THE ASTROPHYSICAL JOURNAL, 417:687–696, 1993 November 10

SPECTRUM OF THE "INVISIBLE" COMPANION OF Z CANIS MAJORIS REVEALED IN POLARIZED LIGHT

BARBARA A. WHITNEY,[1] GEOFFREY C. CLAYTON,[2,3] REGINA E. SCHULTE-LADBECK,[3,4]
NURIA CALVET,[5,6] LEE HARTMANN,[1] AND SCOTT J. KENYON[1,7]
Received 1993 March 29; accepted 1993 May 17

ABSTRACT

Optical spectropolarimetry of the FU Orionis variable Z CMa in 1991–1992 shows larger polarization in the emission lines than in the continuum. The intensity spectrum at this time has absorption lines with some narrow weak emission. The polarized flux spectrum appears similar to an intensity spectrum of Z CMa obtained in 1987 when it was ~0.9 mag brighter at V and showed strong emission lines. We argue that the primary component of the Z CMa binary is an emission line source, perhaps an Ae/Be star, that varies at V by 1–3 mag and was responsible for the 1987 outburst. The primary is mostly obscured from view by an asymmetrical distribution of dust which polarizes the light scattered into our line of sight. The secondary, a normal FU Orionis variable, is seen more directly, and therefore contributes a large amount of unpolarized flux, about 80% of the total optical flux. Most of the polarization is intrinsic to the system and oriented perpendicular to the jet axis. We propose that independent variations in the brightness of both sources are responsible for the appearance and disappearance of a narrow emission line spectrum on the broader FU Orionis absorption line spectrum.

Subject headings: accretion, accretion disks — binaries: close — polarization — stars: individual (Z Canis Majoris) — stars: pre–main-sequence

1. INTRODUCTION

Z CMa is a pre–main-sequence object whose visible luminosity is powered by disk accretion (Hartmann et al. 1989). It is a member of the FU Orionis class of variables, many of which undergo a 4–6 mag optical outburst and remain luminous for decades (Hartmann, Kenyon, & Hartigan 1993a). While Z CMa has not undergone such a large outburst this century, Hartmann et al. (1989) classify it as an FU Orionis variable, based on its broad, doubled optical absorption lines, optical spectral type of F–G, and CO first overtone absorption characteristic of accretion disk spectra (Hartmann & Kenyon 1985, 1987a, b; Kenyon, Hartmann, & Hewett 1988).

Several characteristics differentiate Z CMa from other FU Orionis variables. Z CMa is highly variable (Beyer 1950; Covino et al. 1984). The light curves of most FU Orionis are usually characterized by a gradual decrease in brightness over time scales of 10–100 yr (Hartmann et al. 1993a). In contrast, Z CMa varied irregularly from $V = 8.5$ to $V = 11$ in the years 1925 to 1940. The only other FU Orionis variable known to display large brightness fluctuations is V1515 Cyg (Kenyon, Hartmann, & Kolotiliv 1991). Z CMa is the only known FU Orionis that exhibits such fluctuations repeatedly. Since the 1960s, it has remained near magnitude $V \sim 9.4$, but varied irregularly by about 1 mag (Covino et al. 1984).

Z CMa is also the only known FU Orionis variable that occasionally displays a spectrum of narrow metallic emission lines. Hessman et al. (1991) observed the spectrum of Z CMa during a small outburst in 1987, when the brightness increased from $V \sim 9.5$ to $V \sim 8.7$. A bluer continuum and many strong emission lines replaced the normal F- and G-type absorption spectrum. Hessman et al. found that the separation between the peaks of the doubled lines became marginally larger. They described this change as "a huge difference in the state of an optically thick disk," and in the opposite direction than expected for an outburst of such a disk. Hessman et al. could not explain these spectral changes or the short time scale of the eruption with a simple increase in the accretion rate of a single disk.

Leinert & Haas (1987) and Koresko, Beckwith, & Sargent (1989) found extended structure in Z CMa in the near-IR. Koresko et al. (1991) showed that this extension was due to an infrared companion located roughly 100 AU from the optical source. The IR companion enshrouded in dust, appears to be more luminous than the optical component (Koresko et al. 1991). We therefore refer to the IR source as the primary and the optically brighter source as the secondary in this paper.

Z CMa is surrounded by a curved reflection nebulosity. The associated nebulosity, emission lines, and the presence of strong hydrogen absorption lines led to its classification as a Herbig Ae/Be star (Herbig 1960; Strom et al. 1972). A powerful jet emanates from the Z CMa system with a position angle P.A. = 60° (Poetzel, Mundt, & Ray 1989). The reflection nebulosity curves symmetrically about the jet. The optical polarization is aligned 90° from the jet. The polarization alignment is not unusual for a pre–main-sequence star (Tamura & Sato 1989) and is the expected alignment for an embedded source with evacuated polar regions (Whitney & Hartmann 1993; Kenyon et al. 1993). The binary alignment has P.A. = 120°.

We present spectropolarimetry of Z CMa obtained in 1991 November and 1992 March, when Z CMa was at $V \sim 9.6$–9.8.

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

[2] Center for Astrophysics and Space Astronomy, Campus Box 389, University of Colorado, Boulder, CO 80309.

[3] Visiting Astronomer, Anglo-Australian Telescope.

[4] Department of Physics and Astronomy, University of Pittsburgh, 3941 O'Hara Street, Pittsburgh, PA 15260.

[5] Centro de Investigaciones de Astronomia, Ap. Postal 264, Mérida 5101-A, Venezuela.

[6] Also, Grup d'Astrofiscia de la Societat Catalana de Fisica, Institut d'Estudis Catalans.

[7] Visiting Astronomer, Kitt Peak National Observatory.

The spectra resemble the post-eruptive spectra presented by Hessman et al. when $V \sim 9.6$. The polarization spectrum is remarkable in that *every emission line is polarized.* Even more remarkable is the polarized flux spectrum (polarization times flux), which looks very similar to the high-state *intensity* spectrum when $V \sim 8.7$ (Hessman et al.). The simplest explanation of these observations is that the polarized flux represents the optical spectrum of the recently discovered IR source (the primary), scattered into the line of sight by the dust which obscures the star from view. The $\Delta V \sim 1$ mag variations of the total optical flux, and the appearance and disappearance of the narrow emission line spectrum, could be due in large part to $\Delta V \sim 1$–3 mag variations in the primary. This solution is especially attractive because it supposes that the secondary is now typical in every way of the FU Orionis class. We present the observations in § 2, consider models in § 3, and discuss our favored model in §§ 4 and 5.

2. OBSERVATIONS

The observations were obtained in 1991 November 27 and 1992 March 11 and 12 with the half-waveplate CCD spectropolarimeter at the 3.9 m Anglo-Australian Telescope. The two observing runs used different setups. In 1991 November, the B 250 line mm^{-1} grating in first order gave a free spectral range of about 4120 to 6870 Å, at a spectral resolution (FWHM) of 9 Å. Observations of a nearby star, BS 1294, and the polarized standard HD 298383 provided the polarimetric calibration. In 1992 March, the V 600 line mm^{-1} grating in first order gave a free spectral range of about 4500–6200 Å, at a spectral resolution of 2.3 Å. The aperture widths were 2".7 on 1991 November, 1" on March 11, and 2" on March 12. The aperture heights were 2".7. Star and sky were observed simultaneously through apertures separated by ~25". For the polarimetric calibration, we used the unpolarized standard star HD 98161 and the polarized standard HD 110984. In both observing runs, the instrumental polarization turned out to be very small, about 0.02%. The instrumental efficiency and zero point of the position angle were determined by inserting an HN22 polaroid in the beam. A low-frequency variation in position angle with wavelength was removed by a polynomial fit and was verified by observations of the polarized standards.

The reductions were performed similarly for both runs. Part of the CCD window defined the bias strip. We debiased and cleaned the images of cosmic rays, and then subtracted sky counts and calculated the two-dimensional wavelength calibration. The two sets of alternating star-sky spectra at four wave-plate positions combined to give the linear polarization and position angle. The 1992 March data have been flat-fielded, but the 1991 November data have not. Other than sky and bias subtraction, and cosmic-ray removal, we applied no other calibrations to these data. We normalized the spectra to take out continuum variations caused by the instrumental response.

