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ON THE ALPHA ORIONIS TRIPLE SYSTEM

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ABSTRACT

Detection of two close optical companions to the red supergiant α Ori was accomplished in 1983 November on the Steward Observatory 2.25 telescope. A new two-dimensional photon counting camera (the PAPA detector) was used for data recording, and speckle imaging was used for image reconstruction. The closer of the two sources is located at $0''.06 \pm 0''.01$ from α Ori (P.A. = 273°), the more distant at $0''.51 \pm 0''.01$ (P.A. = 278°). The magnitude differences with respect to the primary, measured at 656.3 (Hα) and 656.8 nm (red continuum) are 3.4 and 3.0 for the close source and 4.6 and 4.3 for the distant source respectively. This observation confirms the reality of the two sources which has been reported in previous work. Our analysis favors an interpretation in which the two optical sources are stellar companions to α Ori. Strong support for the existence of the close stellar companion was found in the polarization data obtained by different observers for α Ori. A periodicity of $\sim$2.1 yr was found in the time-dependent variations in the position angle of the plane of polarization, which appear to reflect the orbital motion of the close companion. The observed polarization can be interpreted as being due to a systemic asymmetry created by the close companion orbiting α Ori inside its extended dust envelope.

Subject headings: interferometry — stars: individual — stars: visual multiples

I. INTRODUCTION

Alpha Ori (Betelgeuse), a supergiant star classified as M2 Ia–Iab, has been intensively analyzed by a variety of techniques. Observations accumulated for more than a century create an ensemble of data (magnitudes, colors, spectra, polarization measurements, interferometric measurements, and many others) showing the extremely complex signature of this star.

Goldberg (1979) proposed an empirical model for the morphology of the atmosphere of α Ori. Following his idea, a "visible" part of the star comprises a photosphere and an envelope of gas and dust in expansion. An intermediate zone, identified as a stellar chromosphere, forms a bridge between the photosphere and the dust envelope.

It is a nontrivial problem to attribute an accurate spatial scale to this model using the photospheric radius as a unit. Direct angular diameter measurements of this supergiant using different techniques appear to be wavelength- and time-dependent (White 1980). Tsuji (1978) interpreted these measurements as being highly affected by the presence and distribution of scattering dust in the circumstellar shell, implying that they do not always accurately estimate the photospheric diameter of the star. Tsuji's spectrophotometric estimation of the photospheric angular diameter is 41 ± 3 mas. Similar values were proposed by White (1980), Ricort *et al.* (1981), and Roddier and Roddier (1983). In our calculations, we adopt a value of 40 mas for the photospheric angular diameter. In this picture, the stellar chromosphere extends to several stellar radii from the photosphere, and its upper layers are in close contact with the lower part of a dust and gas envelope which extends to several thousand stellar radii.

The linear photospheric radius can be calculated using 20 mas as the angular radius combined with the distance to α Ori. The errors in trigonometric parallax measurements are comparable with the measured value of the parallax for α Ori, so instead we adopted the photometric value of 95 pc (White 1980; Hirshfeld and Sinnott 1982) and thus estimated its linear photospheric radius to be $\sim$400 solar radii (1.9 AU). For our calculations, we adopt the value of 20 $M_\odot$ for the mass of α Ori, as estimated by Weymann (1962).

Alpha Ori is characterized by pronounced variability encompassing most of its observed parameters. The star has been classified as a semiregular variable (SRc). Its light and radial velocity curves exhibit variability on two different time scales: a long-period variation of 5.78 yr (Jones 1928) and, superposed on this, "irregular fluctuations" having a time scale of several hundred days (Stebbins 1931). The variable character of the radial velocity of α Ori was delineated by Plummer (1908). Assuming the star to be a spectroscopic double (period = 6 yr), Bottlinger (1911) calculated an orbit. The possibility of α Ori being a double star was rejected in later works (Sanford 1933; Spitzer 1939; Adams 1956), and the variations in the radial velocity curve were attributed to intrinsic variability of the star.

The renaissance of the idea that α Ori is not a single star dates from the discovery of a possible companion through observations carried out in 1982 February using pupil plane interferometry at the NSO McMath 1.5 m telescope (Karovska 1984; Roddier, Roddier, and Karovska 1984). The position angle of the companion was either $85° \pm 5°$ or $265° \pm 5°$ (the 180° ambiguity being inherent in interferometry), and the separation was $0''.5$. The magnitude difference between the primary and the companion was estimated to be between 3.5 and 4.0 at a wavelength of 530 nm. In addition, Karovska (1984) inferred the possible existence of a second companion from an image reconstruction using the Maximum Entropy method. The location of this second source was 0".04 from α Ori, at a position angle of 325° ± 5°. However, this was a super-resolution result, so this evidence for a close second companion was by no means definitive.

In 1983 November, at the Steward Observatory 2.25 m telescope, new observations were obtained that strongly indicated the existence of two companions to α Ori. One of the detected companions was located at P.A. 278° ± 5° and distance 0".51 ± 0".01, thus providing strong confirmation of the reality of the more distant companion. The other companion lay at P.A. 273° ± 5° with a separation from the primary of 0".06 ± 0".01 and thus could be the same object inferred by Karovska (1984) from the earlier data only if the position angle had changed in the interim by ~308° in a counterclockwise direction or 52° clockwise.

Recognizing that the initial inference of a possible close companion was a marginal detection, we have nevertheless explored the consequences if a single object was in fact located at the cited positions at the two observing times, and we conclude that this would be consistent with a stellar body orbiting α Ori at a mean distance of 2.5 stellar radii and a period of ~2 yr. We have analyzed available polarization data (Hayes 1984) and find that these data are also consistent with the existence of a close companion. In addition, observations of asymmetries in other interferometric data and of apparent mass ejections from α Ori in previous decades lend support to the existence of a close companion, whose periodic interactions with α Ori give rise to a number of phenomena associated with the star.

This paper reports the results of the 1983 November observation as well as the analysis of polarization data which appear to be consistent with the existence of the close companion to α Ori.

II. THE OBSERVATIONS

Speckle observations of α Ori were carried out on 1983 November 15 and 16, with the Steward Observatory 2.25 m telescope. The observations were made using the precision analog photon address (PAPA) detector (Papaliolios, Nisenson, and Ebstein 1985), a two-dimensional photon counting sensor which records a catalog of sequential photon positions. The PAPA camera records data at a rate of 100,000 photons s^{-1} with a field size of 256 × 256 pixels. The photon addresses are encoded on a video carrier and stored using a conventional VCR for later digital processing. The speckle process requires that the images be magnified so that the diffraction limit of the telescope is correctly sampled by the recording sensor (a minimum of two pixels per resolution element), the effects of atmospheric refraction are corrected, and the bandpass of the light is restricted to meet coherence requirements. For these observations, we used an optics package developed by K. Hege and J. Beckers. A birefringent filter developed for differential speckle interferometry (Beckers, Hege, and Murphy 1984) was used for recording the α Ori data. This filter produces two images side by side, each having a bandpass of 0.125 nm with one image centered on Hα and the other shifted to the red by 0.5 nm. The two images are recorded simultaneously on the detector. During the numerical processing of the data, the two images may be separately analyzed or, in the differential mode, the entire field may be processed, yielding cross product terms that could yield super-resolution information. In this paper, we discuss only results from conventional processing of the two separate images.

