THE ASTROPHYSICAL JOURNAL, 338:1001–1010, 1989 March 15


# PRE–MAIN-SEQUENCE DISK ACCRETION IN Z CANIS MAJORIS

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*Received 1988 June 7; accepted 1988 August 24*

## ABSTRACT

We suggest that the pre–main-sequence object Z CMa is a luminous accretion disk, similar in many respects to the FU Orionis variables. Z CMa shows the broad, doubled optical absorption lines expected from a rapidly rotating accretion disk. The first overtone $v' - v'' = 2\text{–}0$ CO absorption we detect in Z CMa is blue-shifted, suggesting line formation in a disk wind. Accretion at rates $\sim 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$ over $\sim 10^2$ yr is required to explain the luminosity of Z CMa. The large amount of material accreted ($10^{-1}\ M_\odot$) indicates that Z CMa is in a very early stage of stellar evolution, possibly in an initial phase of massive disk accretion.

*Subject headings*: stars: accretion — stars: individual (Z CMa) — stars: pre–main-sequence

## I. INTRODUCTION

The suggestion that star formation involves accretion from massive disks (e.g., Cameron 1978; Mercer-Smith, Cameron, and Epstein 1984) has received recent observational support. The FU Orionis variables have been interpreted as luminous accretion disks surrounding pre–main-sequence stars (Hartmann and Kenyon 1985, 1987*a*, *b*; Kenyon, Hartmann, and Hewett 1988, hereafter KHH), and may well represent the tail end of a massive disk accretion phase. The accretion disk model implies that very large amounts of material are accreted in FU Ori events; FU Ori itself has accreted roughly $10^{-2}\ M_\odot$ since 1939 (Hartmann and Kenyon 1985). Present event statistics are consistent with every low-mass star accreting 1% of its mass through FU Ori events (Hartmann and Kenyon 1985; KHH), but the recent increase in the discovery rate (Elias 1978; Graham and Frogel 1985; Carr, Harvey, and Lester 1986; Mundt *et al.* 1985; Stocke *et al.* 1988) suggests that these statistics substantially underestimate the total mass accumulated in FU Ori episodes.

The identification of additional accreting pre–main-sequence objects would help assess the importance of such accretion in early phases of stellar evolution and improve our understanding of protostellar disk physics. In his Russell lecture, Herbig (1977) suggested that a variety of irregular light variations observed in pre–main-sequence variables might be powered by the same mechanism as FU Ori objects (presumably, as yet unexplained variations in accretion rates). One irregular variable of special interest is the luminous pre–main-sequence object Z CMa. Although Z CMa is normally classified as an Ae/Be star, it has many features in common with FU Ori objects. It is rapidly rotating and has a spectrum which is at least partly that of type F (Strom *et al.* 1972), consistent with the spectral types of FU Ori objects in outburst. Z CMa also exhibits the very strong blueshifted Balmer and Na I absorption features (Finkenzeller and Jankovics 1984; Finkenzeller and Mundt 1984) typical of the FU Ori class. Z CMa has not staged a large ($\gtrsim 5$ mag) optical outburst as have other FU Ori objects discovered in this century, but it has exhibited unusual irregular optical variability over a range $\sim 2$ mag (see Covino *et al.* 1984). Z CMa is also associated with a curved reflection nebulosity like the other FU Ori objects (Goodrich 1987).

This paper reports high-resolution optical and infrared spectroscopic observations of Z CMa. At our two epochs of observation, Z CMa had doubled optical absorption lines, with a velocity difference of about 100 km s$^{-1}$ between the two components. The data are inconsistent with the profiles expected from a rotating single star, but agree with the predictions of an accretion disk model. The absence of a velocity shift between two spectra obtained one year apart argues against a binary model. We detected 2 $\mu$m first-overtone $v' - v'' = 2\text{–}0$ CO absorption in Z CMa, indicating the presence of material substantially cooler than the optical F-type photosphere, as found in other FU Ori objects. The CO absorption is blueshifted by $\sim 25$ km s$^{-1}$ with respect to the optical velocities, suggesting that a strong wind emanates from the infrared-emitting region, an effect also seen in FU Ori. We suggest that Z CMa is a luminous accretion disk like the FU Ori objects, with an accretion rate $\dot{M} \sim 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$, and with a powerful accretion-driven disk wind.

## II. OBSERVATIONS

### *a*) *Optical Data*

Spectra of Z CMa were obtained with the KPNO 4 m echelle spectrograph and CCD detectors. A red spectrum of 45 minutes exposure time was taken on 1983 December 10 using a 31.6 lines mm$^{-1}$, 63° echelle grating with the 150 lines mm$^{-1}$ cross-disperser. The observation was made through a 200 $\mu$m slit, and the TI CCD chip was binned 2 × 2 to produce a frame containing 400 × 400 pixels. Portions of eight echelle orders were imaged on the chip; the reduced spectra are $\sim 40$ Å long,

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cover the wavelength range between 6290 Å and 6840 Å, and have a resolution of $\sim 15$ km s$^{-1}$. Blue spectra were taken on 1983 December 12 with the same grating and slit setup; these data span the wavelength range 4720–5330 Å in 14 echelle orders each of about 30 Å length. We analyzed the 30 minute exposure of this series. A 12 minute red exposure of Z CMa was secured on 1984 December 5 using the 58 lines mm$^{-1}$, 63° echelle and 226 lines mm$^{-1}$ cross-dispersion grating. The resulting six echelle orders span the range from 6150 Å to 6890 Å in 40 Å intervals.

Standard star spectra were obtained with the 4 m echelle and TI-2 CCD combination during 1988 January. These data have approximately 12 km s$^{-1}$ resolution and completely cover the wavelength range 5100–6800 Å. The data were reduced using the NOAO IRAF system on Sun workstations.

Our optical observational results can be summarized as follows.

1. The absorption lines of Z CMa are clearly doubled in the red spectral region. Individual line profiles are often difficult to determine in the blue spectrum due to extensive line blending, but some strong lines are doubled, and cross-correlations with a standard star produce doubled correlation peaks. The separation of the two absorption features is about 100–120 km s$^{-1}$ in both the blue and red spectra.

2. The centroids of the optical lines are at the same radial velocity as the nearby interstellar medium.

3. There is no evidence for shifts in the systemic velocity or in the profile shapes between 1983 December and 1984 December.

These points are illustrated by the sample data shown in Figure 1. The Li I and Ca I λ6717.7 lines are very broad and obviously doubled in appearance. Within the observational errors, there is no evidence for changes in the Ca I line in the two Z CMa spectra taken 1 yr apart. For comparison, we show a spectrum of the F6 I star SAO 22328, synthetically broadened to a $v \sin i = 100$ km s$^{-1}$ to produce a comparable overall line width (see Hartmann *et al.* 1986 for methodology and limb darkening assumptions).

