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PHOTOMETRY AND POLARIMETRY OF THE UNUSUAL WN5 STAR EZ CANIS MAJORIS

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ABSTRACT

We present new high-precision polarimetric data, based on four observing runs spanning 16 months, and a nearly contiguous 62 night photometric run of the unique Wolf-Rayet star of type WN5, EZ CMa. Even though the shape of the polarization curve changes from one run to the next, the previously known 3.77 day period is always present in each run of data. Moreover, the scatter around a relatively simple curve fitted through the polarization data in each run separately is remarkably low. The light curve behaves in a similar way: the scatter is very low over a 2 week interval in the $3^{d}.77$ phased modulation, but the shape changes gradually during the two month interval. No significant circular polarization variation was detected.

The data are interpreted in terms of a binary system with a low-mass (probably compact) companion or rotating spots on a single star. The former is preferred; if correct, EZ CMa would fill the heretofore missing link in the evolution of massive binaries.

Subject headings: polarization — stars: binaries — stars: individual (EZ CMa) — stars: Wolf-Rayet

I. INTRODUCTION

It is now well known that most Wolf-Rayet (W-R) stars show some intrinsic photometric variability. The amplitude of the variations is largest for the coolest subtypes: WN7 and especially WN8 among WN stars, and WC9 among WC stars (see Moffat and Shara 1986; Lamontagne and Moffat 1987; van Genderen, van der Hucht, and Steemers 1987). Recently, it has also been shown that, with the exception of a few hot WCE stars, all W-R stars observed so far vary in polarization (Drissen *et al.* 1986*a*, *b*, 1987; St.-Louis *et al.* 1987, 1988; Robert *et al.* 1989; Schulte-Ladbeck and van der Hucht 1989). In most cases, these polarimetric fluctuations are random, and, as in the case of photometric behavior, the polarization amplitudes are largest (up to 0.8%) for the slow-wind, cool, WN8 stars. These variations are thought to be caused by asymmetries, such as blobs of ejected material or instabilities, propagating outward in the winds of the stars. Most well-known W-R+O binaries show a double wave per orbital cycle in polarization as predicted by the electron scattering model of Brown, McLean, and Emslie (1978). They also often show phase-dependent light modulation, with amplitude depending on the orbital inclination and separation (Moffat and Shara 1986).

The WN5 star EZ CMa (HD 50896; WR 6 in the catalog of van der Hucht *et al.* 1981) is unique among W-R stars. The shape and amplitude of its photometric light curve changed dramatically between 1975 and 1980, but seems to have been more or less stable since then (Firmani *et al.* 1980; Cherepashchuk 1981; Lamontagne, Moffat, and Lamarre 1986, hereafter LML) and always shows the same 3.77 day period. A more recent light curve (van Genderen *et al.* 1987) still shows the same pattern (one high and two low maxima) and period but is shifted in phase by about 0.35 compared to the previous light curves.

This period is also present in some spectroscopic data (Firmani *et al.* 1980; Niemela and Mendez 1981), but variations in the P Cygni profile of N IV λ1718, the most strongly varying line in the UV, show no systematic phase dependency (Willis *et al.* 1986, 1989). The polarization curve obtained by McLean (1980) is also consistent with a $3^{d}.77$ period and shows a double wave with an amplitude of 0.3%.

These observations, especially the polarimetry, strongly suggest that EZ CMa is probably a binary system, in which case the mass function derived by Firmani *et al.* (1980) gives a secondary of $\approx$1–2 $M_{\odot}$, assuming a mass of 10 $M_{\odot}$ for the WN5 star. If the binary hypothesis is correct, the unseen companion would likely be a neutron star. The X-ray flux of EZ CMa, although not extraordinarily intense compared to other W-R stars, has been shown to be strongly variable, either on long or short time scales (a factor of 3 over 2 yr, see Pollock 1987; a factor of 2 within 30 minutes, see White and Long 1986; see, however, Pollock 1988 for a discussion of the statistical significance of these variations). Nichols-Bohlin and Fesen (1986) rejected a physical association between HD 50896 and the supernova remnant surrounding it because of a difference in distance estimate between the two objects (although 1.0 $\pm$ 0.5 kpc for the SNR overlaps with 1.5 kpc for the W-R star, assuming an error of $\sigma \sim 0.5$ mag for the W-R distance modulus). The same conclusion was reached by Howarth and Phillips (1986). New estimates of the absolute magnitude of HD 50896 lead to distances in the range from 1 to 2 kpc (Hamann, Schmutz, and Wessolowski 1988; Smith and Maeder 1989).

Although the $3^{d}.77$ periodicity is now well documented, and many observations tend to support the binary hypothesis, the