III. DATA PROCESSING

The photon addresses are first converted to conventional digital data through a buffered interface to a Data General Nova computer. These addresses are then divided into subsets (or frames) whose length matches the characteristic correlation time of the atmosphere. The testing of different correlation times allows a maximization of the signal-to-noise ratio in the integrated result. This is important since the correlation time may vary widely throughout the night, resulting in a substantial reduction in signal-to-noise ratio if fixed frame times are used (which would be the case for standard framing cameras). Typical correlation times range from a few milliseconds to tens of milliseconds. Individual images are constructed from the photon list simply by incrementing the addressed array position. The Fourier transform for each image is computed, and the complex correlation arrays required for speckle image reconstruction (Nisenson and Papaliolios 1983) are calculated and integrated. Correction for the atmospheric and telescope transfer functions are performed by using data recorded for an unresolved reference star. This star should be located as close in angular position and time as possible to the stellar data recording. This approach insures that, in almost all cases, the long-term atmospheric statistics are similar for the two data sets. Deconvolution by the reference star results in enhancement of the high angular frequencies in the reconstruction. Many of the problems that made accurate speckle image reconstruction difficult for faint sources, in particular the correction for the photon noise bias (Nisenson and Papaliolios 1983), are completely eliminated for data recorded with the PAPA detector. The fundamental linearity and unlimited dynamic range of the photon-counting camera allows a far more accurate reconstruction of binaries with large magnitude differences and low-contrast stellar features than was ever possible with the conventional detectors used in speckle interferometry.

IV. RESULTS AND ANALYSES

a) Interferometric Data

The existence of two optical sources in proximity to the red supergiant α Ori was confirmed by the 1983 November observations made at Steward Observatory. The result of data processing was the detection of two low-contrast fringe patterns in the power spectrum oriented in slightly different directions. The low contrast of the fringes indicates a large difference in intrinsic brightness of the primary and secondary sources. The power spectrum, autocorrelation, recovered phase, and reconstructed image (Fig. 1 [Pl. 5]) demonstrate the reality of the companions and allow accurate determination of their separation from the primary, position angle, and magnitude differences.

The closer of the two sources was found to be at 0".06 ± 0".01 from the primary, and the second, more distant, source at 0".51 ± 0".01. An essential result of speckle image reconstruction is the elimination of the 180° ambiguity normally associated with interferometry, allowing correct positions of the sources to be determined. The distant source was located at P.A. 278° ± 5°, close to one of the two possible positions (265° ± 5°) derived from the 1982 February data. The derived position angle for the close source is 273° ± 5°, substantially different from that inferred from the observations of 1982 February (325° ± 5°).

Alpha Ori was observed simultaneously through two close spectral windows centered at 656.3 nm (Hα) and 656.8 nm (red

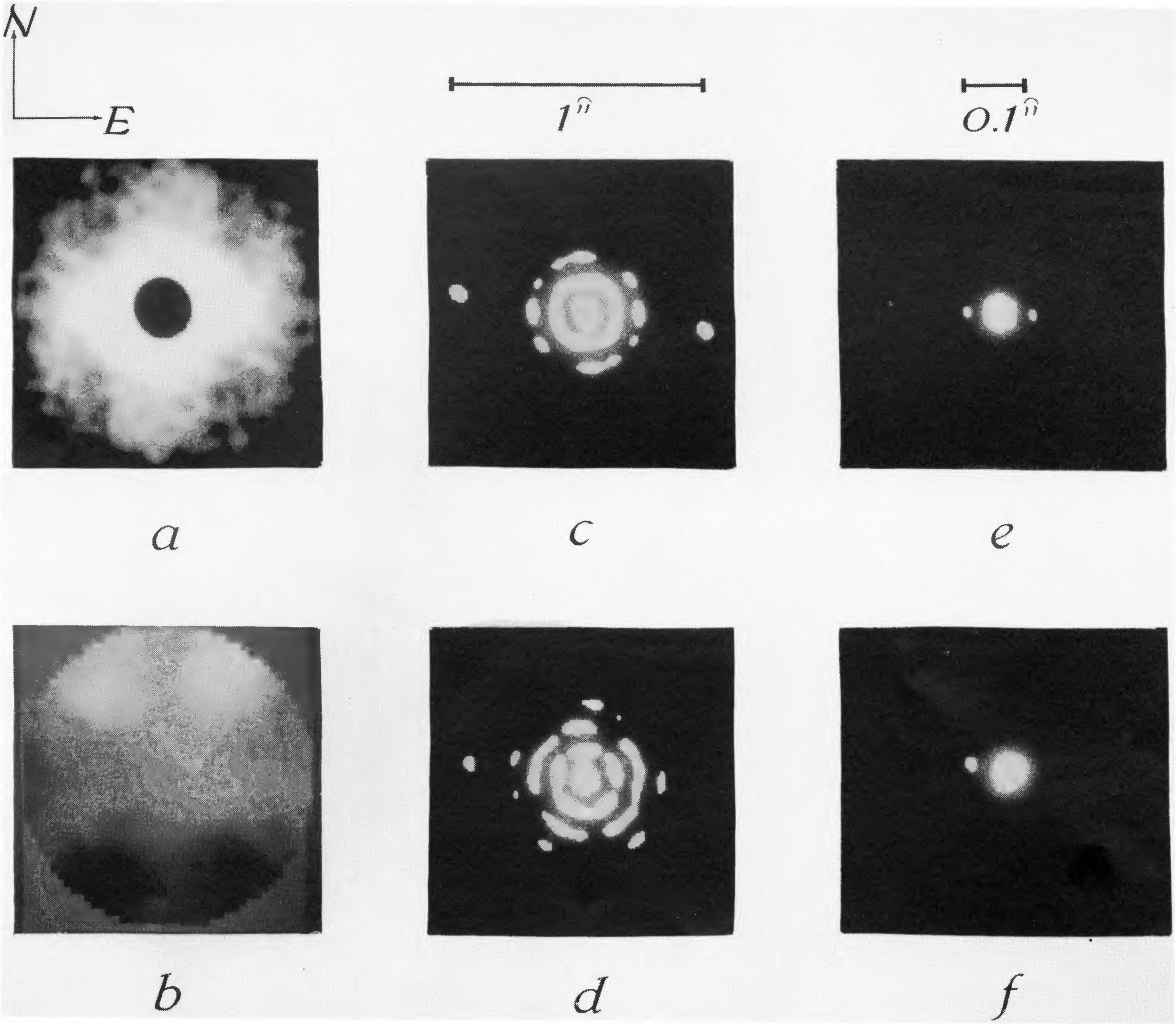

FIG. 1.—Speckle observation (Steward Observatory 2.25 m telescope, 1983 November): (*a*) and (*b*) recovered power spectrum and phase; (*c*) and (*d*) autocorrelation and the reconstructed image for the distant companion; (*e*) and (*f*) autocorrelation and image for the close companion.

KAROVSKA, NISENSON, NOYES, AND RODDIER (*see* page 261) continuum). The bandpass was the same for both observations: 0.125 nm. The derived magnitude difference between the primary and the close source was 3.4 ± 0.1 in Hα and 3.0 ± 0.1 in the continuum. For the distant source this difference was higher: 4.6 ± 0.1 in Hα, 4.3 ± 0.1 in the continuum. The fact that for both companions the Hα magnitude difference is ~ 0.3 mag greater than the off-band magnitude difference suggests that the equivalent width of Hα is about the same for both companions and greater than the equivalent width for the primary.