Velocity measurements of an individual line are uncertain because the lines of Z CMa are so broad. For quantitative measurements we cross-correlated individual echelle orders of the Z CMa spectra (see Hartmann *et al.* 1986). The cross-correlation peaks from most echelle orders showed clear evidence for double structure (see Fig. 2). We used the average of the outer zero-crossings of the doubled cross-correlation peak to determine the average system velocity. The heliocentric radial velocities measured in this way were $+29.5 \pm 1.9$ km s$^{-1}$, $+32.1 \pm 2.7$ km s$^{-1}$, and $+30 \pm 4$ km s$^{-1}$ from the red 1983, red 1984, and blue 1983 observations, respectively. The quoted errors are the formal standard deviations of the results for the individual echelle orders, and probably represent a reasonable estimate of the true uncertainty in the derived mean velocities. These mean Z CMa velocities agree quite well with the heliocentric velocity $\sim +30$ km s$^{-1}$ derived for neighboring interstellar material (32 km s$^{-1}$ from radio CO measurements, Cantó *et al.* 1984; 30–33 km s$^{-1}$ from interstellar Na I D absorption, Finkenzeller and Mundt 1984). The kinematic association of Z CMa with diffuse interstellar material, along

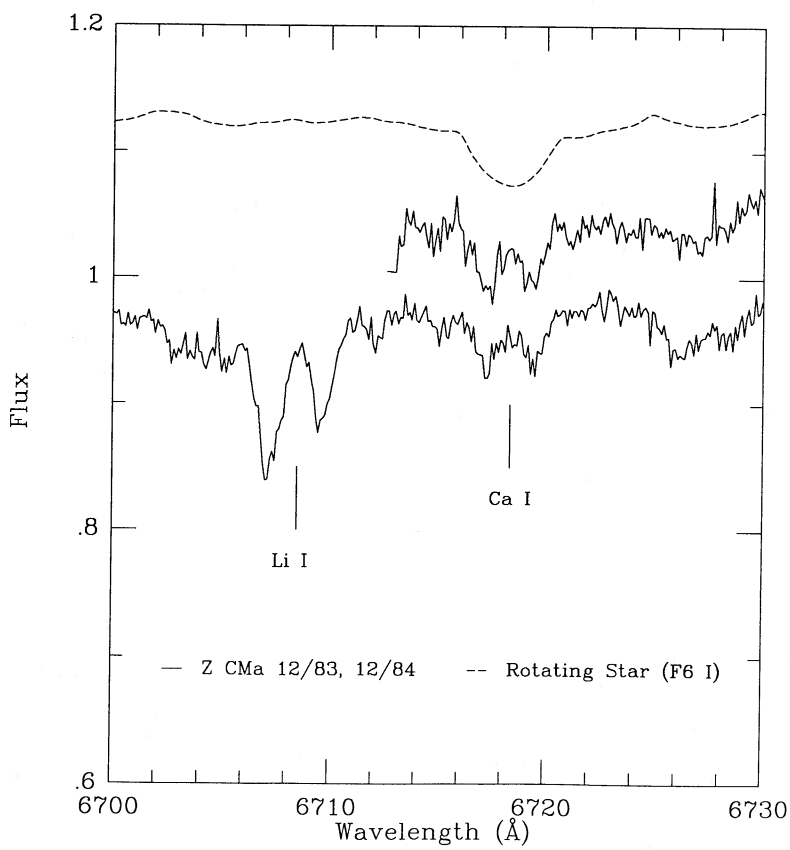


FIG. 1.—Portions of two high-resolution optical red spectra of Z CMa, taken 1 yr apart. The expected locations of the Li I λ6707 and Ca I λ6717.7 lines are indicated assuming that Z CMa is at the velocity of the neighboring interstellar medium (+30 km s$^{-1}$, heliocentric). The Li I and Ca I lines are strongly doubled, as emphasized by the comparison with an F6 I supergiant spectrum artificially broadened to $v \sin i = 100$ km s$^{-1}$. No profile changes are apparent in the Ca I line.

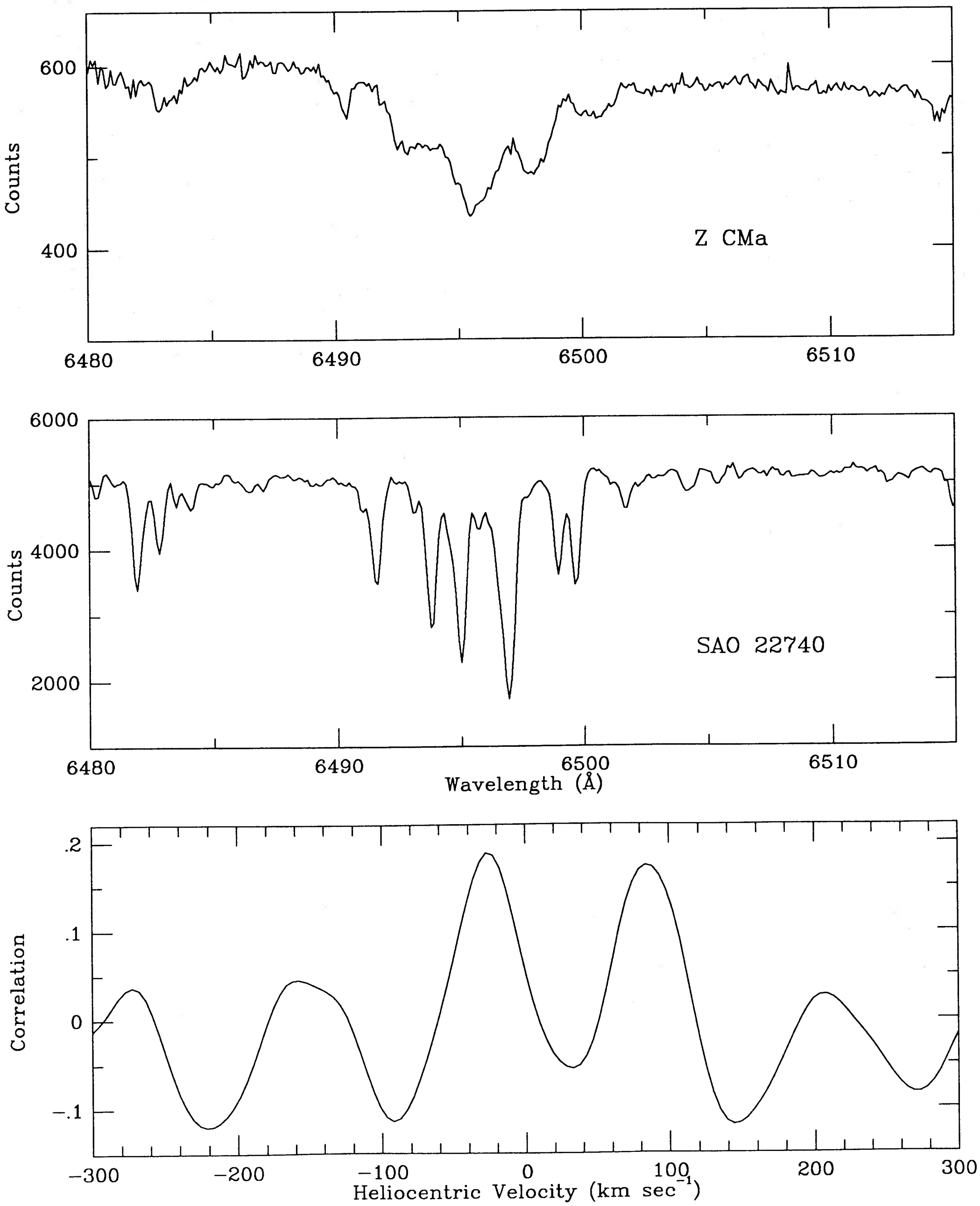


FIG. 2.—A portion of the red spectrum near 6500 Å in Z CMa (*upper panel*); the corresponding spectral region in the G2 I star SAO 22740 (*middle panel*); and the cross-correlation of the upper and middle panel spectra (*bottom panel*). The cross-correlation exhibits two peaks, consistent with doubled absorption lines similar to those seen in Fig. 1. The neighboring interstellar medium heliocentric velocity of +30 km s$^{-1}$ is equidistant between the peaks (see text).

with the strong Li I absorption, confirms the pre-main sequence nature of this object.