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TABLE 1

JOURNAL OF THE POLARIMETRIC OBSERVATIONS

Julian Date (2,446,000+)	P (%)	σ_p (%)	θ	σ_θ	Q (%)	U (%)	ref*
363.003	0.787	0.012	160°.3	0°.4	0.608	-0.500	1
363.947	0.268	0.018	161.2	1.9	0.212	-0.164	1
364.005	0.292	0.019	160.5	1.9	0.227	-0.184	1
364.939	0.210	0.008	171.6	1.1	0.201	-0.061	1
364.974	0.234	0.008	167.2	1.0	0.211	-0.101	1
365.028	0.268	0.011	170.0	1.2	0.252	-0.092	1
365.933	0.498	0.010	185.8	0.6	0.488	0.100	1
365.985	0.544	0.012	187.1	0.6	0.527	0.133	1
366.913	0.734	0.010	154.9	0.4	0.470	-0.564	1
366.922	0.704	0.015	153.1	0.6	0.416	-0.568	1
367.003	0.672	0.006	151.9	0.3	0.374	-0.558	1
367.921	0.257	0.011	165.4	1.2	0.224	-0.125	1
367.940	0.224	0.013	163.6	1.7	0.188	-0.121	1
367.956	0.268	0.009	167.3	1.0	0.242	-0.115	1
367.974	0.306	0.009	167.7	0.8	0.278	-0.127	1
367.991	0.328	0.008	162.3	0.7	0.267	-0.190	1
368.009	0.311	0.012	163.5	1.1	0.261	-0.169	1
368.027	0.361	0.007	167.5	0.6	0.327	-0.153	1
369.008	0.275	0.005	174.0	0.5	0.269	-0.057	2
369.015	0.271	0.010	173.3	1.1	0.264	-0.063	2
369.915	0.595	0.004	180.0	0.2	0.595	0.000	2
369.975	0.660	0.006	175.9	0.3	0.653	-0.094	2
369.997	0.672	0.007	175.0	0.3	0.662	-0.117	2
370.017	0.689	0.008	176.1	0.3	0.683	-0.094	2
370.894	0.531	0.007	140.1	0.4	0.094	-0.523	2
370.928	0.562	0.010	152.0	0.5	0.314	-0.466	2
370.991	0.537	0.008	151.5	0.4	0.292	-0.450	2
371.033	0.512	0.008	159.8	0.4	0.390	-0.332	2
371.891	0.420	0.009	160.9	0.6	0.330	-0.260	2
371.962	0.431	0.007	159.8	0.5	0.328	-0.279	2
372.015	0.443	0.005	157.3	0.3	0.311	-0.315	3
486.617	0.469	0.012	163.9	0.7	0.397	-0.250	4
487.551	0.552	0.012	159.9	0.6	0.422	-0.356	4
487.698	0.517	0.009	158.6	0.5	0.379	-0.351	4
488.543	0.349	0.008	150.3	0.7	0.178	-0.300	4
489.563	0.405	0.013	152.3	0.9	0.230	-0.333	4
489.675	0.328	0.011	146°.1	1°.0	0.124	-0.304	4
490.525	0.450	0.012	166.7	0.8	0.402	-0.201	4
490.618	0.457	0.008	168.9	0.5	0.423	-0.173	4
490.673	0.451	0.008	168.7	0.5	0.416	-0.173	4
491.515	0.508	0.009	155.5	0.5	0.333	-0.383	4
491.637	0.520	0.008	156.0	0.4	0.348	-0.386	4
491.686	0.496	0.008	155.9	0.5	0.331	-0.370	4
492.514	0.262	0.009	151.1	1.0	0.140	-0.222	4
492.683	0.282	0.007	157.2	0.7	0.197	-0.201	4
493.516	0.287	0.011	148.3	1.1	0.129	-0.257	4
493.616	0.233	0.011	153.7	1.4	0.142	-0.185	4
493.692	0.244	0.009	160.3	1.1	0.189	-0.155	4
494.510	0.480	0.007	167.9	0.4	0.438	-0.197	4
494.594	0.541	0.009	166.7	0.5	0.484	-0.242	4
494.679	0.600	0.010	166.2	0.5	0.532	-0.278	4
495.514	0.512	0.008	152.6	0.4	0.295	-0.418	4
495.602	0.519	0.010	152.8	0.6	0.302	-0.422	4
495.688	0.530	0.008	150.9	0.4	0.279	-0.450	4
496.524	0.273	0.010	164.9	1.0	0.236	-0.137	4
496.600	0.344	0.009	165.8	0.7	0.303	-0.164	4
496.690	0.409	0.006	167.5	0.4	0.371	-0.173	4
497.512	0.282	0.010	163.5	1.0	0.237	-0.154	4
497.593	0.366	0.009	166.9	0.7	0.328	-0.162	4
497.679	0.422	0.010	168.4	0.7	0.388	-0.166	4
498.517	0.512	0.009	164.1	0.5	0.435	-0.270	4
498.569	0.502	0.011	161.3	0.6	0.399	-0.305	4
498.685	0.528	0.011	159.2	0.6	0.395	-0.351	4
499.520	0.483	0.007	152.6	0.4	0.278	-0.395	4
499.602	0.456	0.008	151.7	0.5	0.251	-0.381	4
499.682	0.456	0.010	150.5	0.6	0.235	-0.391	4
500.534	0.433	0.010	165.1	0.7	0.376	-0.215	4
500.585	0.461	0.011	163.1	0.7	0.383	-0.256	4
500.676	0.529	0.008	159.9	0.4	0.404	-0.341	4
501.520	0.474	0.009	167.3	0.5	0.428	-0.203	4
501.600	0.540	0.009	166.2	0.5	0.479	-0.250	4
501.665	0.519	0.011	165.1	0.6	0.450	-0.258	4
502.504	0.534	0.010	160.1	0.5	0.410	-0.342	4
502.538	0.540	0.007	158.9	0.4	0.400	-0.363	4
502.597	0.560	0.011	159°.7	0°.6	0.425	-0.364	4
502.647	0.539	0.007	159.0	0.4	0.401	-0.361	4
503.508	0.443	0.011	147.0	0.7	0.180	-0.405	4
503.547	0.437	0.010	147.6	0.7	0.186	-0.395	4
503.616	0.352	0.011	147.9	0.9	0.153	-0.317	4
504.561	0.489	0.012	160.5	0.7	0.380	-0.308	4
504.612	0.506	0.009	157.6	0.5	0.359	-0.357	4
504.658	0.491	0.006	155.0	0.4	0.316	-0.376	4
505.507	0.524	0.008	165.5	0.4	0.458	-0.254	4
505.559	0.522	0.005	163.3	0.3	0.436	-0.287	4
505.652	0.517	0.008	165.8	0.4	0.455	-0.246	4
506.506	0.504	0.010	157.8	0.6	0.360	-0.353	4
506.634	0.495	0.011	156.6	0.6	0.339	-0.361	4
507.517	0.331	0.011	148.7	1.0	0.152	-0.294	4
507.568	0.329	0.012	150.8	1.0	0.172	-0.280	4
507.612	0.312	0.011	154.3	1.0	0.195	-0.244	4
507.659	0.300	0.011	157.0	1.1	0.208	-0.216	4
508.594	0.391	0.009	146.8	0.7	0.157	-0.358	4
508.653	0.339	0.011	151.0	0.9	0.180	-0.287	4
509.518	0.491	0.007	164.4	0.4	0.420	-0.254	4
509.578	0.504	0.008	165.0	0.5	0.436	-0.252	4
509.629	0.487	0.009	166.2	0.5	0.432	-0.226	4
510.509	0.512	0.010	156.2	0.6	0.345	-0.378	4
510.562	0.527	0.010	156.3	0.5	0.357	-0.388	4
511.507	0.311	0.010	171.6	0.9	0.298	-0.090	4
511.561	0.296	0.008	168.6	0.8	0.273	-0.115	4
511.640	0.321	0.012	170.8	1.1	0.305	-0.101	4
512.521	0.406	0.005	157.9	0.4	0.291	-0.283	4
512.569	0.402	0.009	161.0	0.6	0.317	-0.247	4
513.533	0.478	0.012	164.5	0.7	0.410	-0.246	4
513.632	0.454	0.009	165.3	0.6	0.396	-0.223	4
514.523	0.505	0.006	155.1	0.3	0.326	-0.386	4
514.610	0.510	0.011	153.2	0.6	0.303	-0.410	4
516.508	0.472	0.008	164.8	0.5	0.407	-0.239	4
516.582	0.508	0.008	165.0	0.5	0.440	-0.254	4
517.507	0.436	0.010	162.7	0.7	0.359	-0.248	4
517.593	0.469	0.008	161.9	0.5	0.378	-0.277	4
518.511	0.464	0.009	149°.5	0°.6	0.225	-0.406	4
518.624	0.410	0.011	145.2	0.8	0.143	-0.384	4
519.491	0.493	0.008	164.1	0.5	0.419	-0.260	4
519.546	0.501	0.013	163.2	0.7	0.417	-0.277	4
519.602	0.549	0.012	161.3	0.6	0.436	-0.333	4
521.508	0.470	0.009	159.3	0.5	0.353	-0.311	4
521.598	0.485	0.012	158.1	0.7	0.350	-0.336	4
522.503	0.343	0.010	144.7	0.8	0.114	-0.324	4
522.552	0.325	0.008	146.1	0.7	0.123	-0.301	4
522.594	0.280	0.009	143.8	0.9	0.085	-0.267	4
523.495	0.554	0.010	157.1	0.5	0.386	-0.397	4
523.516	0.577	0.011	157.4	0.5	0.407	-0.409	4
523.542	0.564	0.011	155.4	0.6	0.369	-0.427	4

