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THE ORBIT OF THE SPECKLE AND DOUBLE-LINED SPECTROSCOPIC BINARY CHI DRACONIS

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ABSTRACT

We have used high-resolution, high-signal-to-noise-ratio Reticon and CCD observations of the red and near-infrared spectrum of this double-lined spectroscopic binary to measure the first extensive set of secondary velocities and thereby determine a revised spectroscopic mass ratio $\mathscr{M}_1/\mathscr{M}_2 = 1.38$. Analysis of new, and previously published, speckle observations provides the apparent orbit, which, for the first time, can be determined independently of the spectroscopic orbit of the primary. We do adopt for the final visual orbit the spectroscopic period, eccentricity, and epoch of periastron passage, which benefit from the much longer time base of the spectroscopic observations. The analysis of the speckle observations leads to the elements $a = 0\overset{''}{.}122$ and $i = 74\overset{\circ}{.}9$. The high orbital inclination confirms the conclusions of the earlier speckle investigations. These results provide new masses and luminosities for the components: $\mathscr{M}_1 = 1.03\mathscr{M}_\odot$, $L_1 = 1.86L_\odot$, $\mathscr{M}_2 = 0.75\mathscr{M}_\odot$, and $L_2 = 0.29L_\odot$. A significant upward revision of the masses is the principal difference compared with the previous combined speckle-spectroscopic orbital solution. The derived parameters of the components are compared with theoretical isochrones of a slightly metal-poor star. Best agreement is found for an age of 8 billion years. Thus, χ Dra is one of the few systems older than the Sun whose fundamental parameters have been accurately determined, providing a benchmark for evolutionary theory.

I. INTRODUCTION

Wright (Campbell 1898) discovered the spectroscopic binary nature of χ Dra (HR 6929;HD 170153). He soon determined a spectroscopic orbit (Wright 1900) for this nearby ($\pi = 0\overset{''}{.}127$;Breakiron and Gatewood 1974), moderately long-period (280^d) binary composed of an F7 V primary and a fainter late G, or early K, type dwarf secondary. Much more recently, Labeyrie *et al.* (1974) resolved the system as a visual binary by the technique of speckle interferometry. Since then, Bonneau and Foy (1980) and McAlister (1980) have published further speckle investigations of χ Dra. Thus, χ Dra is a nearby main-sequence binary which belongs to that select group of binaries whose periods are long enough for their separation to be measurable by speckle interferometry and, at the same time, are short enough to generate sufficient orbital motion that they are also double-lined spectroscopic binaries. Table I gives the basic data for χ Dra.

Wright's (1900) initial determination of the spectroscopic orbit was followed by an orbit by Crawford (1928) based on additional Lick Observatory observations. Finally, the Lick work culminated in Vinter Hansen's (1942) study, whose orbital elements Batten *et al.* (1978) consider to be definitive. It is of interest to note W. H. Wright's remark, in a forward to Julie Vinter Hansen's investigation, that: "In view of her conclusion that no change has occurred in the orbit of the star during the forty-three years it has been under observation, it seems safe to assume that χ Draconis will not require further observation for radial velocity for a long time." These studies concerned only the primary; Vinter Hansen (1942) reported that: "a careful search for lines of the spectrum of the fainter component failed to reveal them." The first detection of the secondary spectrum was by Spite (1967), who observed secondary lines on 4 Å mm^{-1} photographic plates in the red part of the spectrum. She measured the velocity separation between the primary and secondary spectra on two of these photographic plates and, with the help of the known primary orbit, deduced an estimated mass ratio $\mathscr{M}_1/\mathscr{M}_2 = 1.31 \pm 0.09$.

McAlister's (1980) analysis of the apparent orbit, which was based on 16 speckle observations, resulted in an orbital inclination $i = 79\overset{\circ}{.}9 \pm 0\overset{\circ}{.}9$. This confirmed the high inclination of the earlier, more preliminary, speckle studies (Bonneau and Foy 1980) and ruled out the much lower inclinations of the astrometric studies of χ Dra; Breakiron and Gatewood (1974) measured an inclination of $56\overset{\circ}{.}0 \pm 2\overset{\circ}{.}1$, for example. Although the speckle studies established the high orbital inclination, they all adopted some orbital elements from Vinter Hansen's (1942) definitive spectroscopic orbit, which prompted McAlister (1980) to point out: "the need for a completely independent interferometric orbit when a more favorable distribution of observations becomes available."

The speckle results led to a redetermination of the dimensions of χ Dra's orbit and the fundamental properties of its components. The new masses $\mathscr{M}_1 = 0.88 \pm 0.09\mathscr{M}_\odot$, $\mathscr{M}_2 = 0.67 \pm 0.05\mathscr{M}_\odot$ (McAlister 1980), which were determined from the spectroscopic mass function, mass ratio,

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TABLE I. Basic data for χ Dra.

V	3.57
π^a	0.″120 ± 0.″001
M_V	3.97
Sp. T. (Primary)	F7V
Period	$280.^d5$

[a] Based on the angular size and the spectroscopically determined linear size of the orbit. The trigonometric parallax is 0.″127 ± 0.″006 (Breakiron and Gatewood 1974).

and inclination, are surprisingly low for a system with an F7 V primary and constitute the chief point of interest.