### *b*) *Infrared Data*

Infrared spectroscopic observations of program and comparison stars were made on 1987 December 5–7 through a narrow-band CO filter with the 1.4 m Fourier transform spectrometer (FTS) at the coudé focus of the Mayall 4 m telescope. The data cover the spectral region 4150–4450 cm$^{-1}$ (2.41–2.25 $\mu$m) at an unapodized resolution of 0.3 cm$^{-1}$ ($\sim$20 km s$^{-1}$). Corrections for atmospheric absorption were made by ratioing object data with spectra of nearby A or B stars having comparable air masses. The spectra have not been flux-calibrated, because the observations were made in poor seeing and through variable clouds.

Portions of our infrared spectra for Z CMa are presented in Figure 3, along with data for the Ae star AB Aur and the M6 giant HR 4267. A weak, broad absorption band is apparent on the spectrum of Z CMa at 4355–4360 cm$^{-1}$, and this feature probably can be identified as the CO $v'$–$v''$ = 2–0 band head. Other CO absorption features might be present redward of the band head, but there is little evidence for the $v'$–$v''$ = 3–1 band head at 4305 cm$^{-1}$ on the Z CMa spectrum. There are no obvious absorption features on the AB Aur spectrum, although

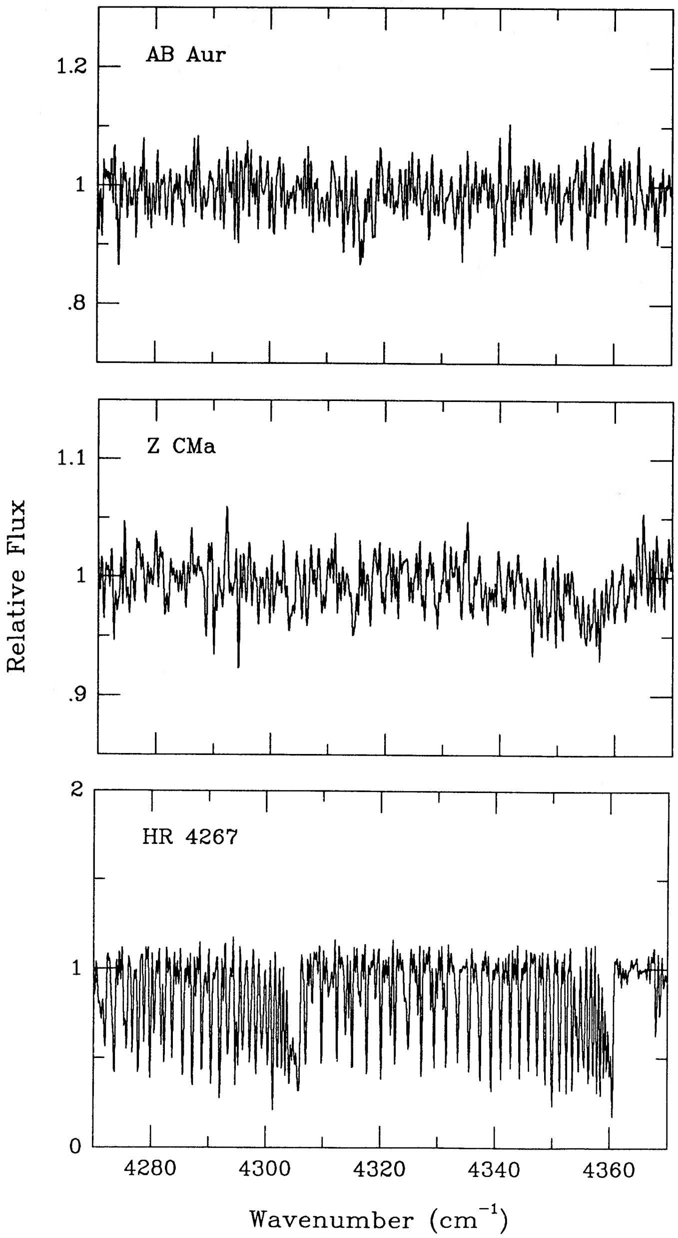


FIG. 3.—High-resolution infrared spectra of the Herbig Ae/Be star AB Aur, Z CMa, and the M6 giant HR 4267. The $v'-v'' = 2-0$ and $v'-v'' = 3-1$ band heads of CO are visible at 4360 cm$^{-1}$ and 4305 cm$^{-1}$, respectively, in the M giant spectrum; evidence for the $v'-v'' = 2-0$ band head is seen in Z CMa. No features are apparent in AB Aur.

the signal-to-noise ratio is a factor of $\sim 2$ worse than the Z CMa data.

Cross-correlations of AB Aur, Z CMa, and a standard M0 giant (HR 2905) using HR 4267 as a template are shown in Figure 4. The $R$-value of the Z CMa cross-correlation ($R$ is the ratio of peak height to the rms noise; Tonry and Davis 1979) is $R = 7.1$. The template spectrum is totally dominated by CO absorption, so the cross-correlation verifies the presence of CO in Z CMa. The correlation peak for Z CMa may be somewhat broader than that of the comparison star, suggesting that the absorption lines are marginally resolved on our spectra. Because CO first-overtone absorption appears only in stars later than $\sim$type G5 (Kleinmann and Hall 1986), these results indicate the presence of gas substantially cooler than the optical F-type photosphere.

No significant peak was found in the cross-correlation analysis of AB Aur. We are confident that this object does not possess either the prominent CO absorption lines found in FU Ori objects or the weak CO features observed in Z CMa. However, the present FTS data probably are too noisy to rule out the existence of CO features a factor of 2–3 weaker than those detected in Z CMa. CO *emission* or no CO features seem to prevail in T Tauri stars (Carr, Harvey, and Lester 1986; Kenyon and Hartmann 1987; Hamann and Simon 1988), so the apparent lack of CO absorption in this relatively normal Ae star is not surprising.

The heliocentric radial velocity derived from our 2 $\mu$m spec-

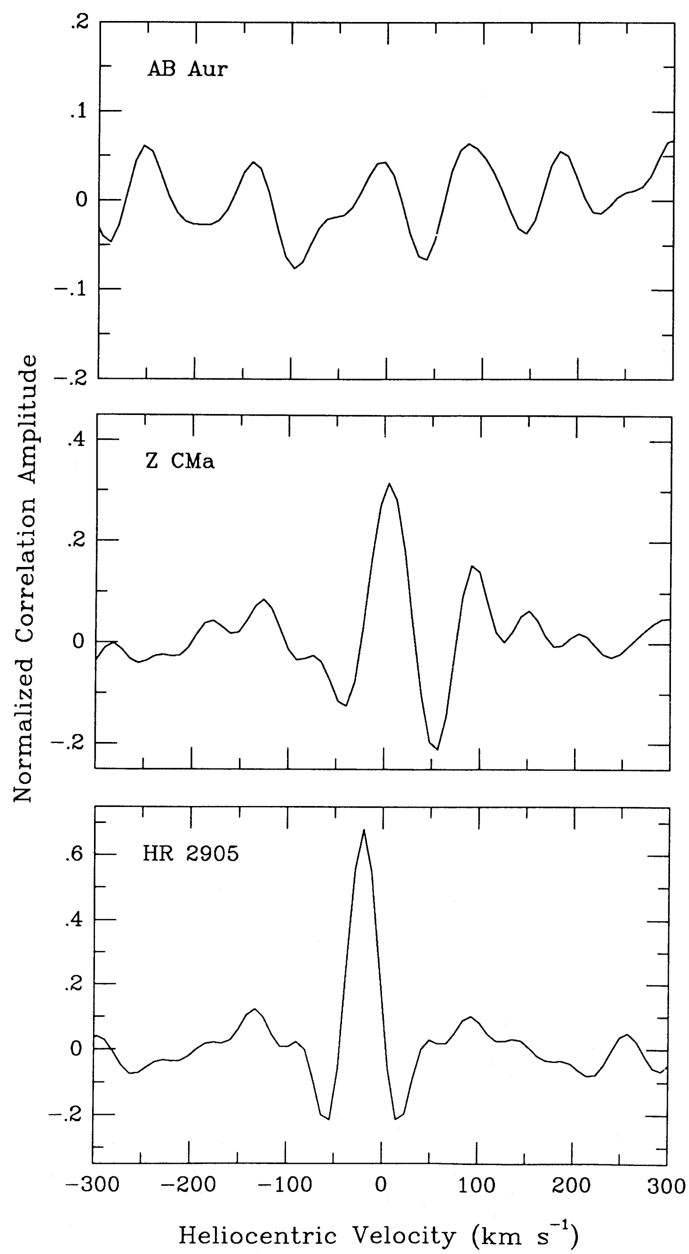


FIG. 4.—Cross-correlations of AB Aur, Z CMa, and an M giant standard (HR 2905) spectra with the spectrum of HR 4267. A strong signal is seen at a heliocentric velocity of $+5$ km s$^{-1}$ in Z CMa.