TABLE 1—*Continued*

Julian Date (2,446,000+)	P (%)	σ_P (%)	θ	σ_θ	Q (%)	U (%)	ref[a]
523.573	0.548	0.011	153.6	0.6	0.331	-0.436	4
523.612	0.560	0.010	152.1	0.5	0.315	-0.463	4
524.501	0.505	0.011	159.9	0.6	0.386	-0.326	4
524.574	0.491	0.013	160.3	0.8	0.379	-0.312	4
525.495	0.489	0.005	152.8	0.3	0.285	-0.398	4
525.599	0.509	0.008	154.3	0.5	0.318	-0.398	4
526.503	0.277	0.012	152.0	1.2	0.155	-0.230	4
526.577	0.295	0.010	158.7	1.0	0.217	-0.200	4
527.502	0.474	0.012	152.2	0.7	0.268	-0.391	4
527.533	0.467	0.011	152.8	0.7	0.272	-0.380	4
527.553	0.465	0.006	153.1	0.4	0.275	-0.375	4
527.591	0.415	0.015	155.2	1.0	0.269	-0.316	4
527.610	0.425	0.013	156.1	0.9	0.285	-0.315	4
711.008	0.373	0.011	153.9	0.8	0.229	-0.295	5
712.004	0.589	0.010	163.3	0.5	0.492	-0.324	5
713.018	0.401	0.015	154.4	1.1	0.251	-0.313	5
717.024	0.439	0.019	166.4	1.2	0.390	-0.201	5
718.024	0.612	0.034	164.8	1.6	0.528	-0.310	5
722.015	0.481	0.011	155.3	0.7	0.313	-0.365	5
723.008	0.587	0.009	169.3	0.4	0.547	-0.214	5
723.993	0.484	0.010	149.0	0.6	0.227	-0.427	5
728.994	0.340	0.009	163.8	0.8	0.287	-0.182	5
730.008	0.337	0.008	164.4	0.7	0.288	-0.175	5
731.013	0.666	0.009	158.9	0.4	0.493	-0.447	5
732.004	0.338	0.007	151.5	0.6	0.184	-0.283	5
734.016	0.498	0.007	173.5	0.4	0.485	-0.112	5

[a] REFERENCES.—(1) 1985, Mount Bigelow 1.55 m; (2) 1985, Mount Lemmon 1.02 m; (3) 1985, Mount Lemmon 1.52 m; (4) 1986, Las Campanas 0.60 m; (5) 1986, Mount Lemmon 1.02 m.

strange behavior of HD 50896's light curve and the absence of phase-related changes in UV lines remains to be explained. As part of a systematic survey of polarization variations among W-R stars, we have monitored EZ CMa frequently during the past 2 yr. We present these results here, along with a new light curve obtained during a contiguous 62 night run.

II. OBSERVATIONS

a) Polarimetry

The linear polarization observations presented in Table 1 were obtained during four different runs. At the University of Arizona Observatories (Mount Lemmon 1.0 m and 1.6 m, Mount Bigelow 1.6 m) in 1985 September and 1986 October, and at the University of Toronto 0.6 m telescope at Las Campanas, Chile, in 1986 February–April, we used the Minipol polarimeter (Frecker and Serkowski 1976) and a wide-band blue filter (Corning 4-96). The columns in Table 1 give, respectively, the Julian date of the observation; the polarization P and its error, σ_P, in percent; the polarization angle in the equatorial system, θ, and its error, σ_θ; the Stokes parameters Q and U; and the telescope used. Instrumental polarization was measured using unpolarized standard stars (cf. Bastien *et al.* 1988) and found to be negligible ($\leq 0.015\%$) at all telescopes and was therefore ignored. Even though most polarized standard stars observed were found to be variable at some level (Bastien *et al.* 1988), the error in the origin of the position angle was reduced to less than 1° for each telescope by averaging the position angle of many stars. Due to the internal calibration of the Minipol, the accuracy in the measure of the position angle within a single run is limited by photon counting statistics. More details concerning the observations are given elsewhere (Bastien *et al.* 1988 and references therein). Nearly simultaneous observations in circular and linear polarization (Table 2) in a broad-band blue filter (the same as for the other polarimetric observations) and a standard Johnson R filter were obtained at the 1.0 m telescope of the South African Astronomical Observatory in 1987 February 3–23. Details about the SAAO instrument and analysis are given by Robert and Moffat (1989).

b) Photometry

The bulk of the photometric data was obtained in Chile in 1987 at three different observatories. From March 10 to April 9, we used the CTIO 0.6 m telescope and a Johnson V filter; from April 6 to 16, the University of Toronto 0.6 m telescope in Las Campanas, with a Johnson V filter; and from April 15 to May 10, the observations were made with the 90 cm Dutch telescope at ESO, La Silla, equipped with the *VBLUW* photometric system of Walraven. In 1987 February, blue and red photometry was obtained in conjunction with the polarimetry at SAAO, with the same filters used in polarimetry. The same comparison stars as LML were used, namely HD 50853 (c1; spectral type A1) and HD 50711 (c2; A2). All these observations are presented in Table 3. Note that the Walraven data are expressed in magnitudes instead of the customary log-intensity scale in order to compare them with the other data. The mean error on each point was estimated from the standard deviation of the mean for the comparison stars to be about 0.003 mag at each epoch.

III. RESULTS AND INTERPRETATION

a) Periodicity

We have submitted all photometric and polarimetric data presented here to a parameter-independent period-search routine similar to the one described by Lafler and Kinman (1965) and to Deeming's period-search method (Deeming 1975). As the Chile data were collected over a long period of time, we have also divided them into 15 day epochs and searched for a periodicity in these subgroups individually. In all the groups and subgroups of data, the best period was always found to be consistent with the previously published $3\overset{\mathrm{d}}{.}77$ period. The most evident aliases, $0\overset{\mathrm{d}}{.}75$ and $1\overset{\mathrm{d}}{.}26$, were also present at a high level at some epochs, but are much less significant than the $3\overset{\mathrm{d}}{.}77$ period for most data (see Gosset and Vreux 1987 for a discussion on a possible interpretation of these aliases). Although the $3\overset{\mathrm{d}}{.}766$ period found by LML may not be exactly the best overall period for reasons described later, we chose to keep their ephemeris in order to compare the new with the previous data.

b) The Light Curve

Figure 1 presents the 1987 light curves of HD 50896 phased according to LML's ephemeris. We show in Figure 1*a* the blue data taken at SAAO, while the Chile V light curve has been separated into three epochs: from JD $-2,440,000 = 6,865$ to 6,881 in Figure 1*b*, from 6,882 to 6,898 in Figure 1*c* and from 6,899 to 6,927 in Figure 1*d*. It is now obvious from this figure that, *although the behavior of the light curve is coherent and relatively noise-free within a 2 week period, its shape changes on a longer time scale.*

TABLE 2

SIMULTANEOUS LINEAR AND CIRCULAR POLARIZATION DATA

HJD (−2,446,800)	P	σ_p	θ	σ_θ	V	σ_V
			B Filter			
30.425..........	0.451%	0.026%	163°0	1°7	...	...
31.385..........	0.360	0.017	155.9	1.4	...	...
32.459..........	0.457	0.017	174.0	1.1	−0.030%	0.011%
33.357..........	0.575	0.013	168.6	0.6	+0.027	0.009
34.357..........	0.428	0.014	161.2	0.9	+0.034	0.011
35.379..........	0.429	0.015	157.6	1.0	+0.032	0.007
36.366..........	0.499	0.016	173.1	0.9	+0.019	0.009
39.424..........	0.496	0.014	164.2	0.8	+0.016	0.010
40.286..........	0.565	0.014	167.4	0.7	+0.027	0.008
41.296..........	0.510	0.009	165.3	0.5	−0.009	0.006
42.292..........	0.371	0.012	160.1	0.9	+0.019	0.007
43.335..........	0.492	0.012	169.2	0.7	+0.012	0.006
44.291..........	0.578	0.014	169.8	0.7	−0.029	0.008
45.291..........	0.532	0.016	158.3	0.9	+0.019	0.008
45.409..........	0.542	0.016	162.4	0.8	+0.038	0.009
46.335..........	0.293	0.011	161.0	1.1	+0.019	0.006
47.379..........	0.468	0.014	174.7	0.9	...	...
48.344..........	0.563	0.013	172.7	0.7	+0.023	0.007
49.286..........	0.419	0.017	161.3	1.2	+0.012	0.008
50.286..........	0.275	0.015	157.8	1.6	+0.039	0.009
			R Filter			
31.456..........	0.326	0.013	154°2	1°1	...	...
33.386..........	0.489	0.016	162.6	0.9	−0.019	0.008
34.325..........	0.367	0.017	155.1	1.3	+0.002	0.009
37.294..........	0.481	0.019	159.7	1.1	+0.027	0.009
39.457..........	0.413	0.018	155.8	1.2	+0.014	0.009
40.347..........	0.476	0.013	168.0	0.8	+0.022	0.009
41.342..........	0.479	0.012	161.0	0.7	+0.019	0.007
42.328..........	0.335	0.019	156.1	1.6	−0.019	0.009
43.292..........	0.423	0.013	162.7	0.9	−0.026	0.008
44.330..........	0.548	0.017	165.3	0.9	−0.016	0.008
45.336..........	0.409	0.014	152.2	1.0	−0.009	0.007
46.292..........	0.285	0.013	152.0	1.3	−0.010	0.008
47.292..........	0.394	0.013	163.8	0.9	...	...
48.376..........	0.507	0.016	167.3	0.9	+0.019	0.008
49.314..........	0.357	0.018	154.3	1.4	−0.008	0.009
50.314..........	0.259	0.014	152.5	1.5	+0.017	0.007