The high intrinsic brightness of α Ori ($M_v \approx -5$; White 1980) and the measured magnitude differences imply a substantial intrinsic brightness for both companions. The high brightness of these sources and the fact that they are not resolved (the angular resolution obtained from our data is better than 0".1) suggest that they cannot be interpreted as reflections from dust clouds in the extended envelope of the supergiant. The presence of large structures (such as prominences) extending above the surface has been also considered as a possible explanation. Since the distant source would be located at a distance of ~ 25 stellar radii, any explanation other than its being a stellar companion is unlikely. This argument is not valid in the case of the close optical companion. We cannot rule out the cause of the change in position angle of the close source from 325° in 1982 February to 273° in 1983 November as being either due to the rotation of a feature extending above the surface of α Ori, or the appearance of a new feature at a different position angle. However, the high brightness of the sources relative to α Ori (in the continuum as well as in Hα) and the fact that they are not angularly resolved with the 2.25 m telescope suggest that a prominence-like structure is unlikely. On the other hand, the high brightness of these unresolved sources could be due to their stellar nature.

If the companion is a stellar object, then the inferred change in position angle of the close source from 325° in 1982 February to 273° in 1983 November is due to its orbital motion. A preliminary estimate of the orbital period can be obtained from the detected change in position angle between the two epochs of observation, assuming that the orbit is circular and situated in the plane of the sky. Since the sense of the orbital motion is not known *a priori*, possible changes in the position angle could be $\Delta\theta_1 = 52°$ or $\Delta\theta_2 = 412°$ (clockwise motion), or $\Delta\theta_3 = -308°$ (counterclockwise motion). Calculated periods are respectively $P_1 = 12.5$, $P_2 = 1.6$, and $P_3 = 2.1$ yr. From Kepler's third law, the sum of the masses of α Ori and the close companion can be calculated for each of these periods and a value for the linear radus of the orbit. Using the adopted value of 95 pc for the distance to α Ori and a mean value of the two interferometric measured distances (0".05), we estimate a linear radius of the orbit of ~ 4.75 AU. This leads to sums of the masses of 0.7, 41.9 and 24.3 $M_\odot$ respectively for P_1, P_2, and P_3. The first value, 0.7 $M_\odot$, can be eliminated immediately, since it is much too low. The large magnitude difference between the close companion and α Ori implies that its mass is substantially smaller than that of the primary. However, the value of 41.9 $M_\odot$, together with the adopted mass of ~ 20 $M_\odot$ for α Ori, would imply that the mass of the companion is comparable to that of α Ori, so the period of 1.6 yr can also be dismissed. Therefore, we consider counterclockwise orbital motion with a period of 2.1 yr and a sum of masses of ~ 24 $M_\odot$ as a more likely solution.

Independent supporting evidence for the existence of the close stellar companion was also found in the polarization data. Analysis of the polarization data strongly suggests that the orbit is elliptical, not circular. This analysis plus the calculated orbit are discussed in § IV*b*.

Some other interferometric observations appear to be consistent with the existence of the close companion. Goldberg *et al.* (1981) observed α Ori using speckle interferometry and reconstructed its image in 650 nm continuum radiation. They detected an "unresolved bright feature" near the southwest limb of the star at P.A. 208° ± 5°. Roddier and Roddier (1983) observed α Ori 2.5 months before Godberg *et al.* in the 534.8 nm continuum, using pupil plane interferometry. They detected a high-frequency excess in the two-dimensional map of the fringe visibility and interpreted this excess as due to a bright feature on the stellar limb (photospheric radius of 0".02) at P.A. 202°. The resolution limit for this observation is close to 0.03, which shows that the observed structure could be located anywhere between 0".02 and 0".05. It seems plausible that Goldberg *et al.* and Roddier and Roddier actually observed the close companion or the consequence of its interaction with the stellar surface. In § V*c* it is shown that the position angles of these bright features match well the predicted position on the calculated orbit for the close companion.

The detected change in position angle of the distant companion is a counterclockwise displacement of $\Delta\theta \approx 13°$. It is difficult to conclude from these data whether this change corresponds to the companion's orbital motion, since the position angles are not significantly different, given the observational errors. The angular separation did not change within the error bars for the two observations. An orbital period of order 65 yr (leading to $\Delta\theta \approx 10°$) would be expected for a companion of a moderate mass having a circular orbit with radius of ~ 48 AU (angular radius 0".5 and distance 95 pc). This would be consistent with our data if the orbit is conterclockwise—that is, in the same sense of rotation as the inner companion.

b) Polarization Data

A number of measurements of the polarization of α Ori were carried out from 1968 through 1981 by Dyck and Jennings (1971), Serkowski (1971), and Tinbergen, Greenberg, and de Jager (1981). Alpha Ori, like most late-type luminous stars, has substantial (up to 1%) intrinsic polarization. Since 1979 the polarization has been monitored regularly, except during the spring and summer interregnums (Hayes 1984). A particularly interesting aspect of these data is that the degree of polarization as well as the position angle exhibit a wide range of variations with time. Hayes (1984) pointed out that the variation of linear polarization observed in the optical continuum (*B* band) is characterized by "ordered (as opposed to stochastic) structures." The time scale of these structures reported by Hayes is of the order of several hundred days and is similar to the time scale of the photometric changes. Figure 2 shows the *B*-magnitude measurements from 1979.7 to 1980.3 (Krisciunas 1982; Guinan 1984) and the degree of polarization data for the same period (Hayes 1984).

Several plausible interpretations of the origin of large changes in the polarization of α Ori have been proposed (Hayes 1984; Schwarz and Clarke 1984): changes in the circumstellar envelope due to mass loss, Rayleigh scattering in the photosphere of α Ori, presence of few large-scale photospheric convective cells, etc. Attempts were made to find the mechanism(s) which could account for the wide range over which the α Ori polarization position angle changes. One of the proposed mechanisms was scattering of light on matter