The purpose of the present study is to try and determine the spectroscopic mass ratio and apparent orbit of χ Dra more reliably and, thereby, obtain more reliable measurements of its fundamental properties, especially the masses of its components. We employ high-resolution Reticon and CCD observations of the red and near-infrared spectrum, which provide the first extensive set of secondary velocities and a revised estimate of the mass ratio. Additionally, we analyze new speckle observations which, in combination with the earlier observations, allow a determination of the apparent orbit independent of the spectroscopic orbit. We will see that the technological marvels, which have so benefited astronomical observations in the time since W. H. Wright's (Vinter Hansen 1942) remark that χ Dra would not need "further observation for radial velocity for a long time," have permitted fruitful new observations sooner than expected.

II. OBSERVATIONS

a) Spectroscopic Observations

The observations were made with the McDonald Observatory 2.7 m telescope, coudé spectrograph and Reticon detector (Vogt, Tull, and Kelton 1978). All of these observations, except for three, were centered at 8800 Å, covered 100 Å with a resolution of 0.20 Å, and had signal-to-noise ratios ranging from 100 to 500. The three exceptions were centered at 6425 or 6700 Å and had the same extent, resolution, and signal-to-noise ratios as the near-infrared observations. A modest number of additional observations were secured with the coudé-feed telescope of the Kitt Peak National Observatory 2.1 m telescope and a Texas Instruments CCD detector. These observations were centered at 6425 Å, covered 90 Å with a resolution of 0.23 Å, and had signal-to-noise ratios ranging from 200 to 300. Table II gives detailed information for all these observations, which were made between 1980 and 1984, including the source and central wavelength for each one.

Iota Psc (F7 V) was observed as the radial-velocity standard star. Most χ Dra observations were accompanied by observations of an Fe-Ne comparison source, which were

TABLE II. Radial velocities of χ Dra.

				Primary		Secondary	
JD-2440000	Site	λ(Å)	Phase	RV(km s^{-1})	O-C	RV(km s^{-1})	O-C
4322.954	McD	8800	0.0008	(19.1)	(0.5)	(50.6)	(-0.1)
4356.992	McD	8800	0.1221	12.9	-0.9	---	---
4358.009	McD	8800	0.1257	12.4	-1.7	57.9	0.9
4359.004	McD	8800	0.1293	12.9	-1.5	57.3	0.8
4362.000	McD	8800	0.1400	14.3	-1.0	54.4	-0.8
4472.798	McD	8800	0.5349	(36.3)	(-2.4)	---	---
4484.781	McD	8800	0.5776	(38.0)	(-2.3)	(22.2)	(1.8)
4534.596	McD	8800	0.7552	45.3	0.1	14.0	0.6
4604.568	McD	8800	0.0046	(17.4)	(-0.2)	(52.9)	(0.8)
4606.568	McD	8800	0.0117	(15.1)	(-0.7)	(53.3)	(-1.2)
4626.062	McD	8800	0.0812	11.6	0.7	60.6	-0.8
4627.068	McD	6425	0.0848	12.4	1.3	62.3	1.1
4807.917	McD	8800	0.7294	(43.2)	(-1.6)	(14.2)	(0.1)
4832.723	McD	8800	0.8178	45.8	0.2	10.9	-2.0
4862.840	McD	8800	0.9252	(36.4)	(-1.9)	---	---
4895.605	McD	6425	0.0420	11.6	0.4	59.8	-1.2
4898.564	McD	6700	0.0525	12.2	1.6	61.7	-0.2
5074.950	McD	8800	0.6812	(42.3)	(-1.3)	(16.1)	(0.3)
5104.965	McD	8800	0.7882	45.0	-0.6	13.0	0.1
5157.717	McD	8800	0.9762	(26.5)	(0.7)	(41.3)	(0.7)
5207.747	McD	8800	0.1546	(18.0)	(1.4)	(56.5)	(3.1)
5217.673	McD	8800	0.1899	(20.9)	(1.3)	(51.9)	(2.7)
5220.594	McD	8800	0.2004	(21.9)	(1.4)	(51.1)	(3.0)
5225.576	McD	8800	0.2181	(23.2)	(1.3)	(49.2)	(3.1)
5546.846	McD	8800	0.3633	(30.6)	(-0.4)	---	---
5571.771	McD	8800	0.4521	(33.5)	(-1.8)	---	---
5599.763	McD	8800	0.5519	(37.3)	(-2.0)	(24.9)	(3.2)
5629.678	McD	8800	0.6585	(42.6)	(-0.3)	(18.7)	(2.0)
5755.032	McD	8800	0.1053	13.1	0.7	59.6	0.3
5942.607	KPNO	6425	0.7739	47.6	2.1	14.9	1.8
5960.629	McD	8800	0.8382	44.1	-1.2	12.8	-0.5
5971.633	KPNO	6425	0.8774	(43.2)	(-0.5)	(15.3)	(-0.3)
5971.638	KPNO	6425	0.8774	(43.1)	(-0.6)	(15.1)	(-0.5)
5972.605	KPNO	6425	0.8808	(44.0)	(0.5)	(16.3)	(0.4)
5972.611	KPNO	6425	0.8809	(43.8)	(0.3)	(16.1)	(0.2)
5974.631	KPNO	6425	0.8881	(44.2)	(1.3)	(18.0)	(1.3)

Note to TABLE II

Velocities from near maximum separation of the primary and secondary spectra are unparenthesized, other velocities are in parentheses. Phases are from the solution of the Lick and maximum separation modern primary velocities (solution 4 of Table III); the O − C are for the solutions of the maximum separation modern velocities for V_0 and K_1 or K_2 with these phases and other elements from solution 4.

used to link the χ Dra observations to the ι Psc observation as part of the radial-velocity measurement procedure. The remainder of the observations were accompanied by their own ι Psc observations, rather than Fe-Ne observations.