The blue-band SAAO data are too few to allow a detailed discussion, but the position of the maximum is consistent with the first part of our Chilean observations, taken 3–4 weeks later. No significant $B-R$ color variation occurred during this period (cf. Table 3B). During the first 2 weeks of observation in Chile (Fig. 1*b*), the light curve was very similar to those obtained in 1980 and 1985 (LML), i.e., one narrow maximum of amplitude 0.085 mag and (probably) secondary maxima. The pattern observed during the third and fourth weeks in Chile (Fig. 1*c*), i.e., a rapid increase in brightness (amplitude 0.06 mag) followed by a slow decrease, was also observed in 1977 by Firmani *et al.* (1980). The final part of our observations is less certain because of the sparseness of the data but is similar to the 1986 data published by van Genderen, van der Hucht, and Steemers (1987). Figure 2 presents the color curves obtained during the last 3 weeks of observation (i.e., the same epoch as Fig. 1*d*). Although no significant variation in $B-V$ occur during this period, the other color curves are clearly variable, with the largest amplitude in $B-L$. As mentioned by van Genderen, van der Hucht, and Steemers (1987), the color curves $B-L$ and $B-U$ vary in phase with each other. However, there is no clear correlation between these colors and the brightness of the star.

As has already been noted by van Genderen, van der Hucht, and Steemers (1987), if we adopt the LML ephemeris, the position of the maximum in the light curve is shifted by about 0.3 in phase between 1985 and 1986 but stays at the same phase since then. We then tried to improve the period by diminishing the phase shift between the 1980, 1985, 1986, and 1987 maxima, but no period was entirely satisfactory. The best overall period, $P = 3^{d}.8300$, reduces the overall spread in phase among the highest maxima to 0.15. Even the 1976 and 1977 maxima fall near phase 0 with this period. Figure 3 shows all the 1980–1987 V observations phased with this period. The high noise is not surprising in view of the continuous changes observed in 1987. However, as discussed in the next section, this period is excluded by the polarimetry. We then have to admit that either the period changes slowly (oscillates?) or the phase shift is real.

Changes in the amplitude of the light curve of EZ CMa are now rather well documented. Observations by van der Hucht, van Genderen, and Bakker (1989) show a rather sinusoidal light curve in 1985 December with an amplitude of ~ 0.03 mag. A recent light curve obtained by Balona and Egan (1988) shows that EZ CMa was again in a "low" state (total amplitude ≤ 0.03 mag, without a sharp maximum) early in 1988, as it was in 1975. In 1988 October, Moffat and Seggewiss (1989)

TABLE 3A

PHOTOMETRY OF HD 50896: *V* Filter

JD −2,446,000	WR 6-C1	JD −2,446,000	WR 6-C1
865.540	0.666	888.527	0.648
866.650	0.644	889.547	0.631
869.508	0.666	889.506	0.622
869.583	0.662	889.604	0.615
870.573	0.662	891.492	0.659
870.633	0.674	891.570	0.661
871.564	0.671	892.488	0.633
871.638	0.662	892.524	0.631
873.512	0.649	892.559	0.622
873.593	0.621	892.589	0.618
873.645	0.618	892.622	0.608
874.511	0.655	893.490	0.624
874.564	0.639	893.524	0.624
874.614	0.654	893.592	0.628
875.510	0.663	893.620	0.631
875.564	0.665	894.492	0.649
876.528	0.662	894.567	0.654
880.524	0.664	895.477	0.663
881.504	0.582	896.602	0.604
881.550	0.587	897.479	0.642
881.592	0.598	898.478	0.658
881.640	0.604	899.475	0.674
882.567	0.634	900.512	0.619
882.622	0.636	902.635	0.637
883.569	0.663	905.604	0.625
884.502	0.664	908.578	0.633
884.575	0.665	909.541	0.637
885.499	0.605	913.545	0.630
885.542	0.614	914.559	0.672
885.618	0.626	918.577	0.658
886.502	0.641	924.537	0.639
886.511	0.647	925.525	0.651
886.603	0.644	927.545	0.652
887.494	0.652		

obtained a light curve showing again a sharp maximum (at phase 0.3 according to LML's ephemeris) with an amplitude of ~0.08 mag.

c) The Polarimetric Curves

Figure 4 shows curves of P and θ as a function of the $3^{d}.766$ period for eight different epochs. The continuous line represents a Fourier fit up to the fourth orbital harmonic.

TABLE 3B

PHOTOMETRY OF HD 50896: *B* AND *R* FILTERS

JD −2,446,000	WR 6-C1 *B*	WR 6-C1 *R*
831.455	...	0.464
833.324	0.425	0.464
834.385	0.430	0.467
840.319	0.410	0.449
841.379	0.408	0.447
845.377	0.417	0.451
846.370	0.413	0.451
847.340	0.358	0.403
848.407	0.420	0.460
849.344	0.419	0.457
850.334	0.412	0.452

NOTE.—These data were obtained simultaneously with the polarimetric data in Table 2.

TABLE 3C

PHOTOMETRY OF HD 50896: WALRAVEN COLORS

JD −2,446,000	WR 6-C1 $B-V$	$L-B$	$U-B$	$W-U$
902.635	0.044	0.392	1.222	0.615
905.604	0.049	0.408	1.231	0.614
908.578	0.046	0.410	1.229	0.610
909.541	0.044	0.413	1.231	0.617
913.545	0.043	0.408	1.224	0.618
914.559	0.042	0.409	1.230	0.613
918.577	0.040	0.418	1.237	0.612
924.537	0.044	0.403	1.223	0.604
925.525	0.041	0.408	1.229	0.610

NOTE.—These values are given in magnitude differences; they are simultaneous with the final *V* data in Table 3A.

