical system and details of the data reduction are discussed in LWH. Speckle data was recorded on Tri-X film in two wavelength regions: $5100 \pm 50 \text{ \AA}$ and $5200 \pm 50 \text{ \AA}$. The first spectral region at 5100 \AA consists mostly of continuum light, whereas the second filter at 5200 \AA is centered on the strong TiO band redward of 5169 \AA . As discussed by LWH, the continuum light which originates deeper in the stellar atmosphere may be expected to be less sensitive to temperature inhomogeneities than the TiO-band light. Two hundred exposures were made in each bandpass of each object. The photographic film was then digitized using the PDS microdensitometer at the Kitt Peak National Observatory. Computer reductions were performed on the Sacramento Peak Observatory's XDS Sigma 5 computer. The basic processing consisted of locating the center of each bright speckle on a frame and

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²⁾ Operated by The Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

then summing these speckles to construct a "mean" speckle for each frame. To increase the ratio of signal to noise, 15 of such mean speckles, one from each original speckle frame, were then summed. The TiO image was subtracted from the continuum image to reveal possible surface structure. Both cross-sectional intensity tracings and a digitally produced photographic image were analyzed.

II. RESULTS

In the present study we have applied limb-darkening fitting as described by LWH. In this method the observed α Ori image is assumed to be the convolution of the point-source image with a disk having limb darkening of the form

$$I/I_0 = 1 \pm \mu(\cos \theta - 1),$$

where I is the intensity at an angle θ , θ being the angle between the lines from the stellar disk center to Earth and from the disk center to the surface point in question, and μ being the limb-darkening coefficient. The results are summarized in Table I, along with previous angular-diameter measurements for α Ori. We note that for both continuum and TiO wavelength regions α Ori is highly limb darkened, with a slight indication that the continuum image is less limb darkened. This result is consistent with the observed differences in diameter between the two wavelength bands, assuming a non-limb-darkened disk.

In this work, as well as in the LWH paper, we have derived estimates of the errors in diameter measurements by considering independent subsets of data. From the 200 images, 180 were digitized and divided into twelve 15-frame subsets. Diameters, limb-darkened values, and uncertainties were then derived from these subsets. In the LWH paper the error estimates derived in a like manner were substantially smaller than the plate-scale-measurement error. The plate scale was determined to be $2.1 \pm 0.3 \text{ cm}^{-1}$ by LWH. In this work we attempted to derive the plate scale to an accuracy comparable to that which the internal consistency of the data indicated. At the time of the current observations, the plate scale was measured to be $2.00 \pm 0.003 \text{ cm}^{-1}$. Thus the diameter values listed in Table I can be considered accurate to 1%–2%. Within the plate-scale-measurement error the observations are consistent with a result of no discernible change in radius occurring between these newer observations and the LWH results. However, we note that the $\sim 8\%$ radius difference between the higher-stellar-atmosphere level (TiO) and photospheric observations (continuum) persists in these current data. This result, being only a relative number, is independent of measurements of image scale.

The high internal accuracy of the results reported in this paper makes it important to consider sources of possible systematic error. The most likely source of such errors is the somewhat subjective selection of "bright"

TABLE I. Measured diameters of α Ori.

Wave-length (Å)	Diam. (0.001)	Limb-darkening coeff. (μ)	Reference
5750 (white light)	34.54 ± 10%		Michelson and Pease (1921), Hanbury Brown (1968)
5000 ± 125	>50		Gezari, Labeyrie, and Stachnik (1972)
4220	69 ± 5		Bonneau and Labeyrie (1973)
4880	67 ± 5		Bonneau and Labeyrie (1973)
5700	55 ± 5		Bonneau and Labeyrie (1973)
7190	52 ± 5		Bonneau and Labeyrie (1973)
10400	≤50		Bonneau and Labeyrie (1973)
4213 ± 34	62 ± 17		Currie, Knapp, and Liewar (1974)
5020 ± 35	47 ± 6		Currie, Knapp, and Liewar (1974)
5803 ± 46	57 ± 9		Currie, Knapp, and Liewar (1974)
5992 ± 15	57 ± 6		Currie, Knapp, and Liewar (1974)
6336 ± 16	44 ± 13		Currie, Knapp, and Liewar (1974)
5100 ± 50 (continuum)	49 ± 1 ^a		LWH (1976)
5180 ± 50 (TiO band)	79 ± 1 ^b		LWH (1976)
5180 ± 50 (TiO band)	53 ± 1 ^a		LWH (1976)
5180 ± 50 (TiO band)	79 ± 1 ^b		LWH (1976)
5180 ± 50 (TiO band)	66 ± 6	0.6 ± 0.3	McDonnell and Bates (1976)
6500 ± 20	51 ± 1		Worden, Stein, Schmidt, and Angel (1977) (autocorrelation method)
6500 ± 20	52 ± 1		Worden, Stein, Schmidt, and Angel (1977) (LWH method)
5100 ± 50 (continuum)	45.3 ± 0.5 ^a		This work
	52.0 ± 1.7	0.75 ± 0.13 ^c	This work
5200 ± 50 (TiO band)	48.9 ± 0.7 ^a		This work
	56.9 ± 1.0	0.93 ± 0.03 ^c	This work

^a Uniform-intensity disk.