The χ Dra observations have sharp, well-defined lines from the spectra of both the primary and secondary components. Figure 1 shows two observations made near maximum separation of the primary and secondary lines on the two branches of the velocity curve. We note that because of the appreciable orbital eccentricity ($e = 0.45$) the separation of the primary and secondary lines for the branch of the velocity curve that includes periastron is significantly greater than it is for the branch of the velocity curve that includes apastron. Inspection of Fig. 1 shows that near maximum separation on the periastron branch, the primary and secondary lines are completely resolved, and near maximum separation on the apastron branch, they are almost completely resolved.

b) Speckle Interferometric Observations

Speckle observations providing direct resolution of χ Dra were first obtained in 1973 by Labeyrie *et al.* (1974) at the 5 m Hale telescope. The system has been regularly observed since that time with telescopes ranging in size from the 1.9 m telescope of the Observatoire de Haute-Provence to the 6 m telescope of the Special Astrophysical Observatory. The majority of the observations have been gathered at the 4 m Mayall reflector on Kitt Peak. At the present time there are 33 resolved speckle measurements, along with an additional three epochs at which the secondary was not seen, available for analysis. These data are collected in Table IV, where the position angles have been precessed to equinox 2000.0. The available data have thus doubled in quantity since the orbital analysis by McAlister (1980). The circumstances of the individual observations can be found by consulting the source references. All the data were reduced by the standard methods of speckle interferometry in which the position angles possess a 180° ambiguity. We adopt quadrants so as to be consistent with the sense of motion in the astrometric orbit.

In collecting these measurements together, we noticed a significant discrepancy in the published position angle of 206°.5 for the observation obtained on 1981.4626 in comparison with three other measurements of χ Dra from the same observing run. Inspection of the measurement records for the reduced power spectra showed that a 10° error was made in the conversion to position angle. The value of θ for the epoch 1981.4626 has, therefore, been corrected in Table IV.

III. MEASUREMENT AND ANALYSIS OF RADIAL VELOCITIES

The radial velocities were measured by the same procedure described in Tomkin (1983). The key step in the procedure is the measurement of the velocity difference between the program star and a standard star by cross correlation of the profiles of selected lines in the program-star spectrum with the same lines in the standard-star spectrum. The adopted velocity of ι Psc, the standard star, is 5.3 km s^{-1} (Pearce 1955).

We note that over a large part of the orbit, the primary and secondary lines are only partially resolved. For this reason and because our observations are in the near infrared, where the primary spectrum is less dominant than it is in the blue, our primary velocities of these phases may be more perturbed by the secondary lines than Vinter Hansen's (1942) blue observations were. Therefore, the spectroscopic orbit of the primary based on the solution of our primary velocities alone may not be as reliable as Vinter Hansen's (1942). The

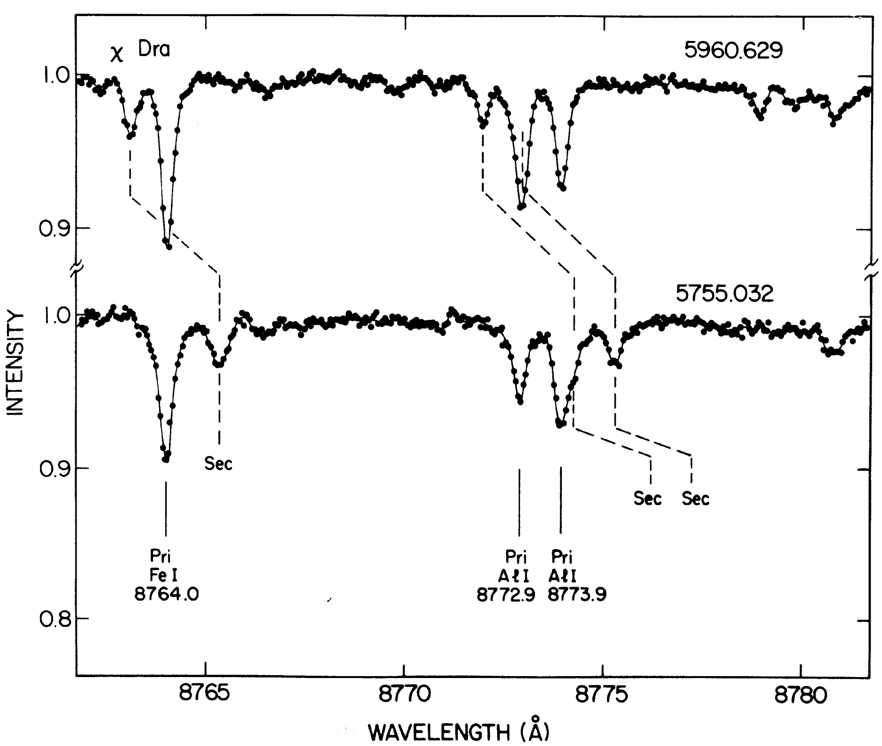

FIG. 1. Sections of two near-infrared observations of χ Dra identified by their Julian Dates (− 2,440,000). The wavelength scale is for the primary and the intensity scale is expanded. Three lines in the primary and their counterparts in the secondary are identified. Note that because of the significant orbital eccentricity ($e = 0.45$), the separation of corresponding primary and secondary lines is appreciably greater in the lower observation, whose phase (0.1053) is near maximum separation for the periastron branch of the velocity curve, than it is in the upper observation, whose phase (0.8382) is near maximum separation for the apastron branch of the velocity curve.

main purpose of our investigation is to make reliable measurements of the semiamplitudes (K_1 and K_2) of the primary and secondary velocity curves. These elements are determined by observations at phases near maximum separation of the primary and secondary lines. As we have seen, at these phases the lines are completely separated so, although our velocities may not provide reliable values for all orbital elements, they do provide reliable values of K_1 and K_2.