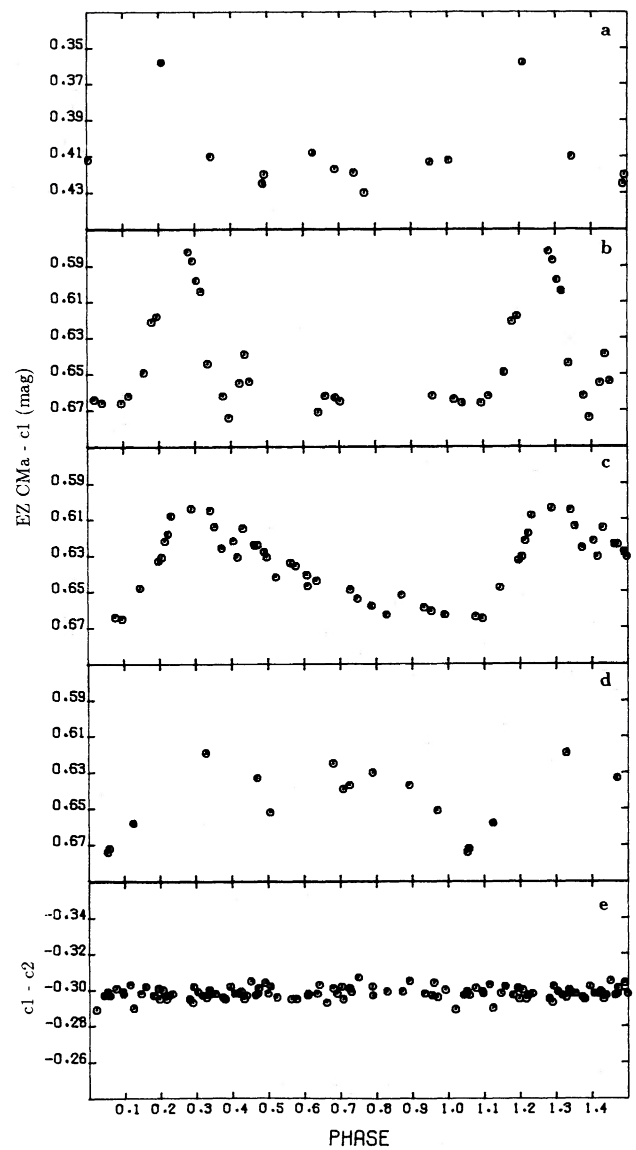


FIG. 1.—Light curves of HD 50896 in 1987; the phase has been computed from LML's ephemeris (see text). (*a*) SAAO blue filter, JD 6,831 to 6,850. (*b*) Chile *V* filter, JD 6,865 to 6,881. (*c*) JD 6,882 to 6,898. (*d*) JD 6,899 to 6,927. (*e*) Difference between the comparison and check star for all the *V* data.

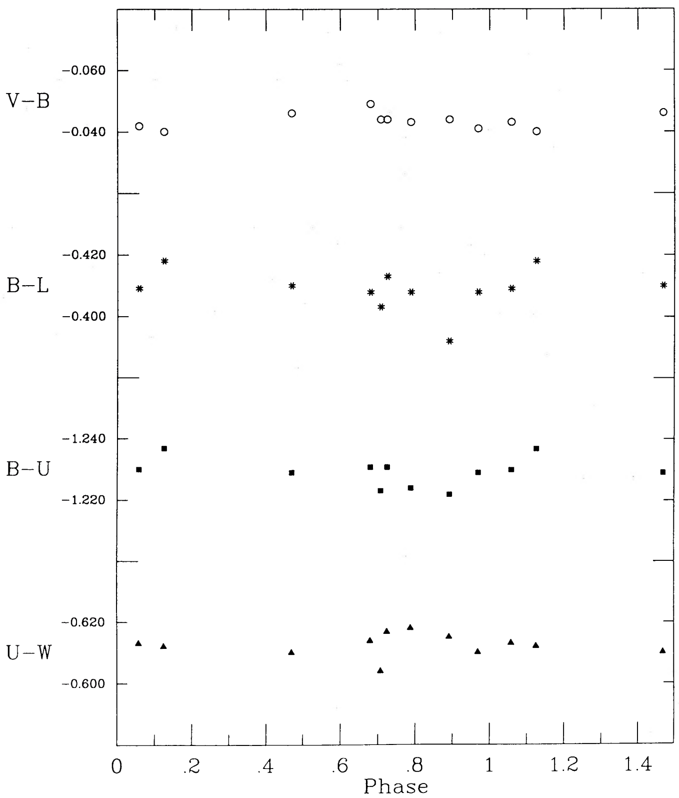


FIG. 2.—Walraven color photometry; note that the scale is in magnitudes

Although the 1970 data (Fig. 4*a*; Serkowski 1970) were taken over a very long interval of time ($\sim$417 d) and with relatively low accuracy, they show that the periodicity was also present at that time (a period-search routine gave $P = 3^{\rm d}.78 \pm 0^{\rm d}.01$ as the best period for P and θ separately). The scatter around the fitted curve for the 1980 data (Fig. 4*b*; McLean 1980) may also be attributed in part to the long baseline of data (around 4 months). McLean showed by fitting a Fourier series to his data that the polarimetric curve favored the binary interpretation of HD 50896, and that the inclination of the system would then be around 71°. The difference between Serkowski and McLean's data was not discussed by McLean.

It then became obvious in 1985 (Fig. 4*c*) that the polarimetric behavior of HD 50896 was variable over a long interval of time. Not only had the shape changed compared to McLean's data, but the amplitude of the variations was also larger in 1985.

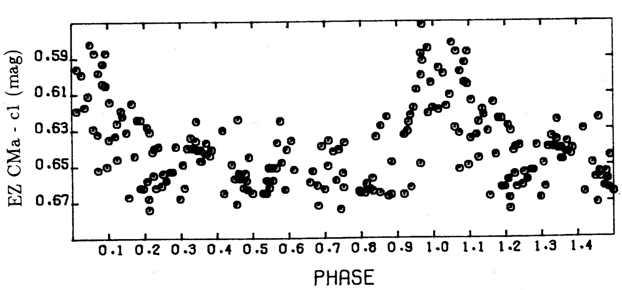


FIG. 3.—V light curve for the 1980–1987 observations (see text for references), phased with $P = 3^{\rm d}.83$.

The 1986 Chile data are divided into three equal 14 night intervals in Figures 4*d*, 4*e*, and 4*f*, to emphasize the fact that, as observed in photometry, *the polarimetric behavior of EZ CMa is coherent within about a 2 week interval* (the standard deviation from the simple fitted curve is less than 0.03% in P, Q, and U in each epoch) *but it is variable on a time scale of months.* The major changes occur between phase 0.2 and 0.5, the rest of the curve being almost unchanged during the 6 week interval. It should be noted that the maximum of the light curve obtained by van Genderen, van der Hucht, and Steemers (1987) simultaneously with our last week of observations occurs at phase 0.37. Unfortunately, no other data are available between phase 0.2 and 0.5 in that paper. The best overall period found for the Chile polarimetric data was $3^{\rm d}.777 \pm 0^{\rm d}.015$. Each epoch separately gave a similar period. The $3^{\rm d}.83$ period found from the photometry can be rejected since it yields a much noisier polarization modulation than $P = 3^{\rm d}.777$.

Figures 4*g* and 4*h* present the 1986 Arizona and 1987 blue-band SAAO data. The red SAAO polarimetric variations are very similar to the blue ones (Table 2), and are therefore not shown here. Note the similarities between Figures 4*f* and 4*h* for the P parameter. Plots of the fits in the $Q-U$ plane are shown at the same scale in Figure 5.

From Figure 4, we note the following:

1. As mentioned before, the polarization variations are relatively smooth and phase-locked to the $3^{\rm d}.77$ period, but important changes occur on a time scale of months.

2. The polarimetric curves present a predominantly double wave per cycle, as in the case of binary systems. However, the two waves do not generally have the same amplitude nor the same length in time for all epochs. This would be expected for eccentric orbits.