The data are shown in Figures 1 and 2. Each figure plots the flux (normalized) in the upper panel, the polarization (%) in the middle panel, and position angle (P.A.) in the bottom. The position angle appears to be constant to within 5° throughout the spectrum in each observation. The average polarization and position angle for each observation are $P = 2.00\%$, P.A. = 150° (1991 November); and $P = 1.40\%$, P.A. = 154° (1992 March). The 1 σ standard deviation in the average polarization is 0.005%. The P.A. is accurate to $\pm 1°.5$. The position angle change between the two observations is probably real

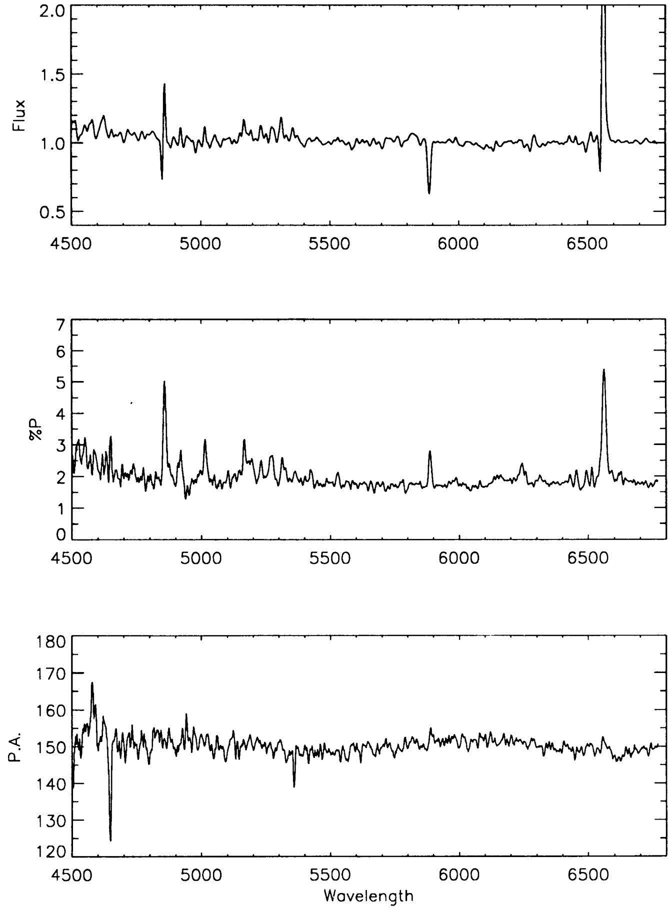

FIG. 1.—The normalized spectrum (*top panel*), polarization (*middle*), and position angle (*bottom*) of Z CMa as a function of wavelength for the 1991 Nov. data set.

and is consistent with past variations (see the Appendix). AAVSO measurements indicate that the brightness of Z CMa decreased from about $V \sim 9.6$ in 1991 November to $V \sim 9.8$ in 1992 March.

The data shown in Figures 1 and 2 are remarkable. In both 1991 November and 1992 March, Z CMa is polarized 1%–2% in the continuum and up to 6% in its emission lines. *Every emission line appears to be polarized.* If all of the polarization is intrinsic to the system, we have the unusual situation of emission lines polarized more than the continuum. The polarization increases across the Na I D $\lambda\lambda$5890,5896 absorption lines as well.

Figure 3 shows the polarized flux (polarization times flux) spectra of Z CMa (top two panels). The polarized flux is a useful quantity because it gives the spectrum of the *scattered* light (assuming the polarization is caused by scattering): light that is not polarized disappears (e.g., Whitney et al. 1992). We conclude in the Appendix that the interstellar polarization is small, so the polarized flux measures the intrinsic polarization of Z CMa. The bottom panel of Figure 3 shows Hessman et al.'s spectrum of Z CMa, obtained during a "high state" in 1987 February. At this time, the brightness of Z CMa increased to $V = 8.7$. We smoothed Hessman et al.'s spectrum to the lower resolution of our March data, and plotted it on the same wavelength scale. This high-state spectrum is dominated by emission lines of Fe I and II, Mg I, Mn I, Sr I, Ti II, Cr I and II,

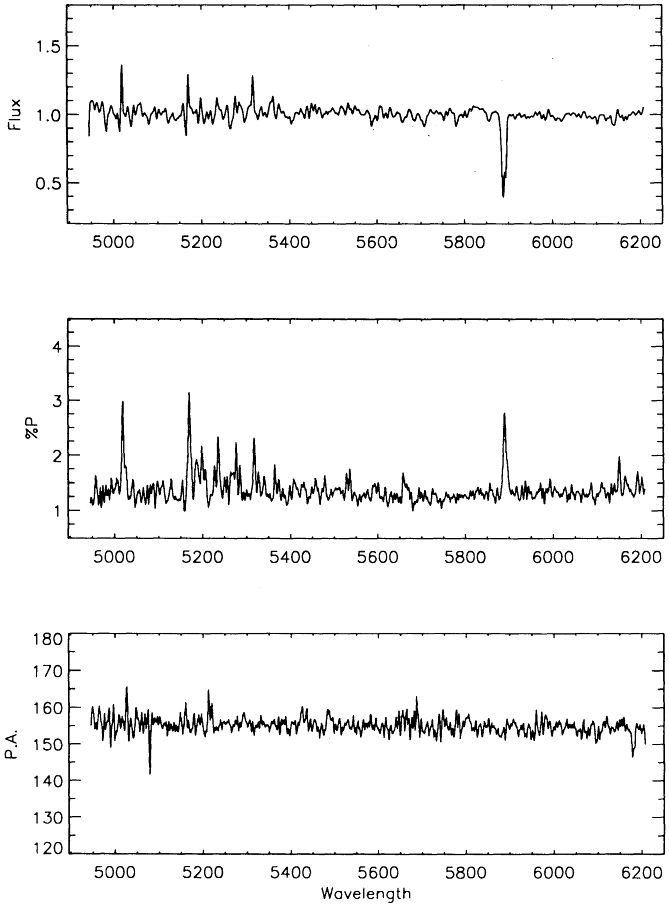

FIG. 2.—Same as Fig. 1, for the 1992 Mar. data set.

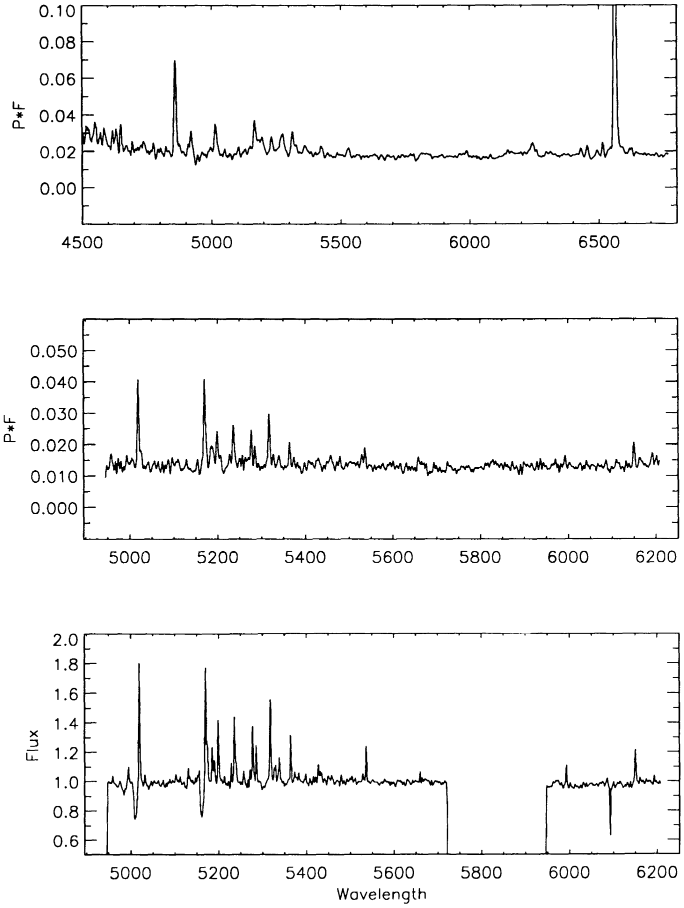

FIG. 3.—The polarized flux (polarization times flux) for the two data sets. The 1987 intensity spectrum of Z CMa (*bottom*) is plotted to the same wavelength scale as the March polarized flux spectrum (from Hessman et al.). *Top*, 1991 November polarized flux; *middle*, 1992 March polarized flux; *bottom*, 1987 February spectrum.

and Sc II, that are marked in Figure 2 of Hessman et al. *The polarized flux spectrum of Z CMa looks very similar to the high-state intensity spectrum.* The main difference is that the polarized flux does not have the broad absorption features at Fe II λ5169 and Hβ.