We also note that the question of resolution of corresponding primary and secondary lines depends on the strengths of the lines, as well as the size of the Dopper-induced wavelength difference between the primary and secondary spectra. For a given wavelength separation, the mutual overlap of corresponding weak lines is less than it is for strong lines, and so weak lines tend to provide the more reliable velocities. For this reason, our velocity measurements used weak lines, such as those shown in Fig. 1. Table II gives the measured primary and secondary velocities.

We ran separate orbital solutions of the modern primary and secondary velocities (Table III, solutions 2 and 5, respectively) and compared the results with those from an identical solution of the Lick primary velocities (Table III, solution 1) obtained by running all the Lick velocities (Vinter Hansen 1942) through the same program. Comparison of the three sets of orbital elements (see Table III) from the solutions of these three sets of velocities shows overall agreement, but also significant discrepancies. The values of V_0 (systemic velocity) of 31.6 ± 0.2 and 33.3 ± 0.2 km s^{-1} from the solutions of the modern primary and secondary velocities, respectively, disagree with each other—in principle, they should be identical—and with the value of 32.5 ± 0.1 km s^{-1} from the solution of the Lick velocities. Also, the primary K (semiamplitude) of 17.2 ± 0.2 km s^{-1} from the modern velocities is significantly less than the value of 17.9 ± 0.1 km s^{-1} derived from the Lick velocities. Inspection of the primary and secondary velocity curves (Fig. 2) shows they are distorted because the primary and secondary velocities from observations in which the primary and secondary lines are only partially resolved are dragged together by the mutual blending of the lines on which they are based. We therefore made a second set of separate solutions of the modern primary and secondary velocities for V_0, K_1, and K_2 alone, based on velocities from observations made near maximum separation of the primary and secondary spectra. Table II and Fig. 2 show the classification of individual velocities as 'maximum separation' or 'other.' The phases and all other elements for these solutions were fixed with the values from the solution of a combination of the Lick and maximum-separation modern primary velocities, which is given as solution 4 in Table III.

The results—see Table III—from the solutions of the limited set of modern primary and secondary velocities for V_0, K_1, and K_2 are much more satisfactory: The disagreement between the V_0 of 32.2 ± 0.4 and 31.7 ± 0.3 km s^{-1} for the primary and secondary velocities, respectively, is insignificant, and the 32.0 km s^{-1} mean V_0 is not significantly different from the Lick V_0 of 32.5 km s^{-1}. The K_1, which for the solution of all modern primary velocities was 17.2 ± 0.2 km s^{-1}, increases to 17.6 ± 0.4 km s^{-1} and is only marginally less than the 17.9 ± 0.1 km s^{-1} Lick K_1. The K_2, which for the solution of all secondary velocities was 24.2 ± 0.2 km s^{-1}, also increases to 24.6 ± 0.3 km s^{-1}, which is the value we adopt.

Figure 2 shows the primary and secondary velocities fitted with the calculated velocity curves for the solutions of the limited set of velocities for V_0, K_1, and K_2 alone.

We conclude that, with the exception of the period, our primary velocities do not allow any significant improvement of the already definitive Vinter Hansen (1942) orbit for the primary, which is based on a large number (75) of high-quality Lick velocities. The lengthened time base, which now extends from 1898 to 1984, gives a refined period of $280^d550 \pm 0.008$ (Table III, solution 4). Our secondary velocities provide $K_2 = 24.6 \pm 0.3$ km s^{-1}. This, combined with $K_1 = 17.87 \pm 0.10$ km s^{-1} (Table III, solution 4), gives a mass ratio $\mathscr{M}_1/\mathscr{M}_2 = 1.38 \pm 0.02$, which is larger, and more reliable, than Spite's (1967) estimate of 1.31 ± 0.09.

IV. ANALYSIS OF THE VISUAL ORBIT

Although the speckle measurements cover some 16 orbital revolutions, the much longer time span of the spectroscopic material (corresponding to more than 110 revolutions) as well as the nonuniform distribution in θ of the speckle measurements led us to adopt the spectroscopically

TABLE III. Radial-velocity orbits of χ Dra.