trum of Z CMa is $+5$ km s$^{-1}$ and is estimated to have an uncertainty of $\pm 2$–3 km s$^{-1}$. This CO velocity is blueshifted with respect to the optical stellar and interstellar medium velocities by $\sim 25$ km s$^{-1}$.

### III. AN ACCRETION DISK MODEL FOR Z CMa

The clear doubling of photospheric lines in Z CMa is reminiscent of the doubled line profiles predicted for rotating disks (cf. KHH). The absence of any detectable change in the profiles in two red spectra obtained 1 yr apart does not favor a spectroscopic binary interpretation. We are motivated to construct an *accretion* disk model for Z CMa by the many spectral similarities of Z CMa to FU Ori objects, which have been modeled as accretion disks (Hartmann and Kenyon 1985, 1987*a*, *b*; KHH). These similarities include an optical spectral type of a middle to late F supergiant; unexpectedly strong 2 $\mu$m CO absorption, given the optical spectral type; and P Cygni Balmer and Na I line profiles exhibiting broad blueshifted absorption with very little redshifted emission (Finkenzeller and Mundt 1984). An accretion disk model can also provide a natural explanation for the large (2 mag) irregular photometric variations through variations in the accretion rate.

#### *a) Optical Spectrum Modeling*

We synthesized an accretion-disk model spectrum to make a quantitative application of these ideas. The methods used to synthesize disk spectra are described in detail by KHH. Briefly, steady accretion disk theory provides a theoretical distribution of surface temperature with radius. We divide the disk up into small annuli, each of which is assumed to radiate as a star of the appropriate effective temperature; this provides the overall eenergy distribution. To model the spectrum at high resolution, we used standard supergiant spectra obtained during the KPNO Janaury 1988 run to represent different annuli in the disk. Each annular spectrum is then convolved with the line profile for a rotating ring, which is double-peaked, and scaled by the rotational velocity given by Keplerian motion. The spectra of the annuli are then added up, weighted by their fractional contribution to the total spectrum at the wavelength of observation.

For a steady-state accretion disk in Keplerian rotation, the temperature distribution scales with the maximum disk temperature $T_{\max}$ (see Lynden-Bell and Pringle 1974). Because of the large ($A_v \sim 2$) and possibly pecular extinction to Z CMa, it is better to use spectral indicators to estimate $T_{\max}$.

Strom *et al.* (1972) have suggested that a late B spectrum is present in Z CMa, in addition to the F-type spectrum. However, it seems clear that much of the "B type" classification depends upon the great strength of the blueshifted Balmer absorption lines, which certainly are produced in an outflowing wind (e.g., Covino *et al.* 1984). The He I absorption lines found by Strom *et al.* (1972) were not mentioned by Swings and Struve (1940, 1942) or by Merrill and Burwell (1949), and Herbig (1960) did not find them on Lick plates. The low-resolution spectra of Covino *et al.* (1984) show a strong G band, but no clear evidence of He I. The spectrum published by Finkenzeller and Jankovics (1984) shows blanketing near, but no evidence for, He I $\lambda$4471, and the observations of Finkenzeller and Mundt (1984) show no evidence for He I $\lambda$5876.

To place better constraints on a hot component in Z CMa, we have examined *IUE* spectra from the NSSDC. Z CMa is heavily reddened, so the UV continuum is quite weak. Nevertheless, two low-dispersion LWR spectra show evidence for an absorption break in the continuum at 2650 Å. This break is quite prominent in F stars but is absent in supergiant stars earlier than about A2. We estimate the spectral type of Z CMa to be about F5 I in this wavelength region (assuming a supergiant classification from the optical data; see below). Thus, there is no evidence for a photospheric component in Z CMa which has a temperature comparable to that of a B-type star.

Based on these considerations, and in view of the uncertainties involved, we have simply adopted the temperature distribution for the FU Ori model of KHH (their Table 4). This model has a mean optical spectral type of $\sim$F9 I, and a mean spectral type at 2700 Å of about F3 I. The rotational velocity scale is a free parameter to be adjusted to match the optical rotation. We increased the rotational velocities of the FU Ori model (KHH, Table 4) by a factor of about 1.3 so $v \sin i$ at the inner disk edge = 120 km s$^{-1}$.

The synthesized disk model spectra are compared with the observed red spectra of Z CMa, along with the rotating F6 I star model, in Figures 5–8. In regions where line blanketing and blending are unimportant, the double profile structure predicted by the model is in good agreement with observations (e.g., the strong $\lambda$6643.7 Ni I and $\lambda$6663.4 Fe I lines in Fig. 5). At somewhat shorter wavelengths, where line blending is extensive, the disk model still does a better job in reproducing the spectral features than does the simple rotating star model (Figs. 6–8).

The disk model has slightly deeper absorption in the $\lambda$6350–6370 region than observed (Fig. 7). These lines are much weaker in F stars than in G stars, indicating that the disk model is somewhat too cool. To explore this quantitatively we constructed a "pseudodisk" model, which has the same line profiles as the standard disk model, but uses only one spectral type for the spectrum synthesis (see KHH). The comparison shown in Figure 7 indicates that the mean red spectral type of Z CMa is later than F6 I. The mean red spectral type of the FU Ori disk model is roughly F9 I, so we conclude that the Z CMa red spectrum is slightly earlier than F9.

The equivalent widths resulting from the use of supergiant standards in the disk model agree quantitatively with the observations of Z CMa. If we had used giant or dwarf standards, the predicted line strengths would be much too small. Thus, the spectrum of Z CMa is consistent with that of a low-gravity atmosphere, as expected for the vertical gravity of a disk rotating at Keplerian velocities.

It is much more difficult to see line doubling in the blue spectral region of Z CMa, due to extensive blending caused by the large velocity broadening. Nevertheless, one can see suggestive structure in a few of the strongest lines (see Fig. 8, and the $\lambda$5226.87 and $\lambda$5227.19 Fe I blend).

#### *b) The Infrared Spectrum Problem*

While the simple steady disk model adequately accounts for the optical spectral energy distribution of Z CMa with an $E(B-V) \sim 0.6$, it fails badly to account for the infrared energy distribution (Fig. 9). The infrared excess in Z CMa is substantially larger than predicted by steady accretion disk models which fit FU Ori and V1057 Cyg so well (see KHH).