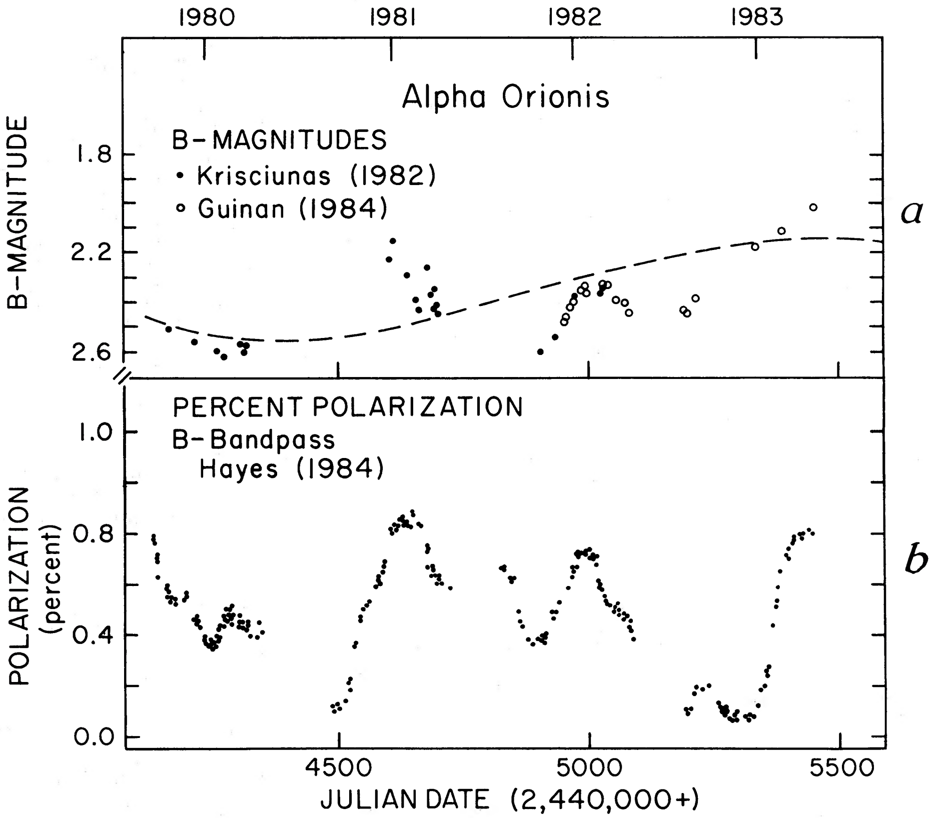

FIG. 2.—Measurements of (*a*) α Ori *B* magnitudes and (*b*) degree of polarization in the *B* bandpass, for the period 1979.7–1983.3. The dashed curve represents Stebbins' (1931) photophotoelectric ephemeris with a period of 5.781 yr (Guinan 1984).

corotating with α Ori as a consequence of binary motion (Hayes 1984). Several reasons led Hayes to dismiss this mechanism as an explanation of the behavior of the position angle: (1) convincing evidence for short-term periodicity is lacking in the photometric or radial velocity data; (2) the polarization does not show periodicity when plotted in the *Q-U* Stokes parameter frame; (3) The characteristic timescale of variations in the position angle (several hundred days), if interpreted as a period of a stellar companion orbiting α Ori, implies a semimajor axis which is smaller than the radius assumed by Hayes of 633 solar radii (Weyman 1977).

Observations of the two optical sources close to α Ori and their interpretation as stellar objects suggested that they may also give clues to the interpretation of polarization data. The results of the wide-band (*B*-filter) linear polarimetry carried out during four consecutive observing seasons, from 1979 to 1983, by Hayes provided the longest continuous data set available for analysis. Measured values for the degree and position angle of polarization are given by Hayes (1984).

The time-dependent polarization data were examined for periodic behavior related to the orbital motion of the close companion. The first step in our analysis was to display the polarization angle (30 day mean) as a function of time, taking into account the 180° ambiguity characteristic of these measurements. The result is presented in Figure 3. The straight line is a linear least-squares fit to these data, plus additional unpublished data for the period 1983 August to 1984 April, kindly supplied by D. Hayes (1985). The individual data points used in the fit were weighted inversely with their estimated error. The slope of the straight line corresponds to a period of 25 months (2.08 yr). A least-squares fit to the data (straight line in Fig. 3) shows a periodicity of 25 months (2.08 yr). The fitted line was subtracted from the data, and the resulting curve revealed the same periodicity. Deviations of the data points from the linear least-squares fit are statistically significant and cannot be interpreted as observational errors.

The degree of polarization appears to manifest periodicity as well (Fig. 2*b*). The period is approximately half that which has been detected for the position angle. The same periodicity (1.05 ± 0.02 yr) was detected in the light curve of α Ori as a result of Fourier analysis of 60 yr of data accumulated by the AAVSO and presented by Goldberg (1984) (Karovska 1984).

The presence of two periodicities in the polarization data (the period of variation of the polarization angle being twice the period of variation of the degree of polarization) is not an unusual phenomenon for close binary systems (Daniel 1981; Rudy and Kemp 1976; McLean 1980). Daniel suggested that tidal distortion of the primary could account for the periodic behavior of the light and the degree of polarization variations. The observed behavior of the α Ori polarization strongly suggests that it may be interpreted as being a consequence of the binary nature of α Ori. If this is the case, the orbital period of the companion will be equal to the period of the polarization angle variations (2.1 yr). The half-orbital period in the variation of the degree of polarization and photometric brightness may be explained by the relative position of the tidal distortion of the primary and the observer (if the orbit is not in the plane of the sky). This period is in perfect agreement with the period we estimated for the close companion from interferometric data. Furthermore, the polarization position angle turns in the

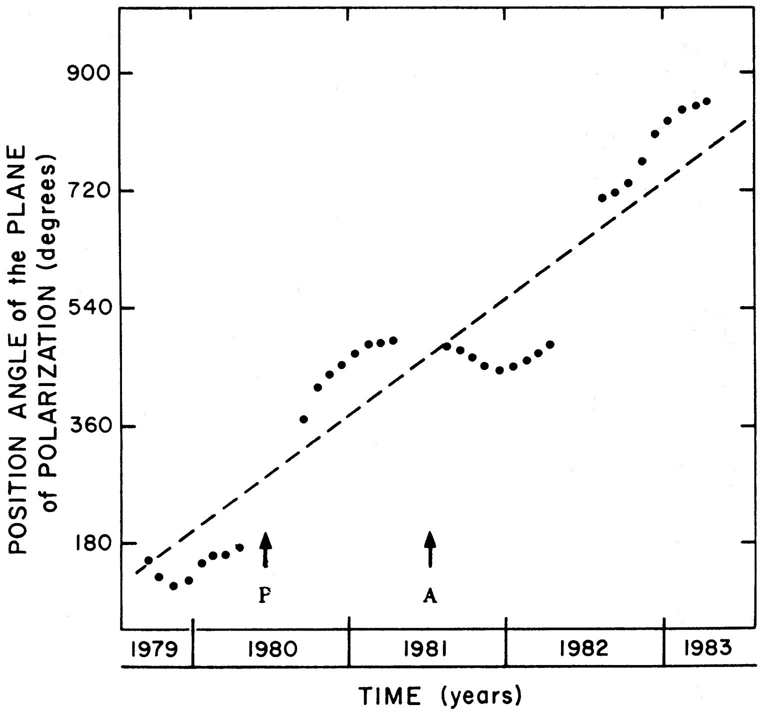

FIG. 3.—Polarization P.A. as a function of time. Dashed line is the linear least-squares fit to the data. "P" and "A" indicate the epochs of periastron and apoastron respectively.

counterclockwise sense, which coincides with the sense inferred for the orbital motion of the close companion.

The short periodicity in the variations of the polarization angle with time makes it unlikely that these variations could be due to the rotation of the large-scale surface features. From the adopted value of 400 solar radii for the radius of α Ori, a rotation period of 2.1 yr would imply an equatorial velocity of about 27 km s^{-1}, which appears to be very high for a single late-type supergiant.