We obtained optical spectrophotometric observations of Z CMa, FU Ori, and MWC 1080 with the cooled dual-beam intensified Reticon scanner (IRS) mounted on the white spectograph at the KPNO No. 2 90 cm telescope. These data, shown in Figure 4, were reduced to the Hayes & Latham (1975) flux scale; the photometric calibration has an uncertainty of $\pm$0.03–0.05 mag. These spectra have the same resolution, 9 Å, as the 1991 November Z CMa data. The Z CMa spectrum, obtained in 1988 November when the V magnitude was about 9.6, shows no apparent emission except at Hα. The spectrum resembles that of FU Ori. MWC 1080 is a member of the class of Herbig Ae/Be stars, which are thought to be high-mass pre–main-sequence stars (Strom et al. 1972; Cohen & Kuhi 1979; Finkenzeller & Mundt 1984). The luminosity of MWC 1080 is $\sim$7400 $L_\odot$ (Evans, Levreault, & Harvey 1986).

Note the resemblance of the MWC 1080 spectrum (bottom of Fig. 4) to the 1991 November Z CMa *polarized flux* spectrum (top of Fig. 3). This and the similarity between the polarized flux and the outburst intensity spectrum are reminiscent of the discovery by Antonucci & Miller (1985) and that the polarized flux spectrum of a type II Seyfert galaxy looks like the intensity spectrum of a type I Seyfert galaxy. They suggested that the nucleus of a Seyfert II galaxy can be hidden by a thick disk when viewed edge-on but can be seen in scattered, or polarized, light, and thus the difference between type I and II Seyferts is only in their inclinations to our line of sight. We suggest that in Z CMa, the primary is mostly obscured from view at visual wavelengths but we can see its spectrum in polarized light. The light is polarized from scattering in an asymmetrical dust cloud. During an outburst in 1987, the primary became bright enough to see in the intensity spectrum. The luminosity of the primary is $\sim$2100 $L_\odot$ (Koresko et al. 1991), of similar magnitude to MWC 1080. The luminosity of the secondary is $\sim$700 $L_\odot$, which is comparable to a normal FU Orionis variable (Hartmann et al. 1993a). Before further speculation about the nature of the sources, however, we must rule out other sources for the polarization.

3. ORIGIN OF THE POLARIZATION

Any observed polarization of Z CMa will be the vector sum of several components, the magnitude of each of which is unknown a priori. Polarization can arise from dust in the foreground interstellar medium, the CMA R1 association (of which Z CMa is a member), the visible reflection nebula, and the

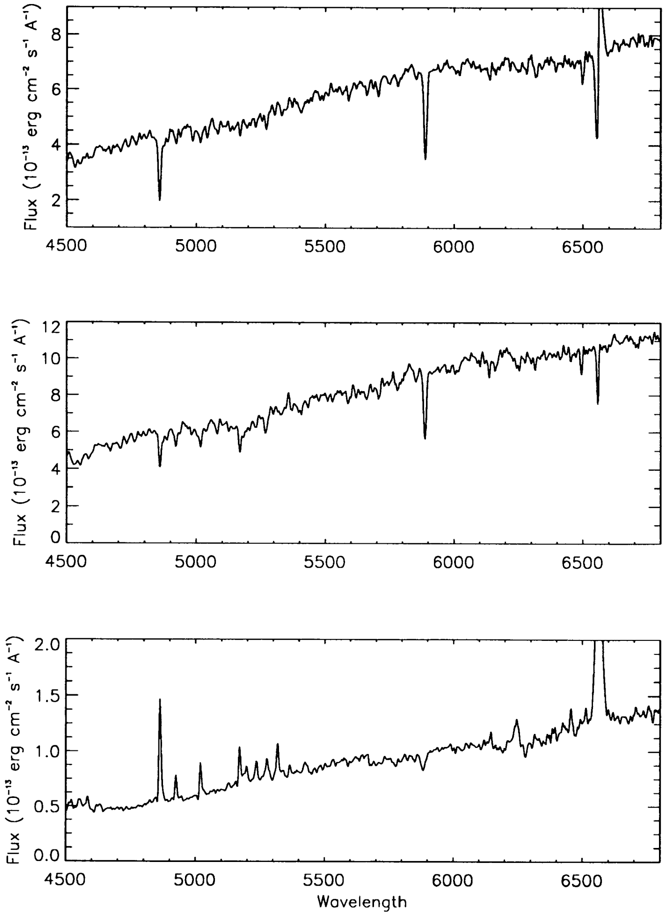

FIG. 4.—Spectra of Z CMa (*top*), FU Ori (*middle*) and MWC 1080 (*bottom*).

circumstellar region. These components are discussed in detail in the Appendix. The conclusion of that discussion is that the circumstellar component is dominant and any other component is small ($\leq 0.5\%$). Therefore, in the discussion below we use the observed polarization values uncorrected for any other polarization components.

The visual flux of the primary is presumably much smaller than that of the secondary, since the primary near-IR brightness decreases toward visual wavelengths (Koresko et al. 1991). In § 3.1, we examine explanations for the polarized emission lines assuming all of the visual flux and polarization comes from the secondary. In § 3.2, we consider the possibility that the primary contributes to the flux and polarization at visual wavelengths.

3.1. *Single Star Interpretation*

3.1.1. *Resonance Line Scattering in the Wind*

Z CMa has a powerful wind (Hartmann et al. 1989; Hessman et al.). The wind lines scatter resonantly several times before escaping. Resonance line scattering can give polarization in an analogous way to electron scattering. In atoms, the phase function for scattering is a linear combination of the Rayleigh phase function, which has a maximum polarization of 100% for 90° scattering, and the isotropic phase function, which is unpolarized (Chandrasekhar 1960). Resonance scattering can be polarized if the Rayleigh component of the scattered light is greater than 0, and if collisions do not change the angular momentum state of the atom (i.e., if the collision time is longer than the radiation time). Resonance line polarization is found in the limb of the Sun in neutral and singly ionized metals such as Ca I, Ca II, and Na I (Brückner 1963; Stenflo 1974; Wiehr 1975; Stenflo, Baur, & Elmore 1980).

An asymmetrical geometry for the wind of FU Orionis variables suggests the possibility that the resonantly scattered lines may be polarized: If the wind arises in a disk, as suggested by Pudritz & Norman (1983), Königl (1989), Pringle (1989), and Pelletier & Pudritz (1992), the lines scatter in a plane-parallel geometry that can give high polarization. Calvet, Hartmann, & Kenyon (1993) found that line profiles computed with the disk-wind geometry agree well with observed profiles.

We have two reasons to believe that resonance line scattering is not responsible for the large polarization seen in all of the emission lines in Z CMa.

1. Scattering lines usually produce emission equivalent widths less than or equal to the absorption equivalent widths, unless a very special geometry is invoked. The strong emission in the Balmer lines, particularly Hα, suggest a large thermal (therefore unpolarized) component.

2. In resonance line scattering, the polarization of a given line depends on the angular momenta of the upper and lower levels, and ranges from 0 to ~50%. For example, the Na I D_1 (λ5896) line should be unpolarized and the D_2 (λ5890) line has a maximum polarization of 50% (Jeffery 1989). The Na I lines are extremely strong scattering lines in FU Orionis variables. Figure 5 shows the polarization across this doublet. The polarization increases across both and is in fact larger across the D_2 component. However, the D_1 line appears to have some polarization above the continuum, in contradiction with the resonance scattering hypothesis. It is clear from Figures 1 and 2 that all of the emission lines have some polarization above the continuum.

3.1.2. *Dust Scattering*

The fact that every line appears polarized suggests a continuum mechanism that polarizes a spectrum of emission lines.