^b Cone-shaped intensity profile.

^c Diameter and limb darkening which best fit the data.

speckles in each photograph. While application of the same selection criteria to the point-source exposures will in some measure account for this problem, the fact that α Ori is a resolved object in and of itself alters the character of α Ori speckle photographs. In a resolved-object pattern, individual speckles will overlap, which they will not do for a point source. This would tend to increase the measured diameter of individual speckles. However, the restriction to use of bright speckles only does tend to reduce this problem, but does not eliminate it. On the other hand, the presence of noise spikes in each speckle photo due to ion and cosmic-ray events in the image tube would tend to decrease the size of a mean speckle correspondingly more for a resolved object than an unresolved one. These problems have been discussed in detail in a recent paper by Worden, Lynds, and Harvey (1976) in which an empirical determination of their effects was described. It is to be noted that altering bright speckle identification criteria did not alter the measured stellar diameter by an amount greater than the internal errors

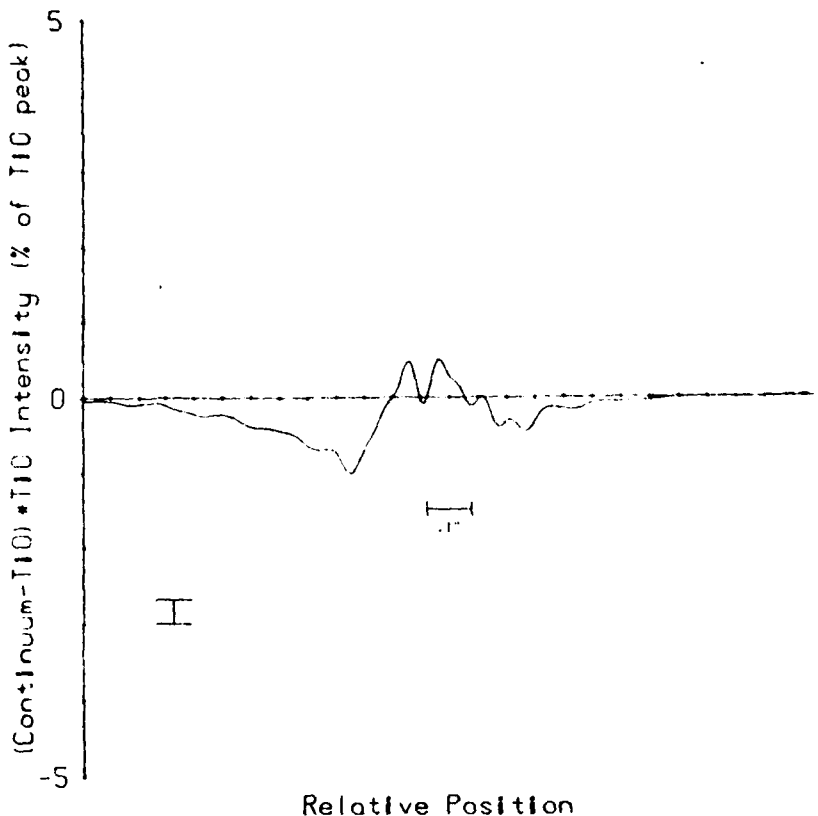


FIG. 1. Subtracted image of α Ori convolved with intensity in TiO [$(I_{\text{continuum}} - I_{\text{TiO}}) * I_{\text{TiO}}$] revealing possible but marginally statistically significant surface structure. Horizontal cross section. Error bar is shown at lower left.