Another point to be considered is the possible mechanism for producing polarized radiation in the α Ori system. Rayleigh scattering (which varies as λ^{-4}) was suggested as a predominant mechanism for the polarized radiation in the atmosphere of α Ori (Tinbergen, Greenberg, and de Jager 1981). Our study of the wavelength dependence of the degree of polarization (polarization data from Dyck and Jennings 1971; Serkowski 1971; Tinbergen, Greenberg, and de Jager 1981) shows that the predominant mechanism is Mie scattering by dust grains, which can only occur in the extended envelope of the supergiant. Least-squares fits to three of the data sets by a linear function of $1/\lambda$ (Mie scattering) are shown in Figure 4. Thus, we are led to consider an interpretation of the changing polarization angle and degree that involves temporal variations in the interaction of radiation with dust in the extended envelope.

V. DISCUSSION

a) Interpretation of Polarization

There is no question that dust grains are present in the circumstellar environment of α Ori. The excess radiation at 11 μm in the spectrum of this star indicates the presence of silicate particles. Dust has also been detected at several tens of stellar radii by interferometric measurements in the infrared (McCarthy, Low, and Howell 1977; Sutton *et al.* 1977) and by direct infrared imaging (Bloemhof, Townes, and Vanderwyck

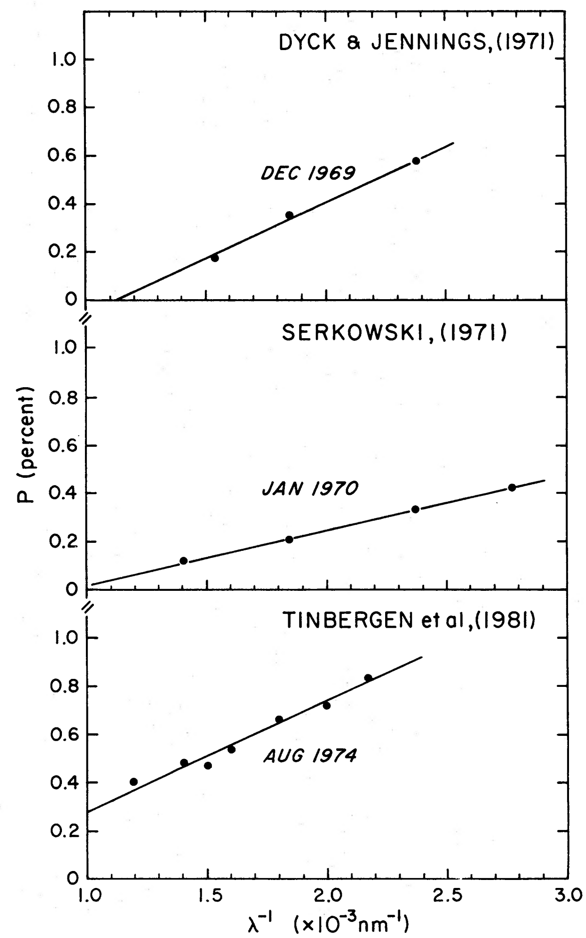

FIG. 4.—Least-squares fit to the polarization degree data by a linear function of $1/\lambda$, showing that Mie scattering from dust grains is the predominant mechanism for producing polarized radiation in the α Ori system.

1984). Observations in the visible (speckle interferometry, Ricort *et al.* 1981; pupil plane interferometry, Roddier and Roddier 1983, 1985; Karovska 1984) showed the presence of dust within a few stellar radii from the surface of the star. These observations are in agreement with the results of Draine's (1981) study of dust formation. Draine has shown that clean silicate grains can survive close to the stellar surface, and he predicted a minimum condensation radius of 1.8 stellar radii for α Ori. Such clean silicate grains close to the stellar surface would enhance the amount of scattered radiation in the visible (Tsuji 1978) and, consequently, the degree of polarized light. The fact that the degree of polarization is coupled to the light variations of α Ori (see Fig. 2) also indicates the presence of polarizing particles close to the star.

We are led to a picture in which the close companion orbits α Ori within its extended chromosphere and inside its extended dust and gas envelope, thereby creating a systemic asymmetry responsible for the observed behavior of the polarization, presented in schematic form in Figure 5. The polarization may be interpreted as being caused by Mie scattering of the light from the companion itself or from the primary which has been rendered asymmetric by tidal distortion due to the proximity of the companion. If this interpretation is correct, the shape of the curve giving the time dependence of the angle of polarization should reflect the goemetry of the orbit and the geometry of the scattering medium.

We may draw some conclusions about the source of the polarization variations from the detailed shape of the polarization curve shown in Figure 3. First, let us assume that the scattering medium is spherically symmetric. In that case, it is easy to rule out an orbit for the companion that is circular and lies in the plane of the sky, for the resulting time variation of polarization angle would then be linear, rather than exhibiting the nearly periodic departures from linearity seen in Figure 3. It is possible that these departures could result from a large eccentricity e or a large inclination i of the orbit, or some combination of the two. We have tried to match the polarization curve with such orbits and found that, under the assumption of a spherically symmetric scattering medium, there is no combination of e or i which matches the polarization curve without entailing one of the two following unacceptable conditions:

a) the eccentricity is so high that the orbit would pass inside the photosphere of α Ori, or