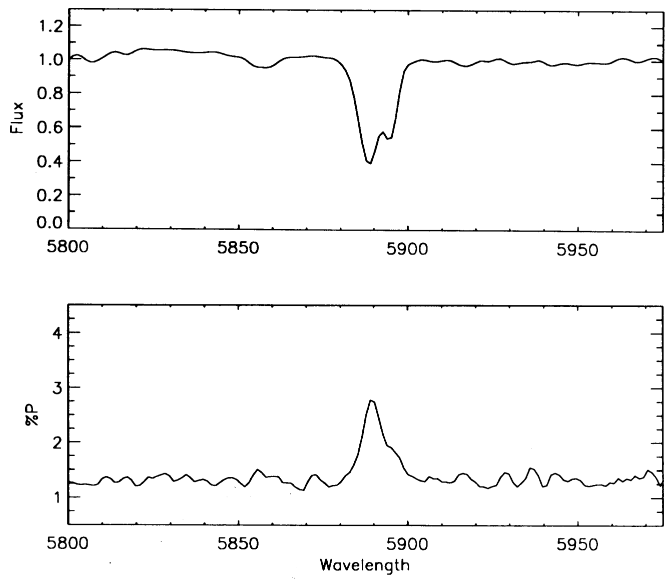

FIG. 5.—Variation of the spectrum (*top*) and polarization (*bottom*) across the Na I D lines.

The most likely continuum process is dust scattering—the temperature and density in the disk and wind are such that the dust opacity is much larger than other continuum polarizing opacities, such as electron scattering.

It is difficult to imagine a geometry in which dust scattering polarizes only the emission lines but not the continuum, assuming they emerge from the same source. If the emission lines arise in the wind, a few stellar radii above the star plus disk, and the continuum arises in the disk, we have to place the dust in such a way as to scatter and polarize the wind lines but not the disk flux. Thus the dust must be practically in the wind to polarize only this emission—dust farther out would polarize the wind and disk flux the same. There cannot be too much dust in the wind because the extinction is small: $A_v = 2.7$ (see the Appendix). We used a Monte Carlo program to calculate the polarization for dust distributed in a layer just above an emitting region, and got a maximum polarization of 3% for a dust optical depth of 2. An optical depth of 4 gave polarization of 6%. If we want dust in the wind to cause the polarization, then we have to increase the estimate of the optical extinction above $A_v = 2.7$ given in the Appendix.

Finally, the Na I D lines complicate the interpretation. Na I D is scattering light out of the beam which is why we see it as an "absorption" line (Fig. 2, *top*). Flux scattered back into the beam is polarized by the dust, but it must be just the right amount that the polarized flux matches the continuum (Fig. 3, *middle panel*).

3.2. *Binary Interpretation: The Obscured Primary as the Source of Polarized Flux*

We noted in the introduction that Z CMa has an unusual spectrum for an FU Orionis variable. Most have optical absorption spectra similar to G supergiants (Hartmann & Kenyon 1985), with broad blueshifted absorption in strong lines (Bastian & Mundt 1985). Z CMa has, in addition to this, emission lines from neutral and singly ionized metals that appear and disappear (Covino et al. 1988; Hessman et al.). These emission lines are narrower than the absorption lines (Hessman et al.), which is difficult to explain with the disk model. We know now that Z CMa is a binary—the primary is brighter in the IR and the secondary is presumably brighter in the optical. What if the emission lines are due to the primary? The primary is mostly obscured from view at visual wavelengths, but some radiation from it could scatter in its surrounding dust cloud into our line of sight. If the dust is distributed asymmetrically about the source, it can both allow light to escape along a path not in our line of sight, and give a net polarization to the scattered light.

The observed polarized flux is then the vector sum of the polarized fluxes of the two sources. The secondary has flux and polarization $F_s(\lambda)$ and $P_s(\lambda)$, respectively. The primary has flux and polarization $F_p(\lambda)$ and $P_p(\lambda)$. Since the position angle of the polarization does not seem to rotate with wavelength or magnitude of the polarization, it is likely that either both sources are polarized with the same position angle (perhaps by the same large-scale dust cloud) or that one source dominates the polarization. In either case we can assume that all of the polarization happens at one position angle, and the polarized flux, $Q(\lambda)$, becomes a simple addition, $Q(\lambda) = P_s(\lambda)F_s(\lambda) + P_p(\lambda)F_p(\lambda)$. If the primary contributes most of the polarization, then $Q(\lambda) = P_p(\lambda)F_p(\lambda)$, and if we know the polarization function $P_p(\lambda)$, we can calculate the spectrum of the primary.

If we assume that all of the emission lines come from the primary and that the primary contributes most of the polarized flux, we can estimate the dust polarization function, $P_p(\lambda)$, and decompose the flux spectrum into the primary and secondary source spectra. The polarization is

$$P(\lambda) = Q(\lambda)/F(\lambda) = F_p(\lambda)P_p(\lambda)/[F_p(\lambda) + F_s(\lambda)] , \quad (1)$$

and the secondary spectrum is

$$F_s(\lambda) = F(\lambda) - F_p(\lambda) = F(\lambda) - Q(\lambda)/P_p(\lambda) . \quad (2)$$

We fit a linear function to $P_p(\lambda)$ such that the Hα and Hβ emission lines in the resulting secondary flux spectrum $[F_s(\lambda)]$ disappear, since other FU Orionis variables do not show this emission (Bastian & Mundt 1985; also Fig. 4). The decomposition eliminates other emission features from the spectrum of the secondary, in agreement with other FU Orionis variables. The signal-to-noise and resolution are not high enough to tell if we are subtracting out exactly all of the emission in the other lines, so we do not claim accuracy to better than about 1% in $P_p(\lambda)$. This function is shown in Figure 6; the decomposed spectra are shown in Figures 7 and 8. The slope of the polarization curve is not unreasonable for a pre–main-sequence star, which can have a variety of polarization curves (Vrba, Schmidt, & Hintzen 1979; Bastien 1988). If the secondary contributes some to the polarization, the calculated P_p will be lower, but the general conclusions will remain the same. Figure 9 plots the MWC 1080 and model primary spectra to the same wavelength scale to illustrate their similarities.

4. DISCUSSION

The binary model provides a very simple and appealing explanation for the complexities in the spectrum of Z CMa. The secondary is a typical FU Orionis variable, with a luminosity, optical spectrum, and spectral energy distribution similar to other FU Orionis variables (Koresko et al. 1991; Hartmann et al. 1993a). The peculiar optical light variations can be attributed, in part, to the primary. Herbig Ae/Be stars with spectral type later than B8 often vary by 0.5 to 2 mag at V (Finkenzeller & Mundt 1984). The narrowness of the emission lines relative to the disk rotation is no longer a problem either (Hessman et al.), since they are due to another source, the primary.

Hessman et al. presented evidence for a marginal increase in the average optical rotational velocity of the Z CMa disk during the 1987 outburst. This was puzzling because simple disk models predict the reverse effect for an increase in the accretion rate. In our model, the increased optical flux in 1987 was not due to the FU Orionis variable, so the rotation should be unaffected by the variation in brightness. The data presented by Hessman et al. are roughly consistent with no change in

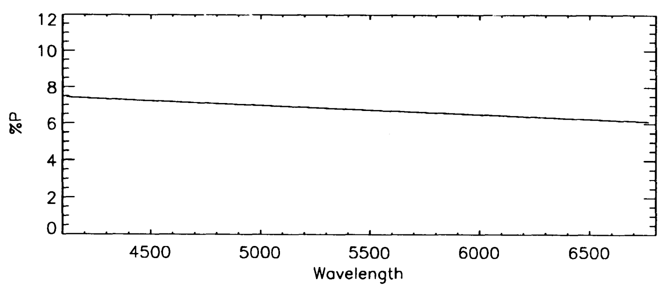

FIG. 6.—Polarization function for the primary.