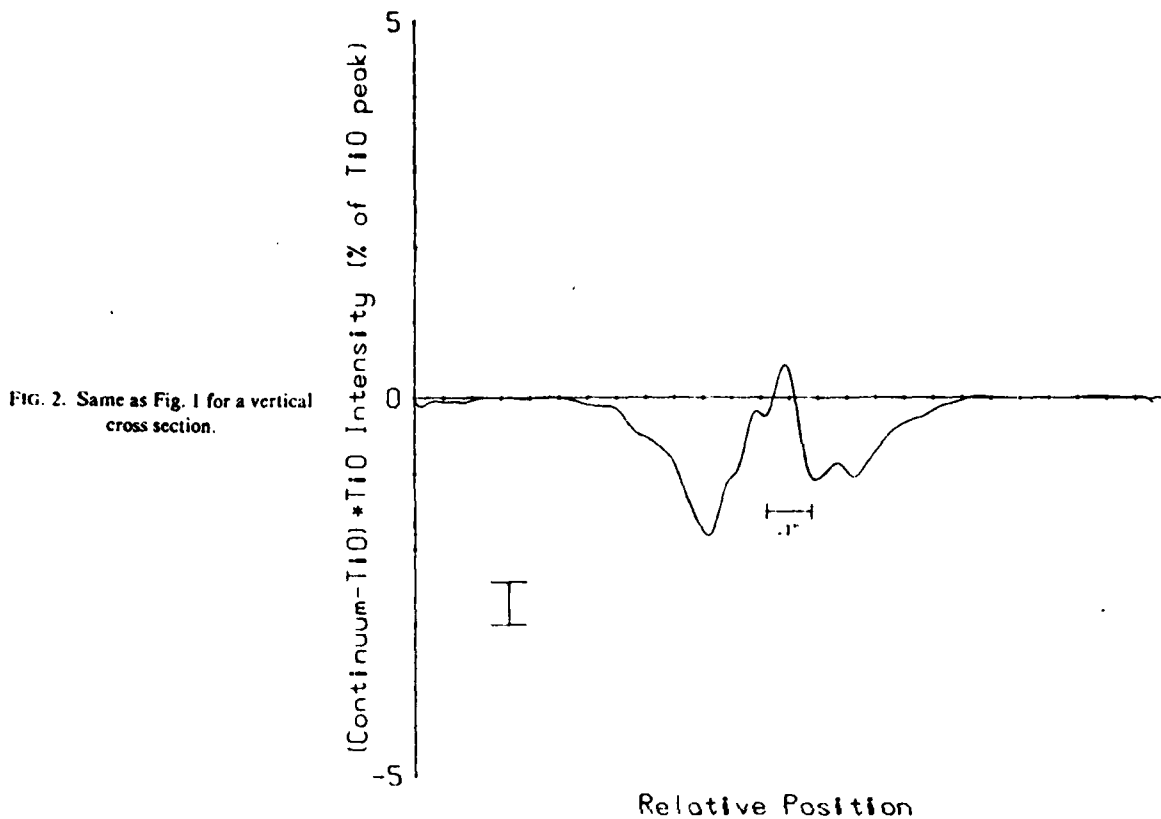
over a wide range of bright speckle identification criteria. Moreover, application of both the LWH method and a nonsubjective (but more noise sensitive) method for deriving angular stellar diameters using speckle autocorrelation functions, revealed no method-dependent difference in the derived diameter for α Ori (Worden, Stein, Schmidt, and Angel 1977).

Since we have produced what are to be considered actual "images," it may be possible to investigate the presence of stellar surface structure as suggested by LWH. However, since the diffraction limit is $\sim 1/2$ the measured stellar diameter, and since our point-source results reveal that we obtain only nearly diffraction-limited results, this technique can reveal under the best conditions only the largest-scale structure on the stellar disk (i.e., that which effects $\sim 1/4$ of the visible stellar surface). Thus, even the 4-m telescope provides a rather insensitive method for studying stellar surface structure. Nevertheless, as done by LWH, we may divide our images into quadrants and investigate any differences between these quadrants. Towards this end, the subtracted image revealed features in the one-dimensional trace (Fig. 1) which may be interpreted as possible surface structure (as in the LWH paper). As with the diameter measurements, the accuracy of this was derived by considering independent subsets of the data. Although the apparent noise in this result, as evinced by the fluctua-

tions along the scan, is less than the LWH result, the apparent structure is only marginally statistically significant. The lack of as significant a result as that shown by LWH does not necessarily mean that no such large-scale surface structure exists, merely that our present analysis contains somewhat larger systematic errors in the two images, as revealed by the large signals at distances much greater than the radius of the star. Such features may be masking any surface structure present. The super-resolution techniques of McDonnell and Bates (1976) may prove more useful in the future for discerning surface structure in this type of data.

III. CONCLUSIONS

In this study we have repeated the LWH measurements on α Ori with a somewhat larger amount of data. Although the variations in previous determinations of the α Ori angular diameter suggest a change with time, we find that within the errors of the measurements and of the image-scale determination there has been no change in the radius of α Ori from data taken almost two years apart. The tracings and images, based on approximately the same number of frames and therefore the same error as the observations conducted by LWH, reveal no statistically significant surface structure for the two nights of observations, although further studies



of the data involving more sophisticated image processing may reveal evidence for such structure. The results further indicate that α Ori is almost completely limb darkened, with limb-darkening coefficients of 0.93 and 0.75 for the TiO and continuum bands, respectively. Moreover, the 8% difference in uniform-disk angular diameter reported by LWH is confirmed.

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