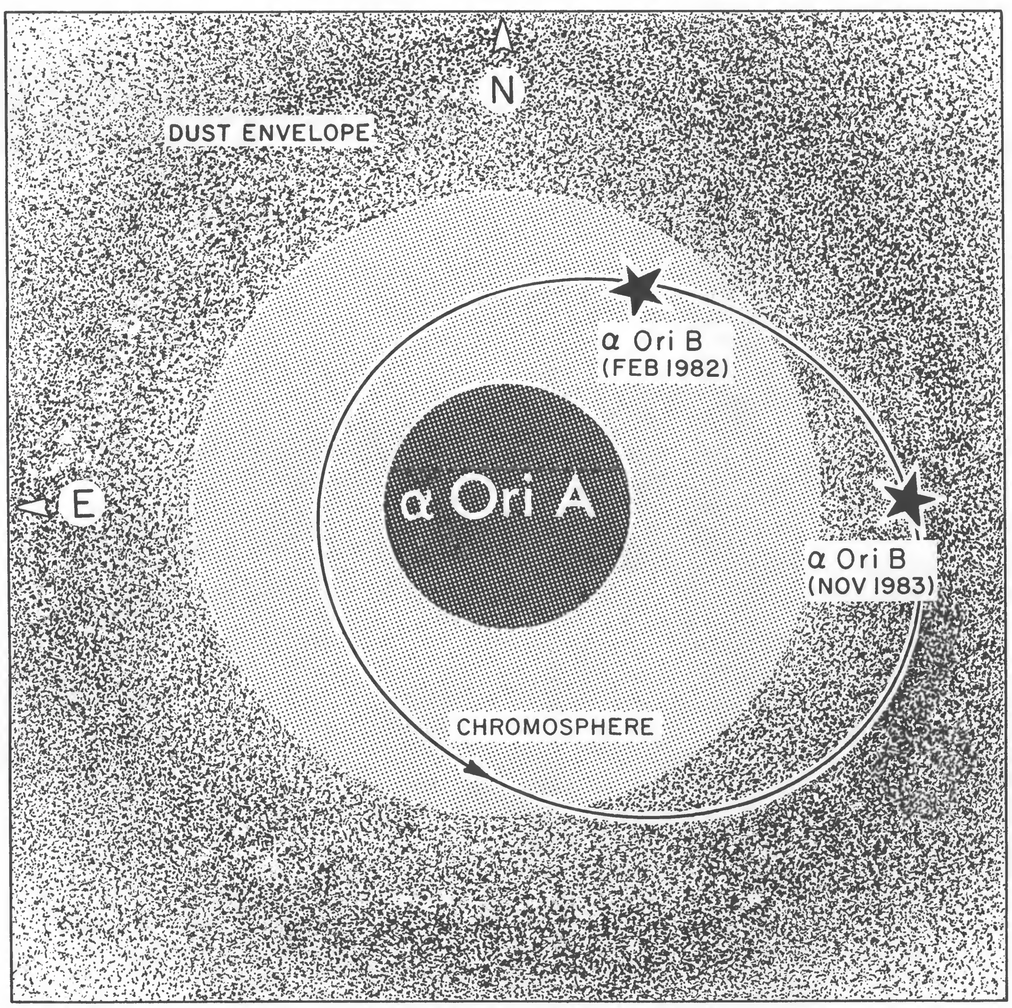

FIG. 5.—Schematic geometry for α Ori and its close companion. The close companion (α Ori B) orbits the primary (α Ori A) within its extended chromosphere and dust envelope. Stars indicate the positions of α Ori B observed in 1982 February and 1983 November.

b) the inclination is so large that Doppler shifts of the primary star would be detectable in the spectrum even for mass ratios for the primary to secondary as large as 10.

It is also the case that for high values of eccentricity or of inclination, the two interferometric positions for the inner companion discussed above cannot be reproduced with a 2.1 yr orbital period.

Therefore, we are led to the interpretation that the amplitude of the polarization curve is due at least in part to an asymmetry of the scattering medium; such an asymmetry, when combined with and elliptic orbit characterized by only moderate eccentricity and inclination, can lead to a predicted polarization curve which matches the observations without violating either of the above constraints.

Given the possibility of a nonspherically symmetric scattering medium, there are then many hypothetical orbits which can fit the two positions of the companion within the error bars. The number of plausible orbits can be reduced by adopting the parameters which have been determined from the polarization angle data: a period of 2.08 ± 0.08 yr, epoch = 1980.4 ± 0.1, position angle of the periastron, with respect to north, $60° \pm 10°$. For the semimajor axis we adopted $0''.05$, the mean value of the interferometrically measured distances of the companion; at the adopted 95 pc for the distance to α Ori, the length of the semimajor axis is then ~ 4.7 AU. Combined with the period of 2.08 yr, these values imply that the sum of the masses of α Ori and its close companion is ~ 24 $M_\odot$. Using the adopted value of 20 $M_\odot$ for α Ori, the mass of the binary companion would be ~ 4 $M_\odot$. At this point, the only free parameters left are the eccentricity and the inclination of the orbit. A good fit to the measured positions of the companion has been obtained by an orbit characterized by these parameters: $P = 2.08$ yr, $T = 1980.4$, semimajor axis $a = 4.7$ AU, position angle of the ascending node $\Omega = 60°$, periastron longitude $\omega = 0°$, $e = 0.35$, $i = 30°$. There is a 180° ambiguity in the position angle of the ascending node and, consequently, in the longitude of the periastron. However, this orbit has to be considered with caution, since its determination is based mostly on parameters originating from the interpretation of the polarization data. New high-resolution observations of the α Ori system are necessary for a more accurate determination of the orbit.

b) *The Dust Envelope*

When the exact form of the orbit of the companion is accurately determined, interpretation of the shape of the time dependence of the polarization angle should allow a determination of the geometry of the scattering medium. The observations of α Ori based on interferometric techniques as well as direct IR imaging indicate the presence of strong asymmetry in the dust envelope surrounding this star. Dust grains which form the inner boundary of the extended shell appear to be the most efficient scattering medium in the star envelope (Lefèvre, Bergeat, and Daniel 1982; Lefèvre, Daniel, and Bergeat 1983). Thus, the shape of the polarization angle curve will be strongly influenced by the geometry of the inner part of α Ori's envelope.

An interferometric image reconstruction of α Ori in the visible performed by Roddier and Roddier (1985) shows that in 1980 November there existed an asymmetric circumstellar structure at 1–1.5 stellar radii from the surface of the star. Karovska (1984) inferred from the 1982 February McMath data that at that time there existed a much fainter feature at 2–2.5 stellar radii, which she interpreted as an outward-expanding residue of the structure observed by Roddier and Roddier 15 months earlier. The apparent fading of this dust "envelope" may explain why it was not detected in our more recently recorded interferometric data.

Goldberg (1984) pointed out that during the last 60 yr an unusually large, rapid decrease in the radial velocity of α Ori followed by a short-lived drop in brightness occurred several times. He suggested that these events may be connected with the star's pulsation: the instabilities in the atmosphere would "trigger mass ejection and the formation of dust grains." In order to examine a possible connection of these instabilities with the orbital motion of the close companion, the epochs of the unusually large decreases in radial velocity were compared with the corresponding epochs of the close companion's periastron passage. The epochs we determined from the data presented by Goldberg (1984) are 1926.6, 1938.8, 1944.9, 1961.5, 1978.3 ($\pm$ 0.2 yr). Using the epoch (1980.4 $\pm$ 0.1) and the period (2.08 yr) determined from polarization data, the times of the periastron passage nearest the times when the five events took place were calculated: 1926.3, 1938.8, 1945.0, 1961.7 and 1978.3 ($\pm$0.1 yr). The extremely close agreement between measured and predicted epochs seems to eliminate any possibility of coincidence.

The dust shell observed at 1–1.5 stellar radii in 1980.9 and 15 months later at 2–2.5 stellar radii may have been the result of an outburst from the primary during the companion's periastron passage in 1978.3. The mean velocity of expansion of the ejected matter would then have been ~ 4 km s^{-1} for the first observation and ~ 5 km s^{-1} for the latter. If the mass loss of the star is known, the flow velocity v at the condensation point is given by Draine (1981):

$$v \lesssim 7[\dot{M}_{-6} L_4^{-1/2} (T/3000 \text{ K})^2 (R/r)]^{1/2} \text{ km s}^{-1} ,$$

where $\dot{M}_{-6} \equiv (\dot{M}/10^{-6}\ M_\odot \text{ yr}^{-1})$, $L_4 \equiv (L/10^4\ L_\odot)$, $R \equiv$ stellar radius, $r \equiv$ minimum and condensation radius, $T \equiv$ stellar effective temperature.

We adopt a mass loss rate for α Ori of 10^{-6} $M_\odot$ yr^{-1} (Reimers 1975) and its luminosity as 4.5×10^{-4} $L_\odot$ (assuming $M_b = -6.9$; White 1985). The adopted effective temerature is 3600 K (Scargle and Strecker 1979). With 1.8 stellar radii for the minimum condensation radius (Draine 1981), the upper limit of the flow velocity during grain nucleation is ~ 4 km s^{-1}. This value is consistent with the previously calculated expansion velocities. Once the dust grains are formed, they may well have been accelerated by radiation pressure to a terminal velocity of ~ 10 km s^{-1} (Goldberg 1979). The drop in brightness which follows the minimum in radial velocity may correspond to the time when the ejected gaseous matter condenses into grains and the grains become optically thick in the visible (Goldberg 1984).