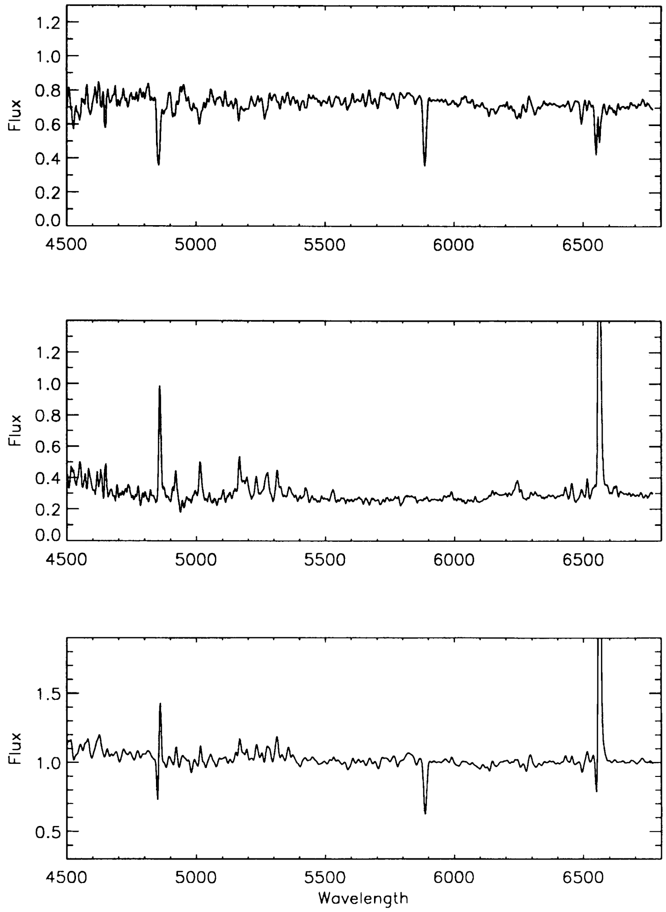

FIG. 7.—Model spectra for the 1991 Nov. data calculated using equation (2) and polarization curve in Fig. 6. *Top*, model secondary spectrum; *middle*, model primary spectrum; *bottom*, combined spectrum.

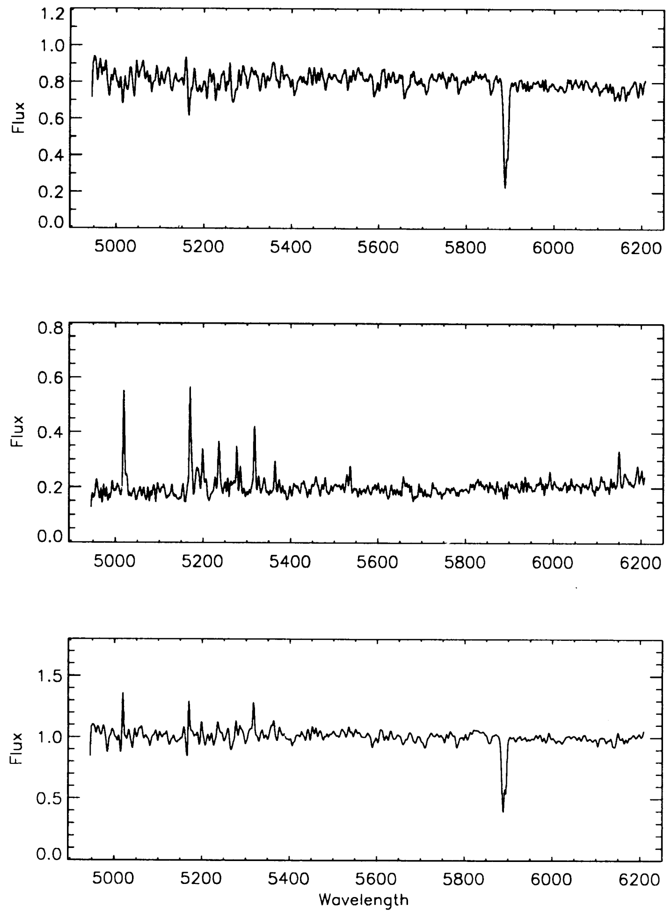

FIG. 8.—Same as Fig. 7 for the 1992 March data.

rotation during outburst, if they underestimated the errors in rotation. This is possible, since in the high state the absorption spectrum was weak and overlaid by emission lines, and it is difficult to estimate errors for a composite spectrum.

The primary spectrum is similar to an embedded high-luminosity pre–main-sequence object such as MWC 1080 (Fig. 9). In MWC 1080, the He I 5876λ line appears in absorption and is broad and blueshifted (Hartmann, Kenyon, & Calvet 1993b). As noted by Cohen & Kuhi (1979), the presence of the He I absorption distinguishes the high-luminosity active young stars from their less luminous counterparts, the heavily veiled T Tauri stars, in which the He I lines appear in emission. It is interesting that Hessmann et al. suggested that a faint absorption line in the "high state" spectrum of Z CMa was broad blueshifted absorption due to the He I 6678.15 line. The appearance of He I is inconsistent with the disk temperature of the optical FU Ori object (Hartmann et al. 1989), but is consistent with the deduced Ae/Be star nature of the primary.

MWC 1080 has far-infrared fluxes comparable to those of Z CMa, although it is weaker at mid-infrared wavelengths (Evans et al. 1986). It powers a CO outflow, which if bipolar would suggest that the system is seen at a low inclination (Cantó et al. 1984). The high polarization observed in MWC 1080 (3.5%, Garrison & Anderson 1978) suggests that it may be seen through light scattered out of the envelope, though a

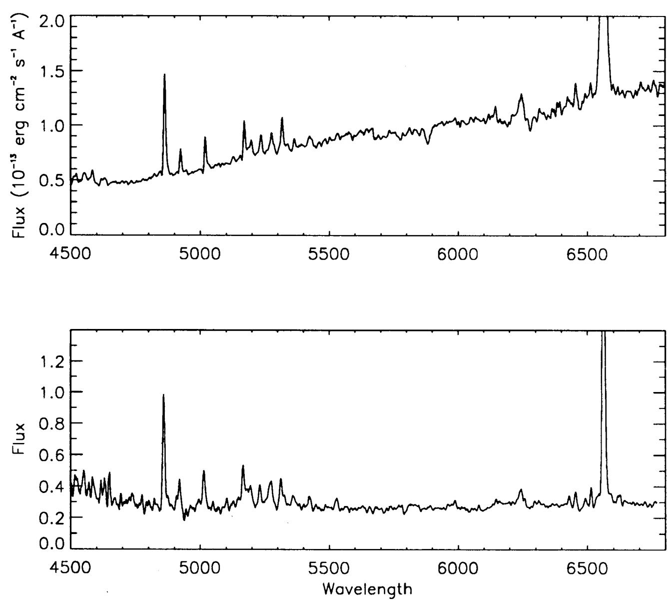

FIG. 9.—MWC 1080 spectrum (top) and model primary spectrum from 1991 Nov. (*bottom*).

significant fraction of the polarization is interstellar (Poetzel, Mundt, & Ray 1992). In addition to the similarity of the spectrum, the evidence indicates that the primary is a slightly less evolved, more embedded, or edge-on, version of MWC 1080.

The binary model easily accounts for the polarization variation across the Na I D lines. Our model primary spectrum has little or no absorption across these lines. Therefore it contributes a constant polarized flux. The effect of the secondary spectrum on the polarization is to dilute it with unpolarized flux. Across the Na I D lines, there is less flux available for dilution. Therefore the total polarization increases across the line (see eq. [1]). This is in agreement with our assumption that the secondary contributes mostly unpolarized flux. The lack of absorption across the Na I D lines in the spectrum of the primary is not unreasonable for an Ae/Be star. MWC 1080 has weak absorption at Na I D, most of it interstellar (Finkenzeller & Mundt 1984). PV Cep, another heavily extincted Ae/Be star, varies from showing strong Na I D absorption to none at all (Cohen et al. 1981).