Polarization curves as seen in Figure 4 are produced by an asymmetry either in the distribution of the scatters (i.e., electrons) in the W-R envelope or in the light source itself.

d) Interpretation

Two basic phenomena can potentially explain our observations: duplicity and stellar spots. Let us examine each of them.

i) *EZ Canis Majoris as a Binary System*

This is the easiest way to explain at the same time the predominant maximum in the light curve, the periodic spectroscopic variations, and the double-wave shape of the polarimetric curve. Note that polarimetric changes of this type can occur in binary systems without any noticeable light variations (see St.-Louis *et al.* 1987). Brown *et al.* (1982) developed a model (an error in their equations has been corrected by Simmons and Boyle 1984) to reproduce polarization variations in binary systems with eccentric orbits. We have tried to fit this model to our Chilean polarization data with relatively good success. The orbital eccentricity, which is responsible for the asymmetry between the two waves (with $e = 0$, the variations would be sinusoidal), is the best defined parameter in our fit: values of e between 0.3 and 0.4 agree reasonably well with the data, while others can be rejected; we then decided to adopt $e = 0.34$ found from the best spectroscopic RV orbit by Firmani *et al.* (1980). The other parameters are often strongly coupled so that more than one solution is acceptable. The best overall fit is reproduced in Figure 6, with the following parameters: $Q_0 = 0.30$, $U_0 = -0.25$, $\tau = 0.075$, $e = 0.34$, $\lambda_p = 115°$, $\Omega = -40°$, and $i = 135°$. The largest discrepancies between the

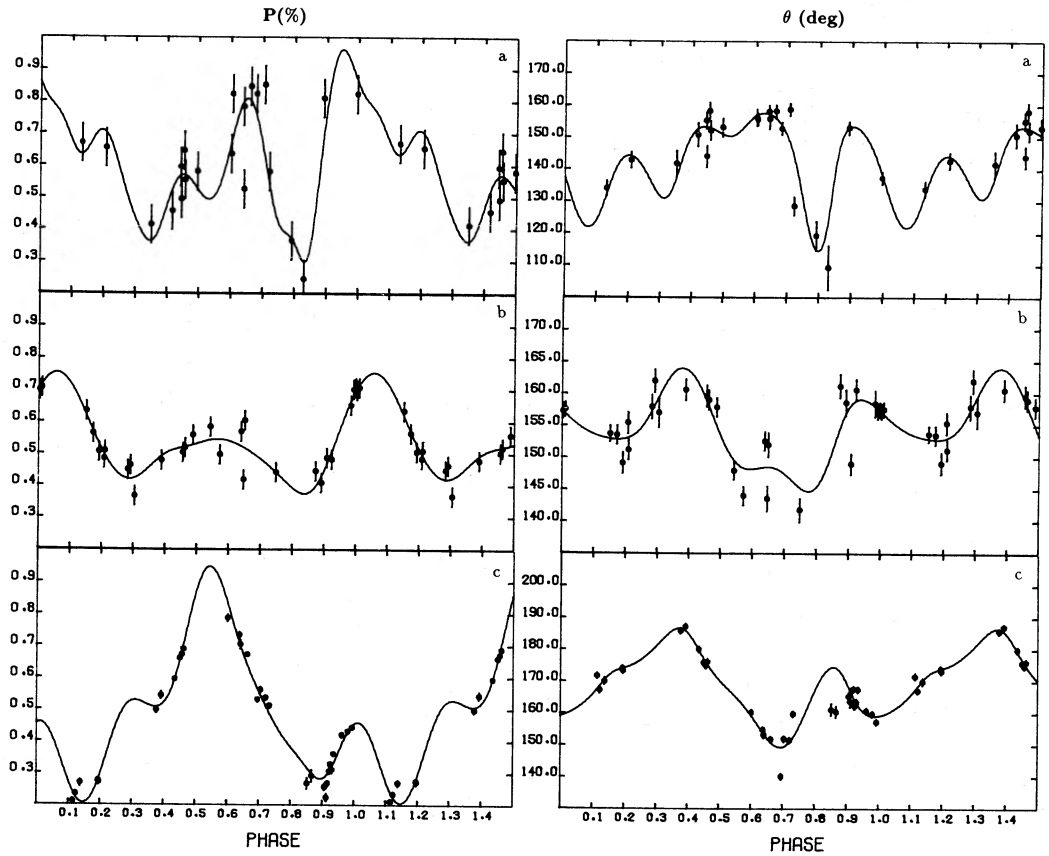


FIG. 4.—Polarimetric curves, phased according to the same ephemeris as Fig. 1. Data are from (*a*) Serkowski 1970; (*b*) McLean 1980 (the exact date of the observations is unpublished; thus the zero-point of the phase is arbitrary); (*c*) Arizona 1985, this paper; (*d*), (*e*), and (*f*) Las Campanas 1986, this paper (divided into three 14 night intervals); (*g*) Arizona 1986, this paper; (*h*) SAAO 1987, this paper. All data were obtained with the same broad-band blue filter. The solid curve represents a Fourier fit up to the fourth harmonic. Note that the scale is the same for each epoch, except for (*a*) and (*c*) in θ.

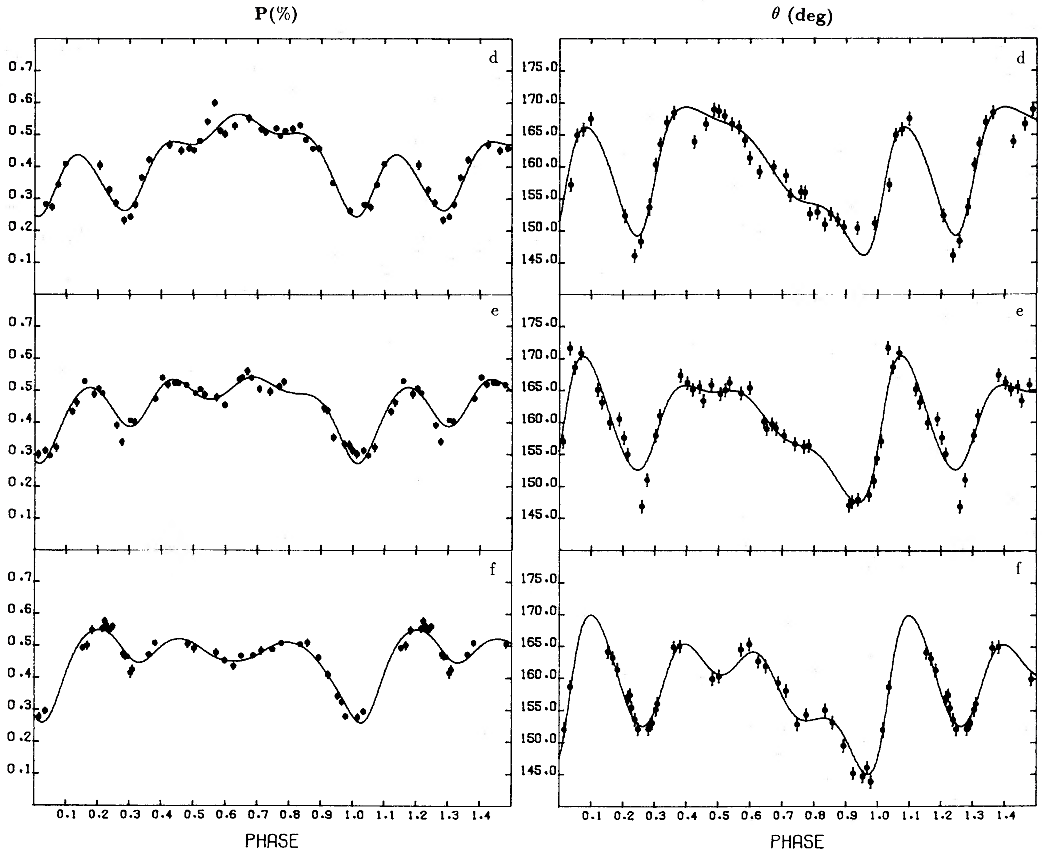
model and our observations occur between phases 0.8 and 0.2. The model is quite simple and does not take into account possible changes in the light curve.