	Primary solutions				Secondary solutions	
	Lick	All modern	Max. sep. modern[a]	Lick & max. sep. modern[b]	All modern	Max. sep. modern[c]
P (days)	280.534 ±0.011	280.0 ±0.3	---	280.550 ±0.008	280.7 ±0.2	---
V_0(km s^{-1})	32.49 ±0.10	31.65 ±0.16	32.2 ±0.4	32.43 ±0.09	33.3 ±0.2	31.7 ±0.3
K (km s^{-1})	17.93 ±0.13	17.2 ±0.2	17.6 ±0.4	17.87 ±0.10	24.2 ±0.2	24.6 ±0.3
e	0.451 ±0.006	0.458 ±0.011	---	0.445 ±0.005	0.415 ±0.008	---
ω	122.1 ±1.1	115.8 ±2.0	---	121.7 ±1.0	292.2 ±1.5	---
T (periastron) -2400000	30294.9 ±0.6	46001.7 ±1.7	---	46006.0 ±0.7	46003.2 ±1.2	---

[a] Solution for V_0 and K only; all other elements fixed with values from solution of Lick + maximum-separation modern primary velocities.
[b] Adopted primary solution.
[c] Adopted secondary K. Solution for V_0 and K only; all other elements fixed with values from solution of Lick + maximum-separation modern primary velocities ($\omega_{sec} = \omega_{pri} + 180$).

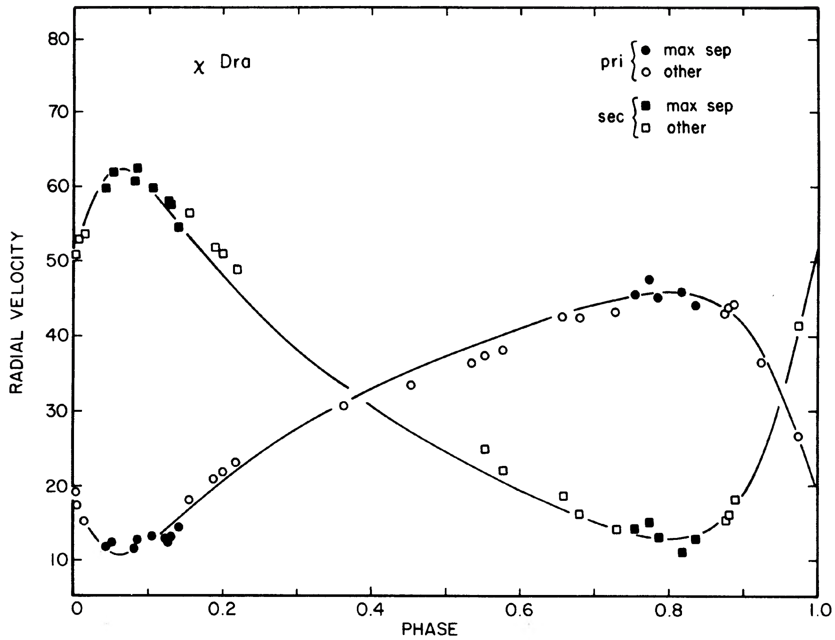

FIG. 2. Primary and secondary velocity curves.

determined values for the period, eccentricity, and time of periastron passage in the determination of the visual orbit. A completely independent orbital solution of the speckle data was carried out for comparison purposes, but the differential correction solution tended to converge to local minima depending on the starting value of the inclination. The local minimum giving the smallest dispersion in the residuals (solution A in Table V) yielded a period of 280.684 ± 0.023 days in comparison with the spectroscopic period of 280.550 ± 0.008 days. The difference of 0.134 ± 0.024 days amounts to only 0.05% of the period and is testimony to the high level of consistency between the spectroscopic and speckle data. The element ω has also been determined independently of the radial velocities and offers another point of comparison between the independent visual and spectroscopic orbits. The two values of ω differ by $3^\circ\!.6 \pm 1^\circ\!.2$. Although the difference exceeds the error range for the two values, we consider the discrepancy of $3^\circ\!.6$ to be small for orbits calculated from entirely different kinds of material. We also note that this discrepancy decreases to $2^\circ\!.5 \pm 1^\circ\!.2$ when solution C in Table V, the adopted solution for the visual orbit, is compared with the spectroscopic orbit.

In choosing to adopt the spectroscopic elements P, T, and e, we are left with only the need to calculate values for the elements a, i, ω, and Ω. This was carried out by a differential corrections solution to the Thiele-Innes elements A, F, B, and G (see, for example, Heintz 1978). We omitted four of the observations in Table IV from the adopted solution because of their relatively lower accuracy in comparison with the remaining sample of 29 measurements. Three of the measurements, those for 1977.6400, 1978.3935, and 1978.3945, were obtained by telescopes with 2 m class apertures and can be expected to have significantly less accuracy than speckle observations at 4 m or larger telescopes for small angular separations such as those shown by χ Dra. Two of these measurements do, in fact, show rather large residuals to the final orbital solution.

A fourth speckle measurement, that for 1983.0703, shows the largest measured angular separation, a result called into question by the fact that this observation was obtained with an ISIT camera as the detector rather than the usual ICCD camera employed with the GSU/CHARA speckle camera system. The ISIT was used during part of one observing run following the failure of the CCD that had been routinely employed up until that time. We subsequently found that the scale calibration of that ISIT data wandered significantly with gain setting and telescope orientation, as can be expected for detectors of this type. Because of the absence of data collected at that time for comparison binaries at high declinations similar to that of χ Dra, we suspect that the scale for this particular data sample was distorted by local magnetic field effects. This distortion could induce a system calibration offset of 5%–10% in scale, and we consequently chose to omit this particular measurement from the adopted orbital solution even though the residuals turned out not to be particularly large.