The infrared luminosity of Z CMa is about 2000–3000 $L_\odot$ (Fig. 9), assuming a distance of 1150 pc (Claria 1974; Herbst and Assousa 1977). If the energy loss is provided *locally* by

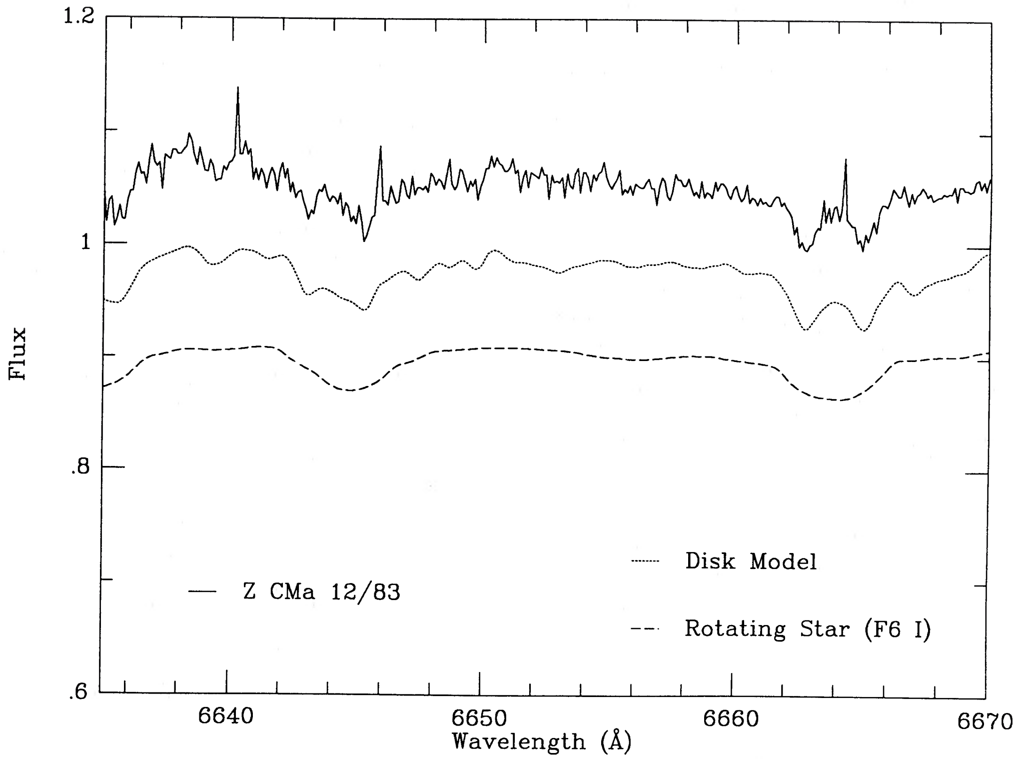


FIG. 5.—Comparison of Z CMa red spectra with an accretion disk model (*dotted line*) and a rotating F6 I star (*dashed line*). The disk model is the same as for FU Ori (KHH, Table 4), except with $v \sin i$ values 1.3 times larger. The disk model does a much better job in reproducing the double structure of $\lambda 6642$ and $\lambda 6663$ than a simple spherical rotating star model.

accretion, then for a given annulus of radial width $\Delta R$ at a radius $R$:

$$\Delta L_{\rm disk} \sim \frac{GM\dot{M}}{R}\frac{\Delta R}{R}\,. \tag{1}$$

For example, if one wishes to obtain a luminosity of about $10^3$ $L_\odot$ from a region at 300 K to produce the observed 10 $\mu$m luminosity, the blackbody emitting area must have a radius $R \sim 10^4\ R_\odot$. For a central mass of 1 $M_\odot$, this requires a clearly unacceptable accretion rate of $\dot{M} \sim 0.4\ M_\odot\ {\rm yr}^{-1}$.

The only way gravitational energy release can provide the required luminosity is if the energy extracted deep in the potential well can be transferred to very large disk radii by some mechanism (cf. Adams, Lada, and Shu 1988). The most obvious and likely method to accomplish this energy transport is to postulate a large dust cloud surrounding Z CMa, which absorbs light generated from interior regions and reemits this energy in the infrared. The estimated optical extinction is too low to provide enough infrared opacity in a spherically symmetric dust cloud, so we suggest that the dust distribution around Z CMa may be flattened or otherwise non–spherically symmetric. A flattened geometry would permit optical light to escape out the poles with modest reddening. Similar conclusions concerning the dust distributions around other pre-main sequence objects were reached by Myers *et al.* (1987).

Z CMa exhibits spatially resolved structure on the 0″.1 level at $H$ and $K$ (Leinert and Haas 1987; Beckwith 1988). There is an optical companion roughly 1″.5 distant and about 2 mag fainter (Finkenzeller and Mundt 1984), but this object apparently does not contribute a significant amount of light in the near-infrared (Leinert and Haas 1987; Dyck 1988; Beckwith 1988). Leinert and Haas (1987) suggest that the near-infrared structure is due to scattered light, perhaps associated with a dusty disk. They proposed that $\gtrsim 40\%$ of the 2 $\mu$m radiation received at Earth has been scattered off an edge-on dusty disk having an angular extent of $\sim$0″.1 in the E–W direction ($\sim 2 \times 10^4\ R_\odot$ if $d = 1150$ pc), arguing that a high-particle albedo and/or disk geometry were needed to reconcile the large infrared scattering with the relatively small optical reddening. The scattering interpretation is supported by the large ($\sim 1'$), linear, optical reflection nebula associated with Z CMa. For comparison we note that our disk model in Figure 9 has a total radius $\sim 900\ R_\odot$, and that the characteristic radius of the 2 $\mu$m emitting region is $\sim 70\ R_\odot$. (The 2 $\mu$m CO absorption comes from the same region as the 2 $\mu$m continuum.) Thus, the disk model implies that our infrared spectral observations correspond to a much smaller region than covered by the infrared speckle data.

Beckwith (1988) suggests that the near-infrared structure might be due to a close binary companion. Although the infrared spectrum could be associated with a rather peculiar giant of spectral type $\sim$K and luminosity $\sim 10^3\ L_\odot$, the infrared excess is broader than a single temperature blackbody (Fig. 8), and the 25 km s$^{-1}$ shift of CO absorption lines relative to the interstellar medium is significantly larger than expected for a binary with a separation $\sim$0″.1. Thus, it seems unlikely to us that the unusual energy distribution of Z CMa can be explained by assuming the presence of a stellar companion.

We suspect that Z CMa actually has an overall energy distribution comparable to that of other FU Ori objects, distorted by absorption in a dust cloud along the line of sight. Much of the optical emission may arise from scattered light which is not very reddened, resulting in an underestimate of the extinction in the line of sight to the central object.