Mass ejection from the primary during the companion's periastron passage can account for the origin of dust and gas shells observed in the circumstellar environment of α Ori (Honeycutt *et al.* 1980; Bloemhof, Townes, and Vanderwyck 1984). The fact that outbursts do not occur during each periastron passage suggests that substantial ejection of mass may occur only when the periastron epoch is close in time to the epoch of the maximum expansion velocity of α Ori, i.e., the minimum of its radial velocity relative to Earth. The spectacular decreases in radial velocity occur just after the time of the minimum in the pulsational radial velocity curve ($P = 5.8$ yr; Goldberg 1984). When periastron passage and maximum pulsational expansion do not occur close together, one might expect to observe alternative outfall and infall of matter from the primary due to the tidal effect caused by the companion each time it passes periastron. Some observations (Boesgaard 1979; Van der Hucht *et al.* 1979; Quercy and Quercy 1985) seem to indicate such behavior of the material located between the surface of α Ori and 1–2 stellar radii distance.

The previous discussion leads to the conclusion that the structure which has been observed close to the stellar surface (Roddier and Roddier 1985; Karovska 1984) can be interpreted as a temporarily enhanced concentration of dust grains, a consequence of an outburst of matter from the primary at the epoch when the companion was in periastron. This outburst could create a supplementary asymmetry and anisotropy in the scattering medium which would be responsible for temporary fluctuations in the observed time variation of the angle and the degree of polarization. (See, for example, the variations in the data in Fig. 3 corresponding to epochs at the end of 1979 and the end of 1981). Such events, coupled with the intrinsic long-term variability of α Ori, can explain why the polarization does not exhibit consistent periodic repeatability when directly plotted in the *Q-U* Stokes parameter frame.

c) Other Possible Detections and the Orbit

The interferometric detections of the two bright sources close to α Ori and our study of the polarization data strongly suggest that α Ori is not a single star but a triple stellar system. It is interesting that there are no other claims of detection of the companions in recent high-resolution observations.[1] However, it should be noted that the small angular distances of the companions from α Ori and the large magnitude differences between the companion stars and the primary make the detection extremely difficult. The new two-dimensional photon camera we used for data recording and the techniques for speckle imaging developed for data processing appear to be a powerful tool for this kind of observation. However, as was mentioned earlier, the bright features observed by Goldberg *et al.* (1981) and Roddier and Roddier (1983) may be identified as the companion itself or as a manifestation of the interaction between the close companion and the primary's photosphere.

We made an attempt to predict the position of the companion for the epochs of these observations using the orbit which has been determined in this work. The predicted position angle and distance from the primary for the epoch when Goldberg *et al.* observed α Ori are 214° and 0".059. For the epoch of the Roddier and Roddier observation, the predicted position angle is 196° and the distance 0".051 (Fig. 6). The agreement of the predicted position angles and distances with the observations of the bright structures is striking.

d) Spectral Classification

The absolute magnitude of the companions at 656.8 nm may be inferred from their intensity ratio to the primary. Using the adopted absolute visual magnitude for α Ori of $M_v \approx -5$ and scaling to 656.8 nm using $V - R = 1.64$ (Johnson *et al.* 1966), we find $M_{656.8} \approx -6.6$ for α Ori. Then, for the inner and outer companions we determine $M_{656.8} \approx -3$ and -2 respectively. Given the limited information on color dependence from the data, it is very difficult to determine the spectral class of the two companions. We assume that the companions are coeval with the primary (age of $\sim 10^7$ yr). Then, either hot early-type main-sequence stars or, alternatively, massive cool stars would be in agreement with the evolutionary tracks in the H-R diagram (Novotny 1973).

However, since no indication of the presence of the companions in the spectra of α Ori has been reported, this sets some limits on the spectral class and mass of these objects. The far-UV spectrum of α Ori (*IUE* data from 120 to 300 nm) shows no indication of a continuum due to the presence of a hot companion. The two companions could be luminous, late-type giants (later than G5). This would also be consistent with their high brightness. In spite of their intrinsic brightness, their large magnitude differences from the primary would explain why their spectrum has not been seen in the visible.

The orbit suggested for the close companion ($e \approx 0.35$ and $i \approx 30$) and its inferred mass (4 $M_\odot$) allow calculation of the amplitude of the velocity curve of the primary (≈ 6 km s^{-1}). Detection of a periodic (2.1 yr) variation of the spectrum of α Ori has not been reported to date. This may be due to the fact that the radial velocity of α Ori has only been monitored irregularly (Goldberg 1984). Also, the variation in the spectrum due to the presence of the companion may well be masked by the variations of the photospheric radial velocity of α Ori (period of 5.8 yr and mean amplitude of ~ 6 km s^{-1}; Goldberg 1979). However, if α Ori is less massive than 20 $M_\odot$ the estimated mass of the companion will increase and Doppler shifts of the spectrum of the primary will be detected unless its orbit is characterized by low eccentricity and inclination.

Another possibility for detecting companions from the spectrum is to search for energy emitted by accreting material (Kenyon and Webbink 1984). The energy emitted by a steady state, time-independent accretion disk around a star of mass M and radius R, and for accretion rate $\dot{m}$, is given by $GM\dot{m}/2R$ (Shakura and Sunyaev 1973), where G is the gravitational constant. We assume that, at most, 10% of the mass lost by α Ori during 1 year is accreted by the companion. We adopt the value 10^{-6} $M_\odot$ yr^{-1} for the mass loss for α Ori (Reimers 1975), which gives, for the accretion rate, $\dot{m} = 10^{-7}$ $M_\odot$ yr^{-1}. If the close companion is a late-type giant of mass ~ 5 $M_\odot$ and radius of the order of 10 solar radii, then the energy radiated by the accretion disk would be ~ 1 $L_\odot$. The emitted energy is far below the luminosity of the companion and α Ori itself, so it would not be detected in the spectrum. We note that all the assumptions made for the calculation of the accretion energy are very liberal upper limits. However, at the periastron passage of the close companion, the mass loss from the primary may significantly increase, and the accretion energy may become detectable.

An intriguing question is how a few solar mass object could be coeval with α Ori. The evolutionary time for a single star with a mass comparable to that of the close companion would be substantially longer than that for α Ori (as estimated from evolutionary tracks; Novotony 1973). On the other hand, the proximity of the companion to the primary suggests that the evolution of each of the components cannot be considered separately, and that we are actually dealing with objects which are products of the evolution of a close binary system with mass exchange.

There are many unanswered questions associated with this system. For example, why has the orbit of the close companion not been circularized during the evolutionary time of the system? Since the current orbit of the close companion appears to be totally inside the primary's chromosphere, why hasn't it

[1] R. H. Wilson, Jr., claimed (Pub. Univ. Pennsylvania, Astr. Series, Vol. **6**, part 4, p. 21) detection of a close companion to α Ori; however, his two observations are highly questionable, since he used visual interferometry on only a 45 cm telescope.