The results of three solutions for the visual orbit are given in Table V. Solution A is the visual orbit with the smallest dispersion in the residuals that was determined completely independently of the spectroscopic elements and excludes the four speckle measurements described above. Solutions B and C adopt the spectroscopic elements for P, T, and e and calculate the remaining visual elements from the speckle observations. Solution B includes all the speckle data, while solution C omits the four observations of suspected lower accuracy. Solution C also shows the smallest dispersions in the x and y residuals. We adopt solution C as the most likely set of visual elements for χ Dra. The speckle observations are shown against the adopted visual orbit in Fig. 3.

The predicted angular separations and position angles for the three epochs at which χ Dra was reported as unresolved are shown in parentheses in Table IV. The expected separation for 1979.4601 is consistent with the resolution limit for that observation, but the separations for 1975.625 and 1976.397 should have been resolvable at the 5 m telescope. Labeyrie's negative results for those two epochs are reported by Bonneau and Foy (1980) without giving the details as to observed wavelength, seeing conditions, hour angles, etc.

TABLE IV. Speckle observations of χ Dra and orbit residuals.

Epoch	θ	ρ	$\Delta\theta$	$\Delta\rho$	Tel. Apert.	Source
1973.2080	240°0	0″096	+3°8	-0″007	5m	Labeyrie et al (1974)
1973.4520	70.0	0.077	-2.4	+0.003	5	"
1973.7580	218.0	0.115	+3.1	-0.005	5	"
1975.625		<0.028	(32.9)	(0.044)	5	Labeyrie (Bonneau & Foy 1980)
1975.7151	63.5	0.090	+1.6	+0.005	4	McAlister (1977)
1976.2991	242.0	0.078	+2.4	-0.009	4	McAlister (1978)
1976.397		<0.028	(35.8)	(0.048)	5	Labeyrie (Bonneau & Foy 1980)
1976.4494	53.2	0.088	-1.2	+0.003	4	McAlister (1978)
1976.4548	53.9	0.082	-1.7	-0.004	4	"
1977.4818	194.3	0.053	+2.3	-0.015	4	McAlister (1979)
1977.4872	189.9	0.057	-3.9	-0.014	4	"
*1977.6400	217.6	0.125	-1.6	-0.007	2	McAlister & Hendry (1982a)
1977.7411	226.9	0.136	-1.0	-0.001	4	McAlister & Fekel (1980)
*1978.3935	224.6	0.119	+6.8	-0.009	2	Bonneau & Foy (1980)
*1978.3945	221.6	0.116	+3.7	-0.012	2	"
1978.5410	229.6	0.124	-1.3	-0.004	4	McAlister & Fekel (1980)
1978.6147	244.5	0.071	+2.1	-0.005	4	"
1979.3600	238.3	0.095	+0.9	-0.002	4	McAlister & Hendry (1982b)
1979.3628	237.5	0.094	-0.4	-0.001	4	"
1979.4601		<0.080	(27.4)	(0.037)	2	Bonneau et al (1980)
1979.5321	54.0	0.094	-2.7	+0.008	4	McAlister & Hendry (1982b)
1980.4769	141.2	0.046	-1.8	+0.004	4	McAlister et al (1983)
1980.7172	218.6	0.136	-1.0	+0.003	4	"
1980.7199	218.1	0.136	-1.8	+0.003	4	"
1980.7255	219.6	0.136	-0.8	+0.001	4	"
1981.4626	216.5	0.134	-1.0	+0.007	4	McAlister et al (1984)
1981.4652	216.4	0.130	-1.3	+0.002	4	"
1981.4680	218.6	0.130	+0.6	+0.001	4	"
1981.4734	218.5	0.139	-0.0	+0.009	4	"
1981.6838	241.7	0.080	+0.2	+0.001	6	Balega et al (1984)
1981.7001	251.1	0.055	+4.3	-0.007	4	McAlister et al (1984)
*1983.0703	224.5	0.149	+0.6	+0.008	4	McAlister et al (1987)
1983.3208	41.9	0.056	+0.0	-0.004	6	Balega & Ryadchenko (1984)
1983.7152	211.6	0.119	+0.2	+0.009	4	McAlister et al (1987)
1984.7009	233.2	0.118	+0.7	-0.003	4	"
1985.4846	238.1	0.115	+3.8	+0.003	4	"

*Observation excluded from orbit solution
Position angles have been precessed to equinox 2000.0

Experience at Kitt Peak with the GSU/CHARA speckle program has shown that, for binaries of large magnitude differences, separations near the diffraction limit are more difficult to detect than would be the case for small magnitude differences. Such circumstances may explain the negative results in question.

The elements of principal interest in Table V are the semimajor axis and the orbital inclination. The high inclination found by Bonneau and Foy (1980) and McAlister (1980) is now well established in contrast to the much lower inclination of the astrometric orbit of Breakiron and Gatewood (1974). The revised inclination we now report is 5° less than

TABLE V. Apparent visual orbits of χ Dra.

Element	Orbit solution A	B	C (adopted)
P(days)	280.684 ± 0.023	280.550[a]	280.550[a]
T − 2400000	46004.6 ± 1.8	46006.0[a]	46006.0[a]
e	0.411 ± 0.003	0.445[a]	0.445[a]
a	0″125 ± 0″001	0″122 ± 0″002	0″122 ± 0″001
i	75°1 ± 0°9	75°4 ± 1°0	74°9 ± 0°9
ω	118°1 ± 0°7	118°8 ± 0°8	119°2 ± 0°7
Ω	227°7 ± 0°7	231°6 ± 0°8	231°5 ± 0°7
σ_x	± 0″0069	± 0″0074	± 0″0065
σ_y	± 0″0056	± 0″0042	± 0″0039

[a] element adopted from the spectroscopic orbit.