The polarization should increase across other absorption lines that are due only to the secondary. The other strong absorption lines are the blueshifted lines in Fe II λ5160, and the H Balmer lines. Indeed, Figure 10 shows that the polarization (*middle panel*) is broader than the flux (*top panel*) in Hα. The polarized flux (*bottom*) is narrow, like the flux (*top*). Thus, it

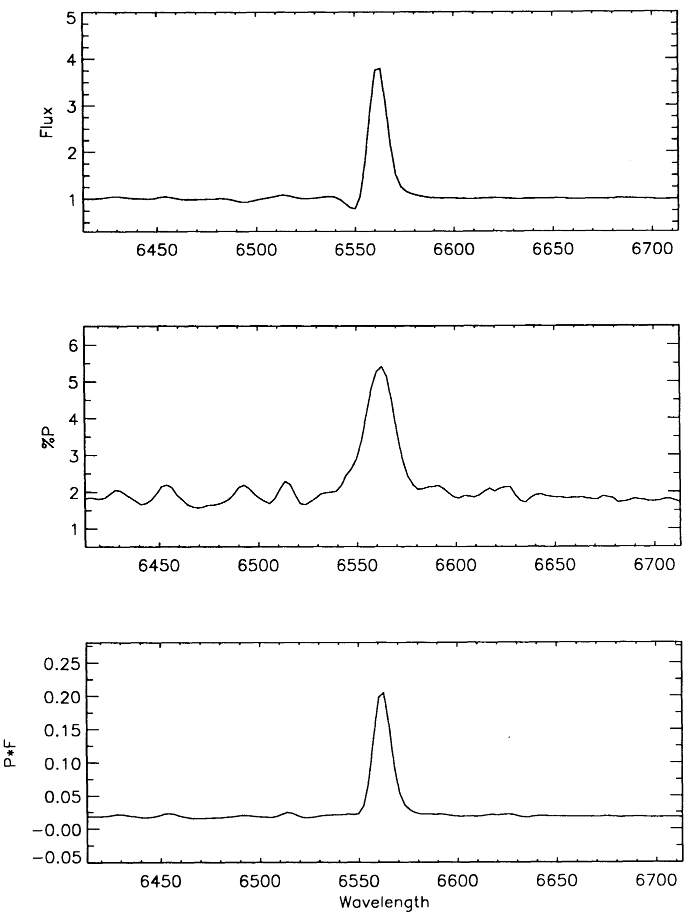

FIG. 10.—The spectrum (*top*), polarization (*middle*), and polarized flux (*bottom*) across Hα.

appears that the polarization across the line is due both to blueshifted absorption of unpolarized flux by the secondary, and addition of polarized flux by the primary. We find this behavior in the other two strong "P Cygni" profiles in our spectra: in Fe II λ5160 and Hβ. In the low state, then, the broad absorption troughs appear to be coming from the secondary, consistent with P Cygni profiles seen in other FU Orionis variables (Bastian & Mundt 1985).

The high-resolution model primary spectrum shown in Figure 8 (*middle*) can be compared to the outburst spectrum in Figure 3 (*bottom*). The model primary spectrum agrees well with the outburst spectrum, except that it lacks the blueshifted absorption in the Fe II lines and Hβ. If the primary always has these absorption lines, we should see them in the polarized flux. If the secondary always has them, we should see them in the model secondary spectrum (Fig. 8, top). This can be explained, in the context of our model, if the primary developed absorption lines during its 1987 outburst. Ae/Be stars do show variability in absorption profiles (Finkenzeller & Mundt 1984); it would be interesting to find a correlation with optical flux.

To further test the model that the primary is the source of the polarized flux, we can compare the polarization and flux of Z CMa at different times, using equation (1) to estimate the contribution of $F_p(\lambda)$ if $P(\lambda)$ and $F(\lambda)$ are measured (taking $P_p(\lambda)$ from Fig. 6). If the brightness increase is due to the primary, the polarization should increase with brightness because the primary contributes most of the polarized flux. This appears to be true when we compare our two observations. In 1991 November, the polarization at 5500 Å was 1.75%; in 1992 March, the polarization was 1.30%. From our estimate of $P_p(5500\ \text{Å}) = 6.75\%$ (Fig. 6), we calculate the magnitude change was about $\Delta m = 0.1$. This is in reasonable agreement with the AAVSO data that shows a change of $\Delta m \sim 0.2$. On 1987 February 12, during the "high state," the magnitude was 8.7. Assuming the secondary did not change in brightness, we calculate that the primary increased in brightness by a factor of 6.3, or 2 mag, to become 2 times brighter than the secondary. This explains why the emission lines dominated the spectrum. We further calculate that the continuum polarization would have been 4.5%. Miroshnichenko & Yudin (1992) made polarimetric observations of Z CMa on 1987 February 26 and found the V-band polarization increased to $\sim$3.7%. Before and after the outburst they observed the polarization at about 1.5%. In the B band, the polarization increased to 5%. This is in good agreement with our models, considering the fact that Miroshnichenko & Yudin (1992) may have used a different size aperture, which would affect our predicted polarization value.

Covino et al. (1988) reported spectra and photometry of Z CMa during 1984–1985, and found the H and Fe II line variability was connected with photometric variability. Specifically, the emission lines became stronger when the optical and IR brightness increased. In the context of our model, this is explained if the primary varied during these observations. At other times, however, it appears the secondary varies as well: Z CMa was the same brightness in 1988 November and 1991 November ($V \approx 9.6$), yet spectra obtained on these dates (Fig. 4, *top*, and Fig. 1, *top*, respectively) show that the 1991 spectrum has more emission lines, particularly in the blue. We conclude that the secondary was fainter in 1991 than in 1988. The primary must have been brighter to give the same total flux. It would be interesting to know if the colors changed, reflecting the differing contributions of the two sources.

We compiled the previous polarimetry and photometry from the literature (see the Appendix for references) and found no correlation between brightness and level of polarization. The comparison is complicated by the fact that polarization measurements were taken with different instruments, filters (*UBVRI*), and apertures, which affect the polarization value regardless of flux. If the lack of correlation is real, it means that the secondary varies as well as the primary.

We can calculate the minimum brightness of Z CMa if the optical variations are due only to the primary. The magnitude change from 1991 November observation would be $\Delta m = 2.5 \log(1/1.3) = 0.3$ since the primary contributed an extra 30% to the secondary's flux in 1991 November when the magnitude was about 9.6 (see Fig. 7). Thus the minimum magnitude is about 9.9. Since 1965, Z CMa has been this magnitude or brighter (Covino et al. 1984), so during this time the primary *could* have been responsible for most of the variation. However, in the 1930s, Z CMa was as faint as 11th mag, indicating that the secondary was faint as well.

Based on the above arguments, we conclude that both the primary and secondary vary with time. Haas et al. (1993) also found with infrared speckle observations that both components vary independently. The variation of one or both of the sources could be due to extinction by moving dust clouds, as reported for V1515 Cyg by Kenyon et al. (1991).

In our model, since the primary contributes all of the polarized flux, the position angle need not change during the outburst, as it would if the secondary contributed polarized flux at a different position angle. Miroshnichenko & Yudin (1992) report no position angle change during the 1987 outburst; however, after the outburst they claim that the position angle got significantly smaller. The position angle of Z CMa measured over the last 30 years has been $150 \pm 20°$ (see the Appendix). The variation, if real, may be due to the different aperture sizes which allow differing contributions from the large-scale nebula. However, our observations were taken in similar apertures and show a small variation, which could be due to a change in the distribution of the dust about the primary or to a small intrinsic component from the secondary.

Figures 7 and 8 show that the primary contributes about 25% of the total optical flux in the November data set, and about 20% in the March data set. The Koresko et al. data show that the primary contributed about 15% of the near-IR flux in 1990 December. According to the AAVSO, the V magnitude was about 9.7, similar to that during our observations. Our suggestion that the primary contributes 20% of the visual flux may seem unreasonable since the dust opacity is larger at visual wavelengths and the companion therefore more extinguished. However, Whitney & Hartmann (1993) and Kenyon et al. (1993) show that a significant amount of scattered light ($\sim$1%–5% of emitted flux) can escape from a highly opaque dusty envelope with bipolar holes. Since the scattering albedo is higher at visual than near-IR wavelengths, more of the primary's flux may scatter into our beam to offset the increased opacity of the obscuring dust. The polarization of the light can be $\sim$5%–20%, depending on the hole size and inclination, and is usually oriented perpendicular to the outflow axis.

5. SUMMARY

We conclude that the polarized flux spectrum of Z CMa is the spectrum of the optically fainter primary, weighted by the continuum polarization function for dust scattering. The primary is an emission line object, perhaps an Ae/Be star like MWC 1080. Direct flux from the primary is obscured by a dusty envelope, so we only see scattered flux that is polarized about 6%. The secondary is a FU Orionis variable whose spectrum is mostly unpolarized. Our interpretation explains several key observational facts about the Z CMa system.

1. Brightness variations of $V \sim 1$–3 mag on short time scales in the optically fainter primary are responsible for at least some of the $V \sim 0$–1 mag variations in the total flux of Z CMa, and for the appearance and disappearance of the narrow emission line spectrum on top of the more broad absorption line spectrum (seen clearly in Hessman et al.).

2. The 1987 optical outburst was due to the primary. The bluer continuum and emission line spectrum do not have to be explained by a huge change in state of a single accretion disk, but instead the addition of a second spectrum that became brighter. We estimate that the primary was twice as bright as the secondary during this outburst.