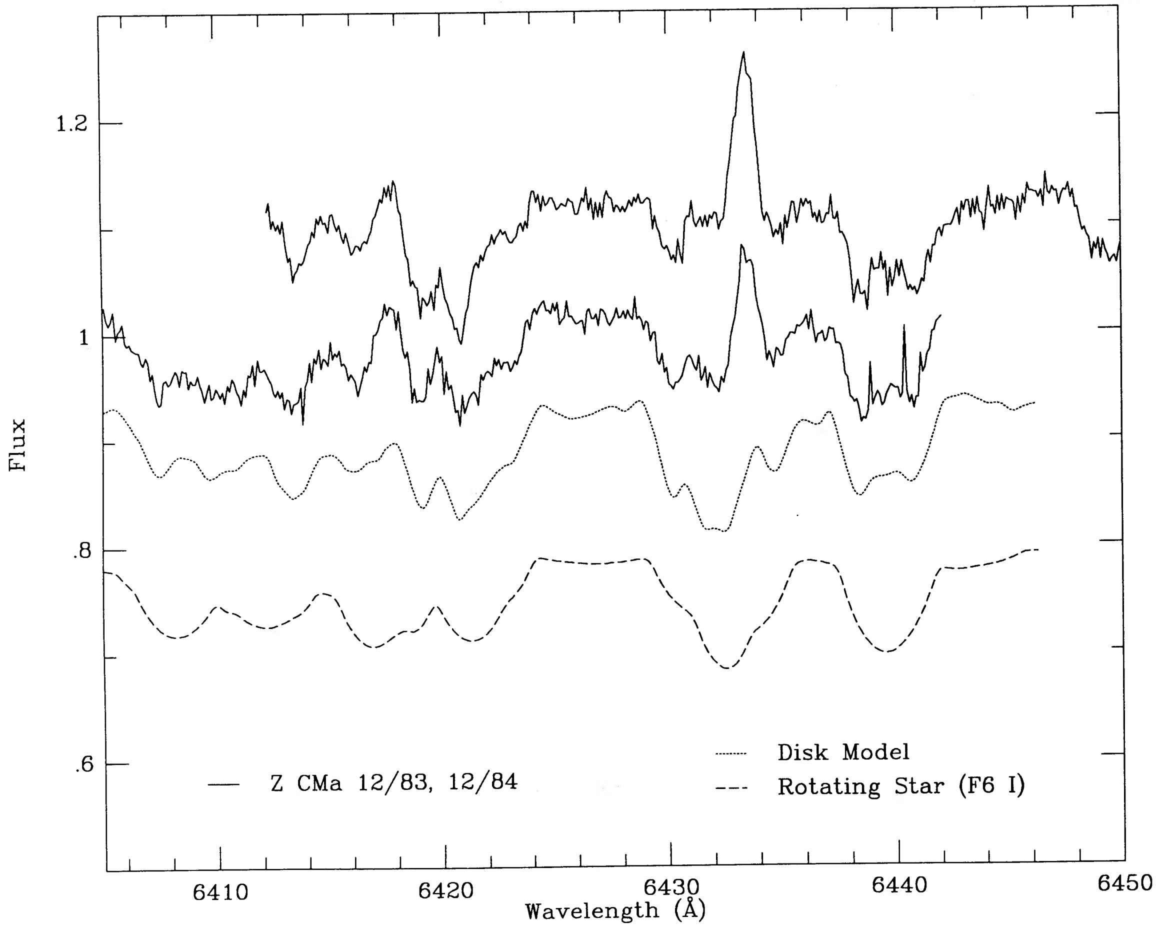


FIG. 6.—Comparison of the accretion disk model and rotating star model with spectra of Z CMa at two epochs. No evidence is found for spectral variability. Note the strong doubling in the feature near $\lambda$6440. The emission line at $\lambda$6432.7 is due to Fe II.

### c) *Two Micron* CO *Line Formation*

The disk model predicts that slower rotation in the outer regions of the disk (e.g., $R \sim 50$–$100\ R_\odot$) should produce smaller rotational line broadening in the infrared than in the optical spectral range. However, the infrared CO line widths in Z CMa are only about 0.2 times the optical line widths, in contrast to the predicted disk model ratio of $\sim 0.5$ and with the ratios of 0.6–0.7 observed in FU Ori and V1057 Cyg (Hartmann and Kenyon 1987*a*, *b*). Because the CO absorption of Z CMa is blueshifted by about 25 km s$^{-1}$ relative to the optical photospheric velocity, we suggest that this absorption originates in the wind, and not in the rotating disk. A relatively narrow circumstellar shell feature might mask any possible underlying (broad) CO absorption produced in the disk photosphere. This interpretation is made more plausible by our previous observation of blueshifted $v'$–$v'' = 2$–0 CO absorption in FU Ori (Hartmann and Kenyon 1987*a*). The $v'$–$v'' = 3.1$ CO lines in FU Ori are not similarly blueshifted, presumably because the wind is too cool to populate the first vibrational state. Higher signal-to-noise ratio FTS observations will be needed to determine if a similar effect also occurs in Z CMa.

## IV. DISCUSSION

The case for disk accretion in Z CMa is not as strong as for FU Ori and V1057 Cyg, given the difficulties in understanding the energy distribution of Z CMa. Nevertheless, the success of the simple accretion disk model in reproducing the shape and relative strengths of Z CMa's optical absorption lines is suggestive. The rapid rotation of the optical object is explained naturally by a disk model. Accretion can also provide the energy source needed to explain the irregular 2 mag variability of Z CMa on time scales of months to years (comfortably longer than the rotational period, the shortest possible time scale).

Estimates of the accretion rate and mass provide insight into the evolutionary status of Z CMa. The luminosity of an accretion disk scales as

$$L_{\rm disk} = \frac{GM\dot{M}}{2R_*} \propto R^2T^4 , \quad (2)$$

where $R_*$ is the inner disk radius and $R$ and $T$ are a characteristic disk radius and temperature. The mass can be estimated from

$$\frac{GM}{\langle R \rangle} \sim \left[\frac{\langle v \sin i \rangle}{\sin i}\right]^2 , \quad (3)$$

where $\langle R \rangle$ is a mean radius appropriate for the wavelength of determination of $\langle v \sin i \rangle$.

To obtain a minimum estimate of the accretion rate we first conservatively consider only the optical, reddening-corrected luminosity (Fig. 9), and assume that the infrared excess is due to some energy source other than the accretion powering the

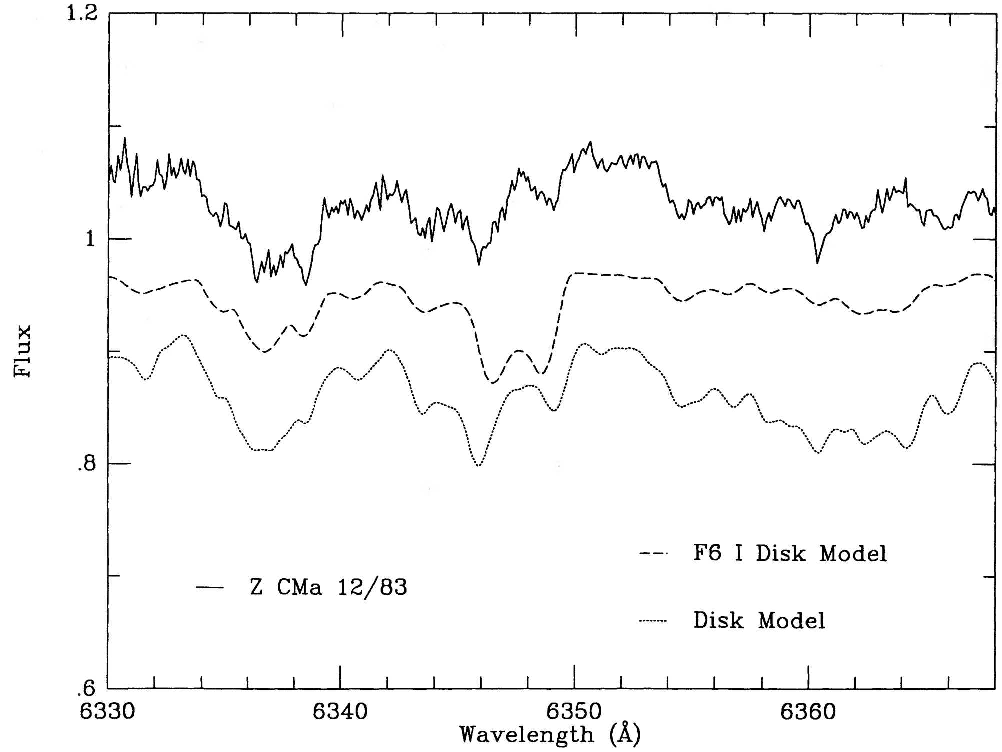


FIG. 7.—Same as Fig. 5, but for a region near λ6350. The disk model has somewhat too much blended absorption in the λ6350–6370 region, indicating that the disk model is a little too cool; however, the complete disk model matches the data much better than does a "pseudodisk" model using only an F6 I spectral standard (see text). This comparison suggests a mean optical spectral type for Z CMa somewhere between F6 I and F9 I (the mean disk model spectral type in this wavelength range).