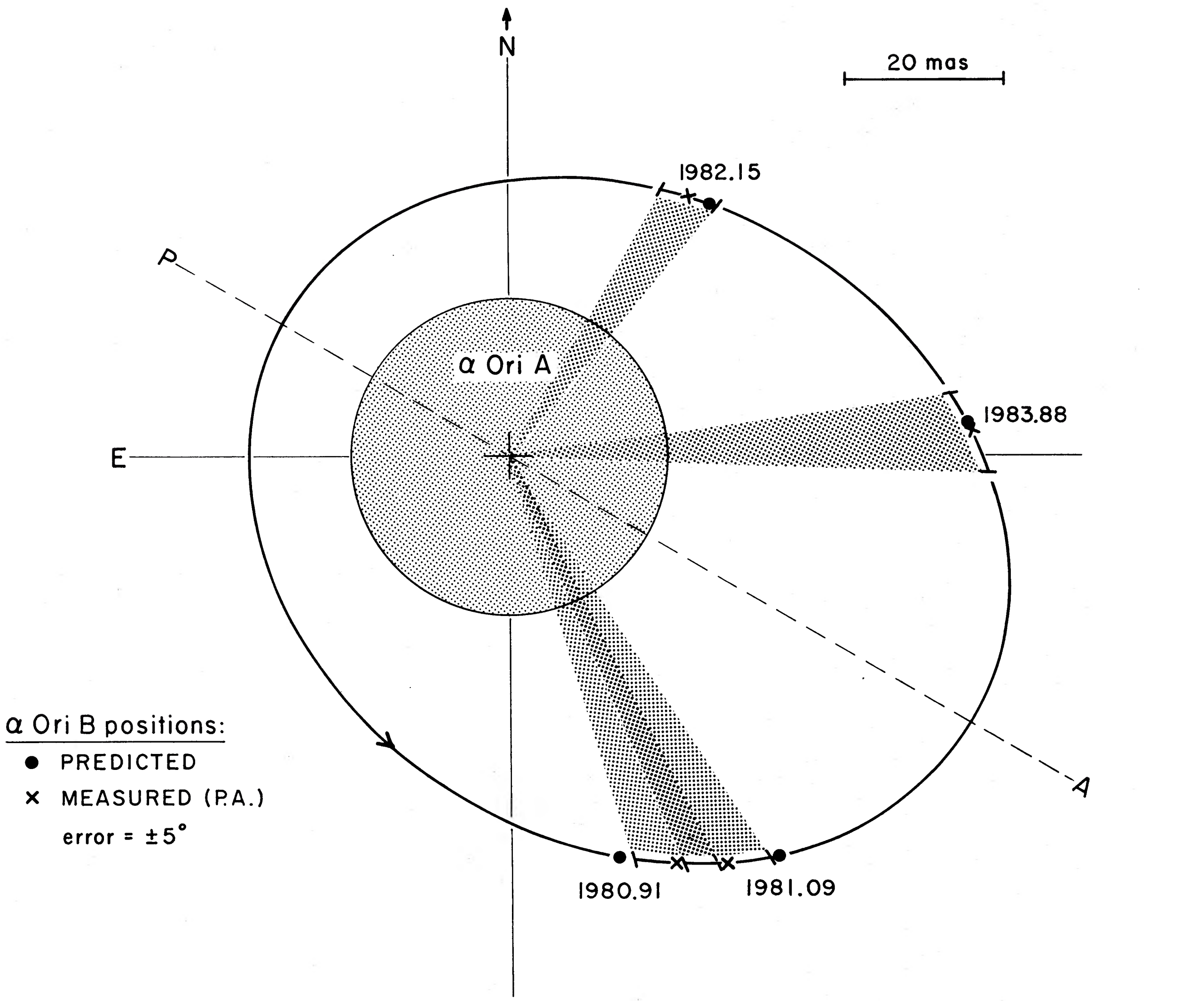

FIG. 6.—Possible orbit for α Ori B. *Circles*: measured positions of the companion in 1982.15 (Karovska 1984) and 1983.88 (this work), and P.A. of the bright features observed in 1980.91 (Roddier and Roddier 1983) and 1981.09 (Goldberg *et al.* 1981). The shaded area corresponds to the error bars in the measurements. *Crosses*: predicted companion's positions on the orbit for the same epochs.

decayed, causing the companion to spiral into the primary? Since α Ori is a massive star, its evolution is very rapid, so it probably has not been in its supergiant stage for very long. If this is the case, until only recently the orbit of the close companion would have been outside the primary's atmosphere, where atmospheric drag would not have affected the orbit.

VII. SUMMARY AND CONCLUSION

Two optical sources in the vicinity of the red supergiant α Ori have been detected with the Steward Observatory 2.25 m telescope using the PAPA camera and the techniques of speckle imaging. The sources were identified with those suggested in 1982 and interpreted as stellar companions to α Ori. In 1983, the companions were located at $0''.06 \pm 0''.01$ and $0''.51 \pm 0''.1$ from the primary at P.A. $273° \pm 5°$ and $278° \pm 5°$ respectively.

Analysis of the available polarization data resulted in a discovery of periodicity in the time-dependent variation of the position angle of the plane of polarization (2.08 yr) and of the degree of polarization (~1 yr). The behavior of α Ori polarization is very similar to that of some close binaries, suggesting that it may be caused by the systemic asymmetry created by the oribital motion of a close companion. A period of 2.08 yr will then correspond to the orbital period of the companion.

Modeling of the polarization data and interferometric positions of the close companion allowed determination of a plausible orbit. This orbit was used to predict the position of the companion for the epochs when Goldberg *et al.* (1981) and Roddier and Roddier (1983) observed a bright feature on the stellar limb and interpreted this structure as a photospheric large-scale convective cell. The predicted and measured angles coincide within error bars, which suggests that they actually may have observed the close companion or its effect on the stellar surface.

Our orbit predicts that at periastron the companion passes only about half a stellar radius above the surface of α Ori, or even closer when the star is near its maximum pulsational expansion. One may expect to see many interesting phenomena when the companion is close to the photosphere of the supergiant: formation of large convective structures on the surface of the supergiant, tidal distortion of the primary, mass ejection from the primary, and possibly, the formation of an accretion disk or envelope around the companion. There is strong evidence that, when the epoch of periastron coincides with the epoch of maximum expansion velocity of α Ori, instabilities induced in the photosphere trigger mass ejection.

Further high-resolution observations are very desirable in order to provide an unambiguous confirmation of the existence of these stellar objects. Future important observational goals would include:

improved accuracy in measurement of the angular diameter of α Ori as well as the distance to this star;

determination of the spectral type of the two companions by multicolor observations;

determination of the orbits and consequently masses of α Ori and its companions;

study of possible interactions between the close companion and the primary, particularly at the epoch of periastron;

search for indications of mass ejection and possible formation of an accretion disk or envelope around the close companion at periastron;

search for tidal distortion of the primary due to the proximity of the companion at periastron;

more accurate measurement of the angular diameter of α Ori in different colors in order to determine its wavelength and time dependencies;

search for large convective cells on the surface, as predicted by Schwarzschild (1975); and

high resolution mapping of the inner boundary of the α Ori dust envelope, providing indispensible information on parameters needed for an accurate modeling of the observed polarization of the system.

In this paper, we believe we have contributed some important new information and insights into the complex nature of the α Ori system. However, there is still an enormous amount to be learned, and a wide variety of observations are required, particularly when the close companion is at periastron (next occurence should be in the fall of 1986). Even more exciting will be observations at the time when the periastron epoch is close to the epoch of the pulsational radial velocity minimum.

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