3. The difference in the 1988 spectrum (Fig. 4, *top*) and the 1991 spectrum (Fig. 1, *top*) indicate that both the primary and secondary vary. The V magnitude was similar for both observations, but the emission lines were fainter in the 1988 spectrum. Thus, the primary must have been fainter and the secondary brighter in 1988 than 1991. In our 1991–1992 spectra, the primary was about one-third as bright as the secondary at visual wavelengths.

4. Our interpretation of the polarization structure in the broad, blueshifted, absorption features—the Na I D λ5890, 5896, Fe II λ5170, and Hα and Hβ lines—is that these come from the secondary, which is therefore an FU Orionis object, and which supplies mostly unpolarized light. Across these features, there is less unpolarized flux to dilute the primary spectrum, so the total polarization increases. The addition of polarized emission (at the rest wavelength) from the primary further increases the polarization across the Balmer and Fe II lines, giving a broad polarization profile (see Fig. 10).

Our model gives a prediction which can be tested with speckle observations. Given simultaneous polarimetric, spectroscopic, and photometric observations, we can say whether the primary or secondary star is varying: If the primary brightens or the secondary dims, the polarization and emission line strength will increase, if the secondary brightens or the primary dims, the polarization and emission line strength will decrease. Photometry will say whether the system is brightening or dimming so we then can say which object is varying. Speckle observations could test our conclusion.

We are grateful to the staff at the Anglo-Australian Observatory and Kitt Peak National Observatory for their assistance with the observations. We thank Marilyn Meade for help with data reduction; Rick Hessman for sending us his spectral data of Z CMa; Janet Mattei and the AAVSO for providing us with visual magnitudes of Z CMa; and B. A. W. thanks David Jeffery for useful conversations. One of the AAT observations was obtained during a joint observing run with J. Hillier. This research has made use of the SIMBAD data base operated by CDS, Strasbourg, France. The Anglo-Australian Telescope is operated by the Anglo-Australian Observatory. Kitt Peak National Observatory is operated by the National Optical Astronomy Observatory under contract to the National Science Foundation. This work was supported by NASA grants NAGW-2977, NAGW-2919, NAGW-2338, NAGW-2306, and NAS2-56777.

APPENDIX

THE INTERSTELLAR POLARIZATION COMPONENT OF Z CMa

Z CMa is a member of the CMa R1 association lying at a distance of 1150 pc (Herbst, Racine, & Warner 1978). Most of the stars in the association are thought to have an age of about 3×10^5 yr. An arc-shaped dust cloud cuts across the association. Much of the star formation activity, possibility triggered by a supernova, lies along the concave edge of this cloud (Herbst et al. 1978). The projected position of Z CMa lies on this concave edge.

1. REDDENING

The reddening of the association members ranges from $E(B-V) = 0.22$–0.74 mag. From this we infer that the reddening foreground to the association is about 0.22, while the additional reddening is due to dust within the association or to circumstellar dust. Most of the stars also have associated reflection nebulae. Z CMa is surrounded by a reflection nebula almost a minute of arc in radius. The actual reddening of Z CMa is difficult to determine since its intrinsic colors are not known. Strom et al. (1972) assumed that Z CMa was a B8 star, based on the strong hydrogen absorption lines, and using an observed $B-V = 1.10$ calculated $E(B-V) = 1.14$. Allen (1976) apparently made the same assumption as Strom et al. and calculated $A_v = E(B-V)R_v = 1.14 \times 3.05 = 3.5$ mag, where R_v is the ratio of total-to-selective extinction. Wallerstein & Cardelli (1987) also use this value. Hartmann et al. (1989) assume a value of $A_v = 2$.

Herbst et al. (1978) collected $B-V$ photometry of Z CMa. From 1967 to 1977, $B-V$ varied only from 1.10 to 1.22. If we use a spectral type of F5 (more typical of a FU Orionis object) then $E(B-V) = 0.7$. This corresponds well to the maximum reddening found in the CMa R1 association, and is consistent with the diffuse interstellar band (DIB) measurements made by Wallerstein & Cardelli (1987). Ae/Be stars generally have very weak DIBs. The strength of the bands in Z CMa indicates not only that there is significant reddening in front of Z CMa but also that it is most likely interstellar cloud dust rather than circumstellar dust.

Therefore, it is likely that $E(B-V)$ for Z CMa is close to 0.7, consisting of 0.2 from the dust foreground to the CMa R1 association and 0.5 from dust in the association itself. For CMa R1 in general, Herbst et al. (1982) find that the association dust has $R_v = 4.2$, so extinction toward CMa R1 stars is $A_v = 3.05E(B-V)_{\rm fgnd} + 4.2E(B-V)_{\rm assoc}$. Assuming $E(B-V)_{\rm fgnd} = 0.2$ and $E(B-V)_{\rm assoc} = 0.5$, then $A_v = 2.7$ for Z CMa.

2. POLARIZATION

The observed polarization of Z CMa will be the vector sum of several components: $P = P$(foreground dust) + P(reflection nebula) + P(circumstellar). The first two components should be nonvariable. The maximum interstellar polarization expected for $A_v = 2.7$ mag is about 8%. This assumes perfect alignment of the grains along a single magnetic field direction, which is unlikely in such a complicated region of the sky. Also, the foreground and association components will probably have different position angles so the combined polarization would be much smaller than 8%. In fact, in CMa R1, one star (CD $-10°1839$) lying less than a degree from Z CMa has $E(B-V) = 0.6$ and $P = 0.1\%$ (Pavlova & Rspaev 1986).

The contribution of the reflection nebula, while intrinsically nonvariable, will vary depending on the size and placement of the aperture used for a particular observation and on where the aperture is placed for the sky subtraction. The apertures used in various studies range from 3 to 15″ in diameter. Multi-aperture polarimetry of the Herbig Ae/Be star V380 Ori that is surrounded by a reflection nebula shows a dramatic effect (Vrba et al. 1979): In the red, the polarization is relatively invariant with aperture size but in the blue the polarization decreases rapidly with increasing aperture. The nebula is blue so the effects are small in the red. The position angle rotates in the blue, indicating that the nebular contribution has a nonzero polarization despite the appearance of a spherical symmetry. The circumstellar component may be intrinsically variable.

We can try to separate the polarization components of Z CMa through observations of the polarization variability of Z CMa itself and through observations of stars projected on the sky nearby. Polarimetry of Z CMa has been obtained at irregular intervals since the 1950s (Hall 1958; Serkowski 1970; Vrba 1975; Garrison & Anderson 1978; Vrba, Baierlein, & Herbst 1987; Jain, Bhatt, & Sagar 1990; Miroshnichenko & Yudin 1992). Virtually all of the observations have been through *UBVR* filters. No previous Hα polarimetry exists except for a very low S/N narrow-band filter observation (0.93% ± 0.44%) by Garrison & Anderson (1978). Even the very high Hα polarization (7%) measured here would not affect the $R-$ band observations more than a few tenths of a percent. So no previous information is available about line effects. Z CMa has shown broad-band polarizations ranging from 0.2 to 3.5% (see references above). Most recently, Miroshnichenko & Yudin (1992) found similar variations between 1986 and 1990.

Only Garrison & Anderson (1978) have previously attempted to distinguish the interstellar and intrinsic components of Z CMa. They used stars lying nearby on the sky, assumed a normal Serkowski wavelength dependence for the foreground interstellar component and assumed that the intrinsic wavelength dependence would be that of a "classical emission-line star" with polarization peaking in the V band. Their result was 2% at 144° for the foreground interstellar component.

The sample of stars that are projected on the sky near Z CMa with polarimetry has been augmented by Vrba et al. (1987), and Pavlova & Rspaev (1986). Vrba et al. (1987) have observed 140 stars in the direction of CMa R1, giving a comprehensive map of the interstellar polarization in this region. These new data reinforce previous data that show that there is no preferred direction to the foreground interstellar polarization in this region of the sky. To the east and north of Z CMa, toward the Galactic equator, there is some indication of a preference in position angle parallel to the Galactic plane (140°) but no star has as much as 2% polarization. The measured polarization is generally 1% or less. The cloud, which arcs through the CMa R1 association very near to Z CMa, obviously affects the magnetic field direction. Stars just west of Z CMa in the area of this cloud have position angles near 10°. Two faint stars very close to Z CMa were measured to have 0.2%–0.3% polarization.