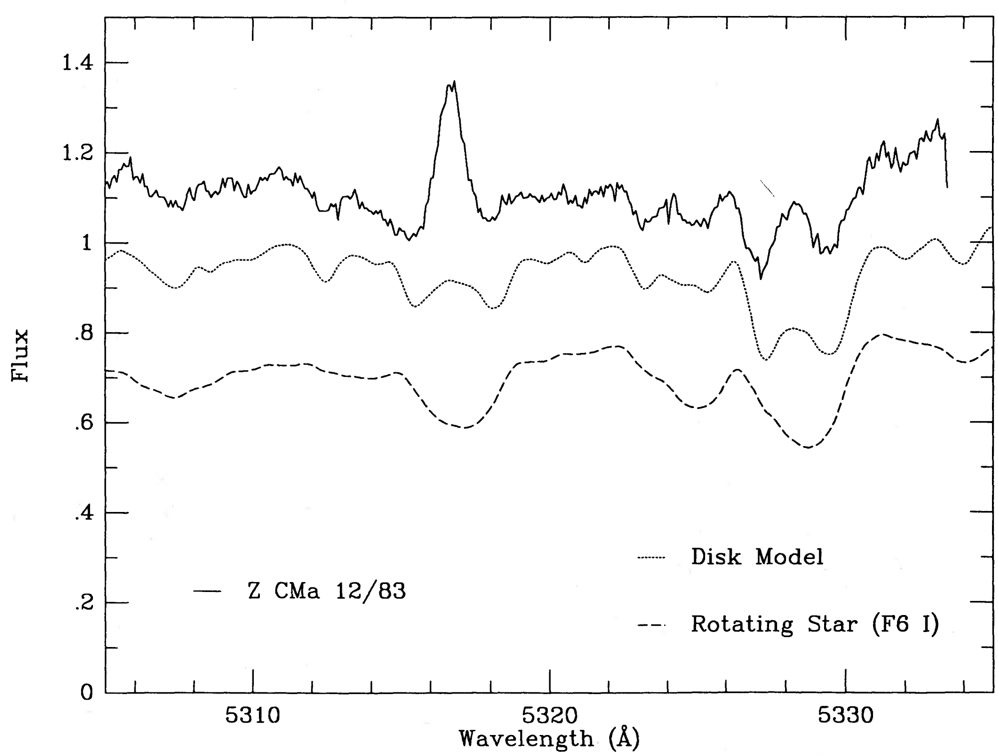


FIG. 8.—A blue spectrum of Z CMa compared with disk and rotating star models. Although blending is much more extensive in the blue than in the red spectral region, a few features indicate line doubling. An Fe II emission line at λ5316.6 is evident.

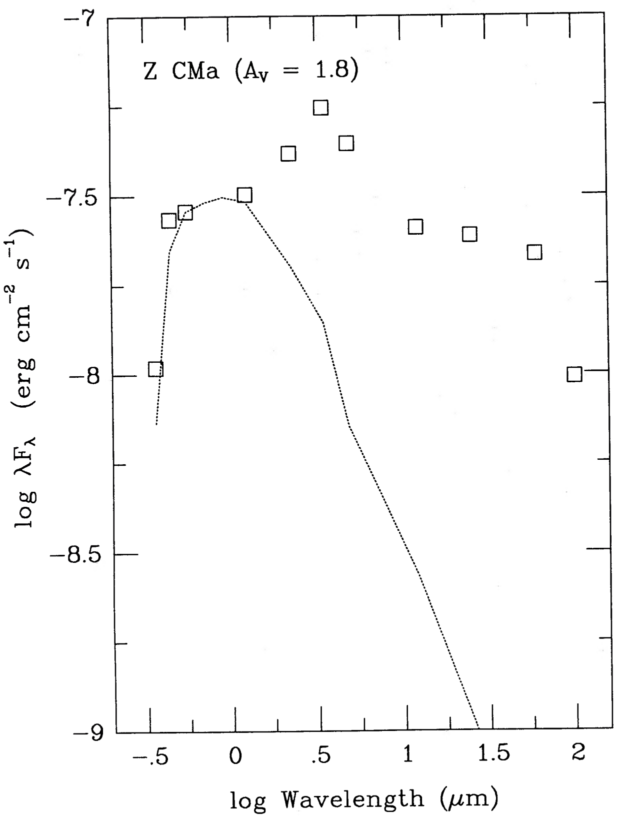


FIG. 9.—Reddening-corrected energy distribution for Z CMa, along with an accretion disk model having an outer radius of $\sim 10^4 R_\odot$. The photometric data are taken from Strom *et al.* (1972), Simon and Dyck (1977), Evans, Levreault, and Harvey (1986), and the *IRAS Point Source Catalog* (1985). The data have been dereddened using $A_V = 1.8$ and the average extinction curve of Savage and Mathis (1979). The model accretion disk spectra have been calculated as described by Kenyon and Hartmann (1987) and KHH.

optical object. Because the optical and ultraviolet data indicate that Z CMa has roughly the same spectral type as FU Ori, we can simply scale from our previous results (KHH) assuming the same characteristic disk temperature. The reddening-corrected optical flux is essentially the same for Z CMa as for FU Ori. The estimated distance for Z CMa of 1150 pc is twice that for FU Ori, so the luminosity of Z CMa is 4 times as large as FU Ori at the same inclination (i.e., $L_{\rm Z\,CMa} \sim 1000\ L_\odot$ if the disk inclination is $i = 40°$). From equation (2) we conclude that the characteristic radius of Z CMa is twice that of FU Ori. Finally, the observed $v \sin i$ for Z CMa is about 1.3 times as large as for FU Ori, so from equation (3) the mass of Z CMa should be $\sim 3.4$ times as large as for FU Ori. Using the FU Ori results from Table 7 of KHH for $i = 40°$, these considerations suggest $M$(Z CMa) $\sim 1.7\ M_\odot$, and an inner disk radius of $R_* \sim 9\ R_\odot$. Since $L \propto M\dot{M}/R$, we estimate $\dot{M} \sim 3 \times 10^{-4}\ M_\odot$ yr$^{-1}$.

If Z CMa is observed nearly edge-on, the true luminosity must be higher to account for the effects of inclination and absorption. One way to estimate the luminosity is to suppose that the large infrared excess is due to dust reprocessing of the inner disk radiation. The total system luminosity including the infrared excess is about 3000 $L_\odot$, or about 12 times the FU Ori luminosity. Still assuming the same disk temperatures, the larger luminosity estimate implies an inner disk radius $R_* \sim$ 15.3 $R_\odot$, $M$(Z CMa) $\sim 1.2\ M_\odot$, and $\dot{M} \sim 3 \times 10^{-3}\ M_\odot$ yr$^{-1}$.

Despite the large uncertainties involved, it seems likely that Z CMa is more massive than FU Ori and has a substantially larger accretion rate. Z CMa has varied irregularly, but has been bright for several decades this century (Covino *et al.* 1984), and was estimated to be 9th mag in the BD. Thus we infer that something like $10^{-2}$ to $10^{-1}\ M_\odot$ has been accreted very recently.

Clearly Z CMa cannot go on accreting at $\dot{M} \sim 10^{-3}\ M_\odot$ yr$^{-1}$ for very long. One possibility is that Z CMa is less than $10^4$ yr old, and the central star is presently undergoing its major accretion phase. The estimated star formation rate in the solar neighborhood (Miller and Scalo 1979) suggests that there may be as many as 400 objects $\leq 10^4$ yr old within 1 kpc of the Sun. Of these young objects, perhaps $\sim 10$ could be in our estimated mass range of $\sim 1$–3 $M_\odot$, assuming a Salpeter mass function $d(\log N)/d(\log M) = -2.35$ and a lower mass cutoff of 0.1 $M_\odot$. It would not be surprising that Z CMa is mostly shrouded by dust if it is this young.