The question that arises now is then: why can the 1986 data be reproduced quite well with an eccentric binary model *with the same eccentricity found by spectroscopy*, while the other data cannot? It could be that either these data do not have anything to do with a binary modulation and that the phenomenon responsible for the polarimetric variations is fortuitously similar to the binary model, or that the *binary modulation is always present in conjunction with another phenomenon.* The amplitude and the shape of the $Q-U$ loci (Fig. 5) differ drastically from one epoch to the next. Dolan and Tapia (1988) have also noticed such changes in X-ray binaries and conclude that the structure of the scattering region in these systems changes on a time scale of $\sim 10^{\mathrm{d}}$. In a binary system, the amplitude of the $Q-U$ locus is affected by the electron density in the system. An increase in the rate of mass loss from the W-R star could then affect the amplitude of the $Q-U$ locus and probably its shape, but not as drastically as observed. Another phenomenon must be complicating the behavior.

An interesting but purely hypothetical way to explain the variations is to assume that the companion of the W-R star is a neutron star surrounded by a slowly precessing accretion disk (if a disk can be formed and maintained, despite the strong W-R wind or the presence of a strong magnetic field associated with the neutron star). Changes in the disk orientation with respect to the observer and the W-R star would then not only modify the viewing aspect of an accretion hot spot (thus changing the length and amplitude of the light curve maximum), but also probably cause a displacement of the hot spot itself. Possibly long-term changes in the rate of mass loss from the W-R star could also change the global density of the wind and attenuate in different ways the light coming from the hot spot.

In this context, the polarimetric behavior is complicated by the different polarigenic sources, i.e., Thomson scattering by photons coming from (*a*) the W-R star scattered by the disk electrons and (*b*) the bright spot scattered by both the disk and the W-R envelope. The orbital movement would be the cause of the double wave seen in the polarization curves, but the changing geometrical aspect of the disk and the bright spot with respect to both the W-R envelope and the observer would be responsible for the complex long-term behavior of these curves.

Stevens and Willis (1989) have recently computed the X-ray flux expected if a neutron star was the companion of the W-R star in EZ CMa. They concluded that the flux should be between 10 and 100 times higher than what has been observed for this system up to now. However, they did not take into account absorption of the X-rays by a possible thick accretion disk or the effects of a magnetic field associated with the neutron star.



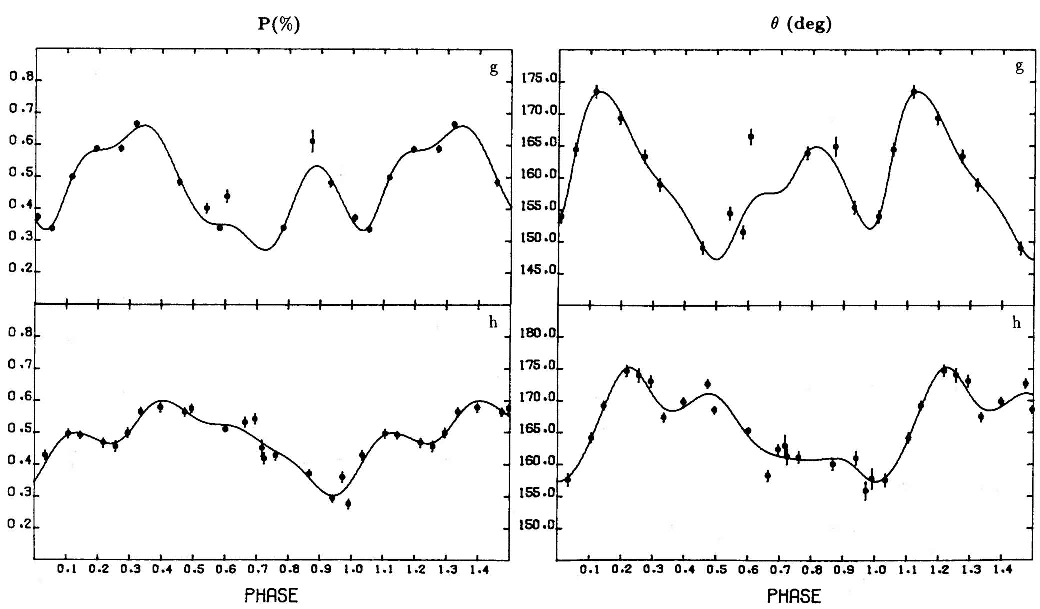


FIG. 4.—*Continued*

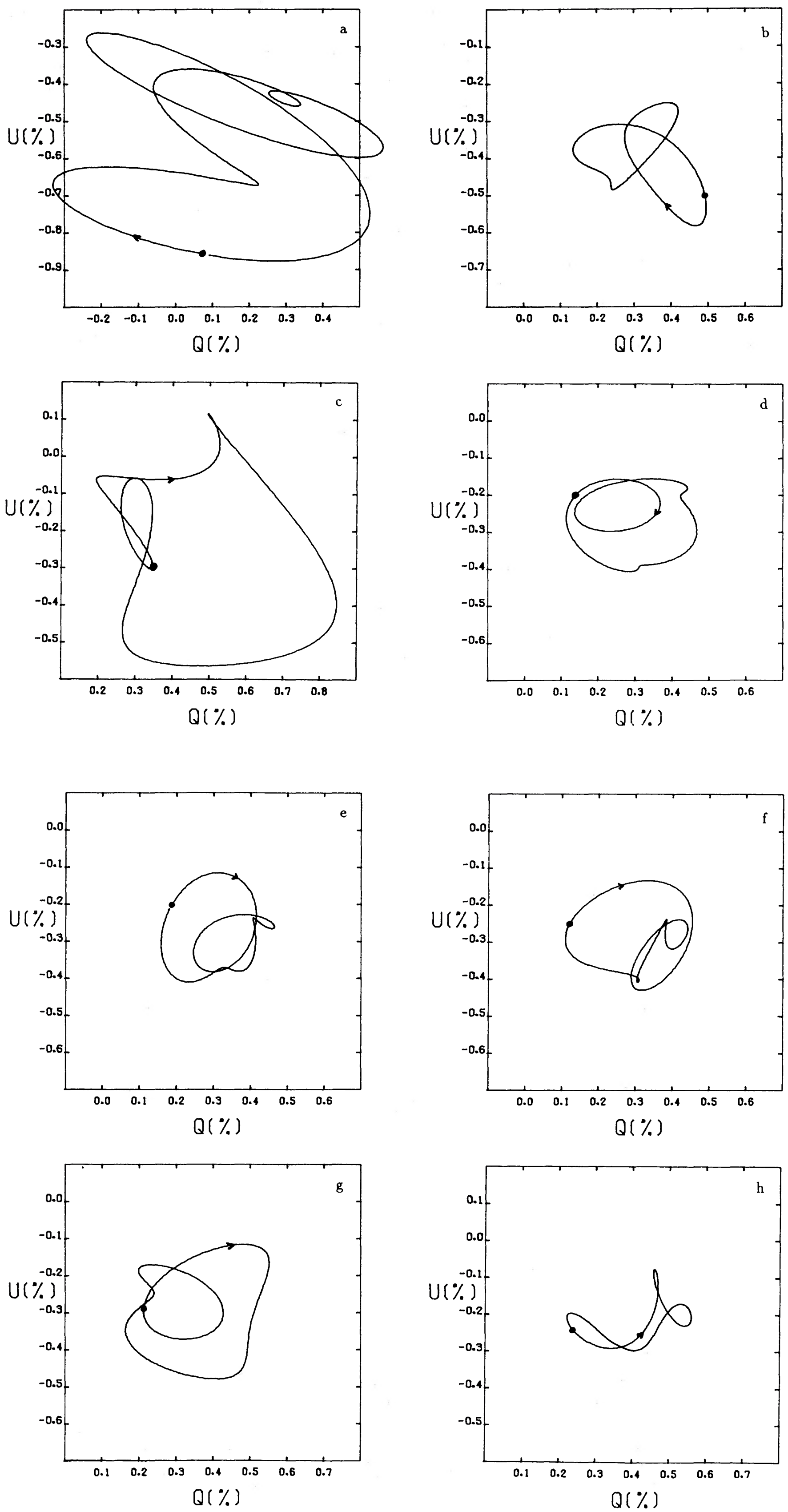


FIG. 5.—Plots of the Fourier fits in the $Q-U$ plane. Letters refer to the same epochs as in Fig. 4. Phase zero and the temporal evolution are indicated along the locus.