The new data presented here offer compelling evidence that most if not all the measured polarization of Z CMa is intrinsic and therefore any interstellar (foreground plus association) component is very small.

i. These new observations were made through smaller (<2".7) apertures than any previous observations (10"–15") reducing contamination due to the large-scale reflection nebula. Also, the sky aperture lies about 25" from Z CMa. This lies outside the bright inner portion of the reflection nebula (Herbst et al. 1978).

ii. The optical jet seen in Z CMa is at P.A. = 60°, exactly 90° from the measured position angle of the polarization, implying an intrinsic source for the polarization. The fact that the position angle of the jet (60°) and the plane of the Galaxy (140°) are about 90° apart implies that the interstellar and intrinsic components may add and subtract from each other without changing the measured position angle, adding to the uncertainty of how large each component is. If the interstellar component were in fact as large as 2% at 144° as proposed by Garrison & Anderson (1978), then the intrinsic polarization measured here would be 0% in the continuum and 5% in Hα, still at 150°.

iii. The measured wavelength dependence (*UBVR*) varies from one epoch to another. The interstellar component would not vary at all. However, these data were obtained by various observers through different apertures, so it is not clear that all of these data are comparable. The two most recent observations are from: (1) Vrba et al. (1987) (*UBVRI*) obtained in 1985, which shows a flat wavelength dependence; they measured $P \sim 2\%$ at 150°, very similar to the AAT observations; the aperture size is unknown; (2) Jain et al. (1990) (*UBVRI* with a 15" aperture), which shows a steep wavelength dependence falling from 1.5% at *I* at P.A. = 155°; perhaps the large aperture is causing this wavelength dependence.

iv. All the existing observations (14 epochs) show only a ±20° variation in position angle. Some of these variations may be real but systematic errors in comparing polarimetry from different instruments are common and difficult to eliminate. A large majority of the observations indicate that the P.A. is within 3 σ of 150°. At the same time the continuum polarization varied greatly from about 0.2% to 3.5%. It seems reasonable that the low measured value which is zero within the errors was obtained when the intrinsic polarization was near zero. The large measured variations ($\delta P = 3\%$) with little or no position angle variation indicate that there is only one significant component, that which is intrinsic to Z CMa.

v. Within the accuracy of the observations, the continuum and line polarizations have the same position angle. Since the continuum is polarized 2% and Hα is polarized about 6%, any significant interstellar component would result in different measured position angles in the intrinsic continuum and line polarizations unless the interstellar component is at exactly 150° or 60°. Different intrinsic continuum and line position angles may be imaginable but the interstellar and intrinsic components would have had to conspire to add such that the resulting polarization has the same position angle at all wavelengths. Therefore it is more likely that the interstellar component is fairly small (<0.5%).

REFERENCES

Allen, D. A. 1976, MNRAS, 174, 29P
Antonucci, R. R. J., & Miller, J. S. 1985, ApJ, 297, 621
Bastien, P. 1988, in Polarized Radiation of Circumstellar Origin, ed. G. V. Coyne et al. (Vatican Obs.: Vatican City State), 541
Bastian, U., & Mundt, R. 1985, A&A, 144, 57
Beyer, M. 1950, Astron. Abh. Hamburg, 12, 1318
Brückner, G. 1963, Z. Astrophys., 58, 73
Calvet, N., Hartmann, L., & Kenyon, S. J. 1993, ApJ, 402, 623
Cantó, J., Rodríguez, L. F., Calvet, N., & Levreault, R. M. 1984, ApJ, 282, 631
Chandrasekhar, S. 1960, Radiative Transfer (New York: Dover), 50
Cohen, M., & Kuhi, L. V. 1979, ApJS, 41, 743
Cohen, M., Kuhi, L. V., Harlan, E. A., & Spinrad, H. 1981, ApJ, 245, 920
Covino, E., Terranegra, L., Vittone, A., Giovannelli, G., & Rossi, C. 1988, in Physics Formation of Fe II Lines outside LTE, ed. R. Viotti et al. (Dordrecht: Reidel), 143
Covino, E., Terranegra, L., Vittone, A. A., & Russo, G. 1984, AJ, 89, 1868
Evans, N. J., II, Levreault, R. M., & Harvey, P. M. 1986, ApJ, 301, 894
Finkenzeller, U., & Mundt, R. 1984, A&AS, 55, 109
Garrison, L. M., Jr., & Anderson, C. M. 1978, ApJ, 221, 601
Haas, M., Christou, J. C., Zinnecker, H., Ridgway, S. T., & Leinert, Ch. 1993, A&A, 269, 282
Hall, J. S. 1958, Publ. US Naval Obs., 2 Ser., 17, 21
Hartmann, L., & Kenyon, S. J. 1985, ApJ, 299, 462
———. 1987a, ApJ, 312, 243
———. 1987b, ApJ, 322, 393
Hartmann, L., Kenyon, S. J., & Calvet, N. 1993b, ApJ, 407, 219
Hartmann, L., Kenyon, S. J., & Hartigan, P. 1993a, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: Univ. of Arizona Press), 497
Hartmann, L., Kenyon, S. J., Hewett, R., Edwards, S., Strom, K. M., Strom, S. E., & Stauffer,J. R. 1989, ApJ, 338, 1001
Hayes, D. S., & Latham, D. W. 1975, ApJ, 197, 593
Herbig, G. H. 1960, ApJS, 4, 337
Herbst, W., Miller, D. P., Warner, J. W., & Herzog, A. 1982, AJ, 87, 98
Herbst, W., Racine, R., & Warner, J. W. 1978, ApJ, 223, 471
Hessman, F. V., Eislöffel, J., Mundt, R., Hartmann, L. W., Herbst, W., & Krautter, J. 1991, ApJ, 370, 384
Jain, S. K., Bhatt, H. C., & Sagar, R. 1990, A&AS, 83, 237
Jeffery, D. J. 1989, ApJS, 71, 951
Kenyon, S. J., Hartmann, L., & Hewett, R. 1988, ApJ, 325, 231
Kenyon, S. J., Hartmann, L., & Kolotilov, E 1991, PASP, 103, 1069
Kenyon, S. J., Whitney, B. A., Gomez, M., & Hartmann, L. 1993, ApJ, in press
Königl, A. 1989, ApJ, 342, 208
Koresko, C. D., Beckwith, S. V. W., Ghez, A. M., Matthews, K., & Neugebauer, G. 1991, AJ, 102, 2073
Koresko, C. D., Beckwith, S. V. W., & Sargent, A. I. 1989, AJ, 98, 1394
Leinert, C., & Haas, M. 1987, A&A, 182, L47
Miroshnichenko, A. S., & Yudin, R. V. 1992, Izv. Pulkovo Obser., 209, in press
Pavlova, L. A., & Rspaev, F. K. 1986, Astrofizika, 25, 461
Pelletier, G., & Pudritz, R. E. 1992, ApJ, 394, 117
Poetzel, R., Mundt, R., & Ray, T. P. 1989, A&A, 224, L13
———. 1992, A&A, 262, 229
Pringle, J. E. 1989, MNRAS, 236, 107
Pudritz, R. E., & Norman, C. A. 1983, ApJ, 274, 677
Serkowski, K. 1970, ApJ, 160, 1083
Stenflo, J. O. 1974, Solar Phys., 37, 31
Stenflo, J. O., Baur, T. G., & Elmore, D. F. 1980, A&A, 84, 60
Strom, S. E., Strom, K. M., Yost, J., Carrasco, L., & Grasdalen, G. 1972, ApJ, 173, 353
Tamura, M., & Sato, S. 1989, AJ, 98, 1368
Vrba, F. J. 1975, ApJ, 195, 101
Vrba, F. J., Baierlein, R., & Herbst, W. 1987, ApJ, 317, 207
Vrba, F. J., Schmidt, G. D., & Hintzen, P. M. 1979, ApJ, 227, 185
Wallerstein, G., & Cardelli, J. A. 1987, AJ, 93, 1522
Whitney, B. A., Clayton, G. C., Schulte-Ladbeck, R. E., & Meade, M. R. 1992, AJ, 103, 1652
Whitney, B. A., & Hartmann, L. 1993, ApJ, 402, 605
Wiehr, E. 1975, A&A, 38, 303