Notes to TABLE V

Solution A: 29 speckle observations were used to calculate the visual orbit independent of the spectroscopic elements.
Solution B: 33 speckle observations were used to calculate the visual orbit after adopting the spectroscopic values for P, T, and e.
Solution C: 29 speckle observations were used to calculate the visual orbit after adopting the spectroscopic values for P, T, and e.

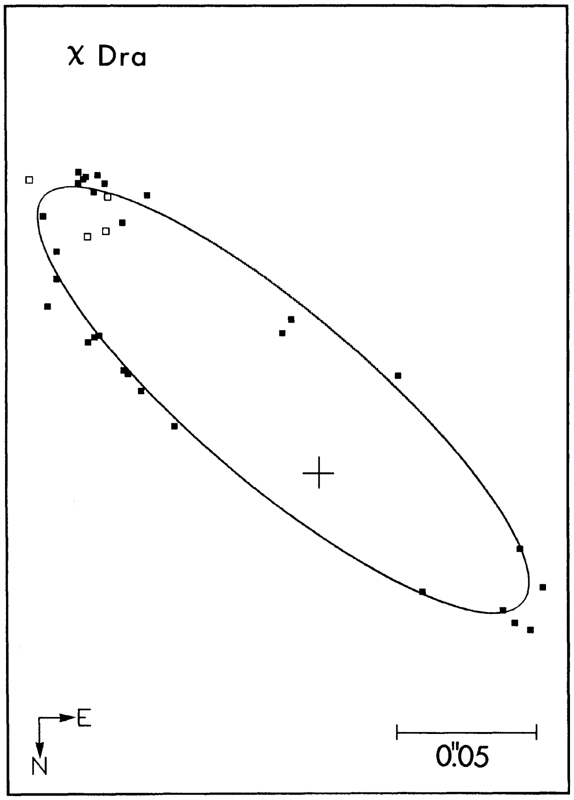

FIG. 3. Speckle measurements of χ Dra are shown against the visual orbit determined from the observations plotted as dark squares. Light squares indicate speckle observations with suspected lower accuracies that were not included in the orbit determination.

that found by McAlister (1980) and is virtually identical to the value of 75°.0 ± 2°.5 found by Bonneau and Foy (1980). The variation in the inclination for the three values in Table V is small and would translate into a difference in total mass of less than one percent between the extreme values of solutions B and C. The variation in the semimajor axis amounts to a discrepancy in distance, when applied to the spectroscopic $a \sin i$, of only 2.4%. The visual orbit of χ Dra can only be improved over the current determination by observations secured in the position-angle range 90°–210°.

V. DISTANCE, MASSES, AND LUMINOSITIES

With the combined elements from the spectroscopic and visual orbits now in hand, we can directly determine the physical parameters for the system. The spectroscopically determined quantity $a \sin i = 0.981 \pm 0.008$ AU combines with the angular semimajor axis $a = 0.''122 \pm 0.''001$ and the inclination $i = 74.^\circ9 \pm 0.^\circ9$ to give a geometrically determined distance of 8.33 ± 0.10 pc. This revised distance represents an increase of 6.5% over the distance found by McAlister (1980) and results in a distance modulus of $m - M = -0.40 \pm 0.03$ mag. This result implies that the components of χ Dra have absolute magnitudes 0.13 mag brighter than those deduced by McAlister (1980).

The masses of the individual components were found by combining the spectroscopically determined quantities $\mathscr{M}_1 \sin^3 i = 0.926 \pm 0.020$ and $\mathscr{M}_2 \sin^3 i = 0.673 \pm 0.013$ $\mathscr{M}_\odot$ with the interferometrically determined quantity $\sin^3 i = 0.900 \pm 0.011$ to yield $\mathscr{M}_1 = 1.03 \pm 0.03$ and $\mathscr{M}_2 = 0.75 \pm 0.02$ $\mathscr{M}_\odot$. These new mass determinations mean that the primary is slightly more massive than the Sun and, as we will see later, remove the discrepancy between the mass of the primary and its luminosity.

We used the 6425 Å spectra to estimate the fractional luminosities of the components, and thence, their magnitude difference, at this wavelength. This was done with the aid of a program (Barden 1985) that combined the spectra of two individual stars, chosen beforehand, to represent the primary and secondary of χ Dra, and adjusted their fractional luminosities for a best fit with the observed χ Dra spectrum. Choice of a star to represent the primary (F7 V) was straightforward and a comparison of potential secondary representatives with χ Dra indicated that the spectral type of the secondary must be between G8 V and K2 V. Fractional luminosities of 0.825 and 0.175, or 0.859 and 0.141, were determined according to whether a G8 V or a K2 V star was used to represent the secondary. Fractional luminosities of 0.84 and 0.16, which are an average of these results and correspond to the adoption of an intermediate K0 V spectral type for the secondary, were adopted. The corresponding magnitude difference is 1.80 mag.

The $V - R$ colors for F7 V and K0 V spectral types (Johnson 1966) were then used to convert this magnitude difference, which is at 6425 Å, into a magnitude difference of 1.99 in V. This supports the V magnitude difference of 2.07 mag determined by McAlister (1980) on the basis of the effective temperatures, surface gravities, and masses of the components. We adopt the magnitude difference of 1.99, in view of its more direct derivation.