On the other hand, the central stellar object could be older than $\sim 10^4$ yrs and have completed its initial accretion phase. In this case, the current activity would be caused by a burst of accretion in a residual disk, as Hartmann and Kenyon (1985) suggested for FU Ori and V1057 Cyg. This possibility would allow more time for the enshrouding dusty material to fall in or disperse, permitting optical radiation to escape.

The "radius" estimates for Z CMa are 2–4 times larger than the values found for V1057 Cyg and FU Ori. We speculate that the difference is due to the large amount of material that has fallen in, causing the central object to spin up and expand outward. Better ultraviolet observations would help constrain the hottest disk temperatures and thus the inner disk radius.

An active accretion disk is an attractive energy source for the powerful wind of Z CMa. Studies of the Na I wind components in FU Ori suggest that the mass loss rate is $\sim 10^{-5}\ M_\odot$ yr$^{-1}$ (Croswell, Hartmann, and Avrett 1987). Z CMa has equally strong wind absorption, over a larger velocity interval (up to $\sim 1000$ km s$^{-1}$ in H$\alpha$ compared to $\sim 500$ km s$^{-1}$ in FU Ori; Finkenzeller and Mundt 1984). Moreover, the above radius estimates suggest that the Z CMa wind emanates from a region with a larger surface area than FU Ori. The actual mass loss rate thus probably exceeds $10^{-5}\ M_\odot$ yr$^{-1}$. The kinetic energy loss in the wind is of order $\sim 10\%$ of the total system luminosity, given the very high terminal velocity $\sim 1000$ km s$^{-1}$ indicated by H$\alpha$ (Finkenzeller and Mundt 1984). We suggest that the optical mass loss probably arises from the inner disk or boundary layer, where the majority of accretion energy is liberated. It also appears that some material leaves the surface of the outer disk, given the blueshifts of the CO 2 $\mu$m lines.

## V. SUMMARY

We suggest that Z CMa is a luminous pre–main-sequence accretion disk, rotating at $\sim 100$ km s$^{-1}$ around a central object of mass $\sim 1$–3 $M_\odot$ and radius $\sim 9$–16 $R_\odot$. The accretion rate is $\dot{M} \sim 10^{-3}\ M_\odot$ yr$^{-1}$, and has continued for $\sim 10^2$ yr. Thus Z CMa must be surrounded by a fairly massive disk in comparison with the central object, and presently may be building up a large fraction of the star through disk accretion. The strong optical P Cygni lines, in conjunction with the blue-shifted 2 $\mu$m CO absorption found by us, testify to the ability of pre–main-sequence accretion disks to eject large quantities of mass. Following Herbig's (1977) original suggestion, other irregular pre–main-sequence variables should be examined for evidence of disk accretion.

We acknowledge the continuing assistance of Ken Hinkle in obtaining and reducing the 4 m FTS data, and thank S. Beckwith and M. Dyck for helpful discussions. George Nassiopoulos helped with the *IUE* data analysis, and we acknowledge the receipt of *IUE* data from the NSSDC. This research was supported in part by the Scholarly Studies program of the Smithsonian Institution.

REFERENCES

Adams, F. C., Lada, C., and Shu, F. H. 1988, *Ap. J.*, **326**, 825.
Beckwith, S. 1988, private communication.
Cameron, A. G. W. 1978, *Moon and Planets*, **18**, 5.
Cantó, J., Rodríguez, L. F., Calvet, N., and Levreault, R. H. 1984, *Ap. J.*, **282**, 631.
Carr, J., Harvey, P. M., and Lester, D. F. 1986, *Bull. AAS*, **18**, 1026.
Claria, J. 1974, *Astr. Ap.*, **37**, 229.
Covino, E., Terranegra, L., Vittone, A. A., and Russo, G. 1984, *A.J.*, **89**, 1868.
Croswell, K., Hartmann, L., and Avrett, E. 1987, *Ap. J.*, **312**, 227.
Dyck, H. M. 1988, private communication.
Elias, J. 1978, *Ap. J.*, **224**, 453.
Evans, N. J., II, Levreault, R. M., and Harvey, P. M. 1986, *Ap. J.*, **301**, 894.
Finkenzeller, U., and Jankovics, I. 1984, *Astr. Ap. Suppl.*, **57**, 285.
Finkenzeller, U., and Mundt, R. 1984, *Astr. Ap. Suppl.*, **55**, 109.
Goodrich, R. W. 1987, *Pub. A.S.P.*, **99**, 116.
Graham, J. A., and Frogel, J. A. 1985, *Ap. J.*, **289**, 331.
Hamann, F., and Simon, M. 1988, *Ap. J.*, **327**, 876.
Hartmann, L., and Kenyon, S. J. 1985, *Ap. J.*, **299**, 462.
———. 1987*a*, *Ap. J.*, **312**, 243.
———. 1987*b*, *Ap. J.*, **322**, 393.
Hartmann, L., Hewett, R., Stahler, S. E., and Mathieu, R. D. 1986, *Ap. J.*, **309**, 275.
Herbig, G. H. 1960, *Ap. J. Suppl.*, **6**, 337.
———. 1977, *Ap. J.*, **217**, 693.
Herbst, W., and Assousa, G. E. 1977, *Ap. J.*, **217**, 473.
*IRAS Catalogs and Atlases, Explanatory Supplement*. 1985, ed. C. A. Beichman, G. Neugebauer, H. J. Habing, P. E. Clegg, and T. J. Chester (Washington: US Government Printing Office).
Kenyon, S. J., and Hartmann, L. 1987, *Ap. J.*, **323**, 714.
Kenyon, S. J., Hartmann, L., and Hewett, R. 1988, *Ap. J.*, **325**, 231 (KHH).
Kleinmann, S., and Hall, D. N. B. 1986, *Ap. J. Suppl.*, **62**, 501.
Leinert, Ch., and Hass, M. 1987, *Astr. Ap.*, **182**, L47.
Lynden-Bell, D. and Pringle, J. E. 1974, *M.N.R.A.S.*, **168**, 603.
Mercer-Smith, J. A., Cameron, A. G. W., and Epstein, R. I. 1984, *Ap. J.*, **279**, 363.
Merrill, P. W., and Burwell, C. G. 1949, *Ap. J.*, **110**, 387.
Miller, G. E., and Scalo, J. M. 1979, *Ap. J. Suppl.*, **41**, 513.
Mundt, R., Stocke, J., Strom, S., Strom, K., and Anderson, E. 1985, *Ap. J. (Letters)*, **297**, L41.
Myers, P. C., Fuller, G. A., Mathieu, R. D., Beichman, C. A., Benson, P. J., Schild, R. E., and Emerson, J. P. 1987, *Ap. J.*, **319**, 340.
Savage, B. D., and Mathis, J. S. 1979, *Ann. Rev. Astr. Ap.*, **17**, 73.
Simon, T., and Dyck, H. M. 1977, *A.J.*, **82**, 725.
Stocke, J., *et al.* 1988, *Ap. J. Suppl.*, **68**, 229.
Strom, S. E., Strom, K. M., Yost, J., Carrasco, L., and Grasdalen, G. 1972, *Ap. J.*, **173**, 353.
Swings, P., and Struve, O. 1940, *Ap. J.*, **91**, 576.
———. 1942, *Ap. J.*, **96**, 258.
Tonry, J. L., and Davis, M. 1979, *A.J.*, **84**, 1511.

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