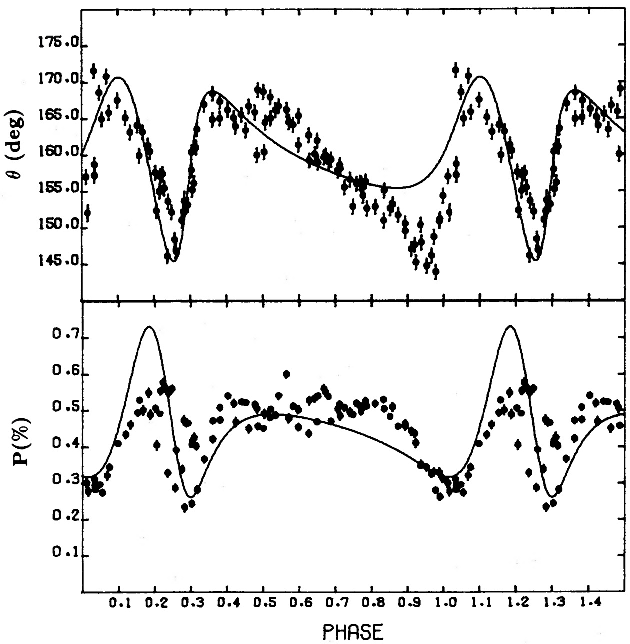


FIG. 6.—Fit to the 1986 Las Campanas polarimetric observations according to the binary model of Brown *et al.* (1982) (with corrections from Simmons and Boyle 1984).

ii) *EZ Canis Majoris as a Single Star*

The idea that EZ CMa is a single star has been mentioned by many authors to explain the lack of phase-dependent RV variations in some UV lines and the weak X-ray flux observed. However, this hypothesis has only been mentioned superficially.

It is now well accepted that a large number of (mainly cool) stars may harbor spots of magnetic origin at their surface. To be easily observable, they should cover an appreciable portion of the star, and the study of this phenomenon is therefore restricted to a relatively small sample of objects. Polarization variations attributed to rotating dark spots have been observed in cool stars, for example in FK Com stars (Huovelin *et al.* 1987) and in T Tauri stars (Bastien 1988). Up to now, no such phenomenon has been reported for W-R stars.

The presence of a *rotating semistable bright spot* somewhere in the W-R envelope could probably explain the strange behavior of the light curve, and especially the fact that the maximum in the light curve does not always occur at the same phase. A hole or eddy in the envelope, i.e., a region where the hotter layers are exposed could also produce the observed light curve (van Genderen, van der Hucht, and Steemers 1987). However, many points remain unsettled. For instance, it seems difficult to explain how a bright spot can be created and maintained for a long period of time (weeks) in such a strong wind (replacement time ~hours), unless it is strongly magnetically confined. Up to now, no evidence for strong magnetic fields has been found in W-R stars. The low mean circular polarization obtained for EZ CMa in two different filters is probably of interstellar origin ($\bar{V}_B = 0.015\%$ and $\bar{V}_R = 0.001\%$; see Robert and Moffat 1989 for details of the analysis). As shown in Figure 7, where V_B is plotted as a function of the orbital phase, there is no trend for a periodic variation (the standard deviations in both filters are $\leq 0.020\%$, i.e., $\leq 3\bar{\sigma}_V$). These data preclude the presence of a strong longitudinal magnetic field in the W-R star (and its companion if any) confirming the results of McLean *et al.* (1979).

It is also difficult in this context to explain the asymmetric double wave (unless more than one spot is present) and the rapid changes in the polarization angle seen in the Chile data.

IV. CONCLUSIONS

The previously reported $3^{d}_{.}77$ periodicity in the light curve of EZ CMa has been confirmed beyond doubt on the basis of a few extended photometric and polarimetric runs. It is found that the variations (both in photometry and polarimetry) are smooth and coherent within 2 week intervals, but long-term variations are evident. A more extensive and contiguous data base is needed to look for a long-term periodicity (~ a year?). The fact that *the light curve, although highly variable, repeats itself*, is indicative of a recurrent, if not periodic, phenomenon. Similarities in the polarimetric curves obtained one year apart (Figs. 4*f* and 4*h*) also favor this hypothesis.

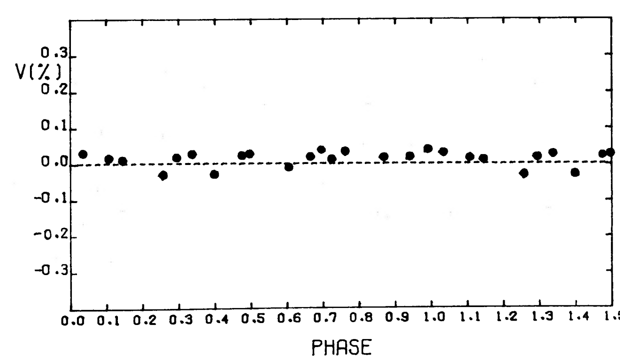


FIG. 7.—Circular polarization, obtained at SAAO in 1987; same ephemeris as Fig. 1. These data should be compared to the *simultaneous* linear polarization data in Fig. 4*h*.

The shape and the amplitude of the polarimetric curves are reminiscent of those of hot binary systems. The low scatter around a simple curve through the polarimetric data for each interval separately indicates that the blob activity observed in other W-R stars is quite low in EZ CMa. This is in good agreement with the trend shown by the scatter in polarization versus terminal velocity presented by Drissen *et al.* (1987) and Robert *et al.* (1989), since EZ CMa is a relatively fast-wind star.

We still favor the binary hypothesis to explain the periodicity, long-term modulation possibly being caused by the precession of an accretion disk around a neutron star companion. If confirmed, this would be the most convincing case for the hitherto missing link in massive binary evolution from O+O through W-R+O, c+O to c+W-R and finally c+c with probable separation into two high-speed neutron stars. All these phases have been observed so far in nature except c+W-R. The spotted single star hypothesis cannot be rejected, but the existence and relative stability of the bright spot in a W-R wind remain to be explained.

Despite the large amount of data already published for this star, much more remains to be done observationally and theoretically. In particular, simultaneous spectroscopy, photometry, polarimetry (linear and very high precision circular), and spectropolarimetry should be carried out. Search for a magnetic field via synchrotron radiation in the radio domain might also prove interesting.

It is a pleasure to thank the directors of the European Southern Observatory, the University of Arizona Observatories, the Cerro Tololo Inter-American Observatory, the University of Toronto Southern Observatory, and the South African Astronomical Observatory for the generous allotment of telescope time. We would also like to thank Dr. Santiago Tapia for his help with the Minipol polarimeter. We are grateful to Drs. Virpi Niemela, Eric Gosset, and Raman Prinja for a critical reading of the manuscript. Support for the maintenance of the Minipol was provided by NSF grant INT 82-13103 and grant 006-85 from the Space Telescope Science Institute. L. D., C. R., and N. St.-L. acknowledge the financial support of the Formation de Chercheurs et Aide *à* la recherche du Québec and C. R. and A. F. J. M., the financial assistance from the Natural Sciences and Engineering Research Council of Canada.

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