Employing the same discussion of bolometric corrections as that of McAlister (1980), the revised 1.99 V magnitude difference, and distance modulus of $m - M = -0.40 \pm 0.03$ mag, we summarize the astrophysical parameters for the χ Dra system in Table VI. We continue to adopt Spite's (1967) evaluation of the effective temperatures of the component stars.

On the basis of the earlier speckle studies, Popper (1985) pointed out that the primary of χ Dra is the only main-sequence late F type star of mass less than that of the Sun whose luminosity exceeds the Sun's. With the aid of the revised parameters for χ Dra, particularly the masses of 1.03 ± 0.03 and 0.75 ± 0.02 $\mathscr{M}_\odot$, which show that the primary is marginally greater than $1 \mathscr{M}_\odot$, we reconsider this question.

TABLE VI. Mass-luminosity results for χ Dra.

	Primary	Secondary
$M/M_\odot$	1.03 ± 0.03	0.75 ± 0.02
$\log (M/M_\odot)$	+0.013 ± 0.013	-0.125 ± 0.011
M_{bol}	4.07 ± 0.12	5.74 ± 0.27
M_V	4.12 ± 0.12	6.11 ± 0.27
$L/L_\odot$	1.86 ± 0.18	0.29 ± 0.08
$\log (L/L_\odot)$	0.270 ± 0.047	-0.541 ± 0.105
T_{eff}(K)*	6150	4940

* from Spite (1967).

Figure 4 compares the positions of the primary and secondary in the H-R diagram with the 8 billion year isochrone (VandenBerg 1985) for $Z = 0.010$. This Z, which corresponds to [Fe/H] = −0.23, is appropriate for the modest metal deficiency ([Fe/H] = −0.3) of χ Dra (Spite 1967). The thick-line sections of the isochrone correspond to the 1.03 ± 0.03 and $0.75 \pm 0.02 \mathscr{M}_\odot$ masses and the lengths of the isochrone associated with the estimated errors of the masses. The primary and secondary are expected to be of the same age and therefore, in principle, should lie on the appropriate mass sections of the same isochrone. The primary lies very close to its section of the 8 billion year isochrone, while the secondary lies at a marginally inconsistent distance above its section of the isochrone. The separation of the secondary from the isochrone is not so large as to indicate a real anomaly, but, rather, suggests that the M_v and effective-temperature errors of this faint component may have been underestimated or that there may be significant uncertainty in the isochrones of low-mass stars.

VI. CONCLUSIONS

We have used secondary velocities, measured from red and near-infrared spectra, to make the first determination of the secondary's semiamplitude ($K_2 = 24.6$ km s^{-1}) based on an extensive set of velocities. An independent determination of the visual orbit from new, and previously published, speckle observations is in satisfactory agreement with the spectroscopic orbit. The final visual orbit, which adopts the spectroscopic period, eccentricity, and epoch of periastron passage, leads to the elements $a = 0''.122$ and $i = 74^\circ.9$. The spectroscopic minimum masses combined with the inclination from the visual orbit provide masses of $\mathscr{M}_1 = 1.03$ and $\mathscr{M}_2 = 0.75 \mathscr{M}_\odot$.

The position of the primary in the H-R diagram is consistent with the 8 billion year isochrone of VandenBerg's (1985) evolutionary models, while the position of the secondary is slightly inconsistent with the same isochrone. This age estimate, which means that χ Dra is somewhat older than the Sun, is in keeping with χ Dra's modest metal deficiency ([Fe/H] = −0.3; Spite 1967) and is consistent with its identification as an old-disk star (Spite and Spite 1982). As such, χ Dra's parameters provide an important benchmark for comparison with theory.

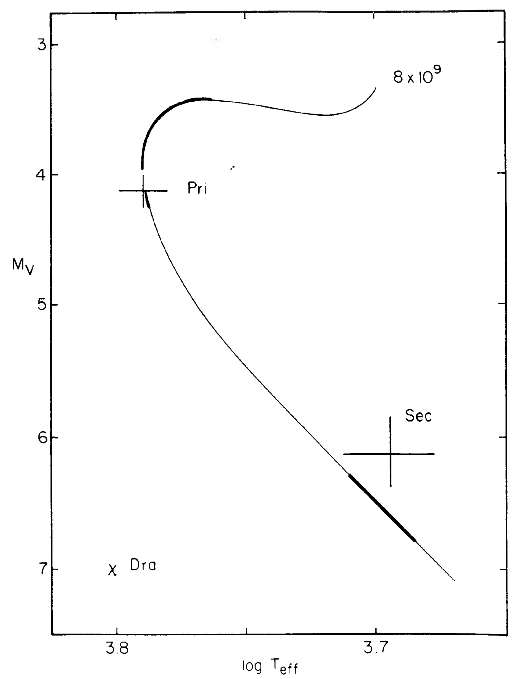

FIG. 4. The primary and secondary of χ Dra compared with the 8 billion year isochrone for $z = 0.01$ ([Fe/H] = −0.23). The sizes of the crosses show the observational errors, which for the primary and secondary effective temperatures were estimated to be ±150 and ±200 K, respectively. The thick-line sections of the isochrone locate the 1.03 ± 0.03 and $0.75 \pm 0.02 \mathscr{M}_\odot$ masses of the primary and secondary, and the lengths of the isochrone associated with the estimated errors.

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