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ULTRAVIOLET SPECTROSCOPY OF PRE–MAIN-SEQUENCE ACCRETION DISKS

S. J. KENYON[1] AND L. HARTMANN[1]
Smithsonian Astrophysical Observatory

C. L. IMHOFF[1,2]
Astronomy Programs, Computer Sciences Corporation

AND

A. CASSATELLA[1]
IUE Observatory, European Space Agency

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ABSTRACT

We present low-resolution, ultraviolet spectra of the pre–main-sequence objects Z Canis Majoris, V1057 Cygni, and FU Orionis. Ultraviolet absorption features indicate spectral types of A5 I for FU Ori and F5 I for Z CMa. These results are in reasonable agreement with predictions of simple accretion disk models. The lack of significant veiling of ultraviolet absorption features implies that a hot boundary layer at the inner edge of the disk contributes less than $\sim 20\%$ of the radiation at 2600–3200 Å, which is significantly smaller than expected. We suggest that accretion has significantly modified the structure of the underlying pre–main-sequence stars in these systems (perhaps by expanding the photosphere or by spinning up a radiative photosphere close to breakup velocity, or both), or that the boundary layer region is much more extended above the disk midplane than standard thin disk theories predict.

Subject headings: spectrophotometry — stars: accretion — stars: individual (FU Ori, V1057 Cyg, Z CMa) — stars: pre–main-sequence

I. INTRODUCTION

In a series of papers, Hartmann and Kenyon (1985, 1987*a*, *b*) and Kenyon, Hartmann, and Hewett (1988; hereafter KHH) have shown that many optical and infrared properties of the FU Orionis variables can be explained by accretion from a massive protostellar disk. The inferred accretion rates of $\sim 10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$ suggest that the two brightest objects, FU Ori and Z CMa,[3] have accreted $\sim 0.01\ M_{\odot}$ during their current outbursts (see KHH; Hartmann *et al.* 1989). It is possible that the accretion of angular momentum and energy from the disk during an eruption is sufficient to expand the stellar photosphere or spin up the star to a large fraction of breakup velocity. Unfortunately, the stellar photosphere produces a negligible amount of luminosity compared to the disk in these objects, so it is not possible to determine how accretion has affected the underlying star until the systems return to minimum.

Although it is difficult to observe the nature of the central star directly, there are several indirect methods to probe the stellar photosphere before accretion subsides. In simple viscous disk models, the accretion luminosity, L_{acc}, is related to the maximum disk temperature, T_{max}, and the stellar radius, R_*, via $L_{\mathrm{acc}} \propto R_*^2 T_{\mathrm{max}}^4$. Fits to the energy distributions of V1057 Cyg and FU Ori suggested $T_{\mathrm{max}} \sim 6500$–$7000$ K for both objects, and analyses of optical and infrared line profiles imply $R_* \sim 4$–$5\ R_{\odot}$ (KHH). However, the optical spectrophotometry presented by KHH is sensitive to disk emission at radii ~ 2–$3 R_*$ and does not provide the best estimates for T_{max} and R_*. The models predict that inner disk regions with $T \sim T_{\mathrm{max}}$ should produce absorption features characteristic of F-type stars for $\lambda < 3000$ Å, so ultraviolet spectra can be used to constrain T_{max} and R_*.

Another way to investigate the response of the star to accretion is to identify emission from the *boundary layer*, where disk material rotating at the local Keplerian velocity comes to rest on the stellar surface. This region emits a luminosity comparable to that of the disk if the star is rotating well below the breakup velocity, and there should be little boundary layer emission when the star rotates close to breakup (see Lynden-Bell and Pringle 1974; Pringle 1981). In most cases of interest for pre–main-sequence stars, the boundary layer should be optically thick and hotter than the innermost disk regions, so ultraviolet spectroscopy is needed to test for the presence of the boundary layer.

In this paper, we report ultraviolet spectroscopy of FU Ori, V1057 Cyg, and Z CMa with data obtained by the *International Ultraviolet Explorer* (*IUE*). Prominent absorption lines detected on these spectra indicate spectral types of A5 I for FU Ori and F5 I for Z CMa. The depths of these features are comparable to those expected from the pure accretion disk model described in KHH and are consistent with values for T_{max} predicted from optical spectra. We estimate that the boundary layer region contributes no more than $\sim 10\%$–20% of the radiation at 2600–3200 Å. Simple models predict that a boundary layer surrounding a slowly rotating star should emit most of the ultraviolet radiation observed in FU Ori and Z CMa, so our observations indicate that any possible boundary layer emission is significantly smaller than expected. We

[1] Guest Observer with the *International Ultraviolet Explorer* satellite, which is sponsored and operated by NASA, the European Space Agency, and the Science and Engineering Research Council of the United Kingdom.

[2] Staff member, *IUE Observatory*, Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center.

[3] Z CMa historically has been classified as a Herbig Be star. Observations reported by Hartmann *et al.* (1989) show that this system is not a Be star, but does possess many features, such as an F supergiant optical spectrum, doubled optical absorption lines, and 2.3 μm CO absorption features, characteristic of FU Orionis variables.

TABLE 1

JOURNAL OF LOW-RESOLUTION *IUE* OBSERVATIONS

Object	Spectrum	JD	Exposure Time (s)	Observer	m_{2700}	m_{3100}
Z CMa..........	LWR 4293	2,443,981	4200	De Boer	13.21	11.86
	LWR 5702	2,444,143	1200	Vittone	12.91	11.76
FU Ori	LWR 3933	2,443,938	3600	Penston	13.65	12.32
	LWR 13935	2,445,195	1500	Imhoff	13.48	12.37
	LWR 13936	2,445,195	2400	Imhoff	13.62	12.33
	LWR 16704	2,445,578	21,300	Imhoff	13.84	sat
	LWR 16705	2,445,578	2100	Imhoff	13.52	12.63
	LWP 3060	2,445,791	1920	Reipurth	13.85	12.38
	LWP 12006	2,447,109	2100	Imhoff	13.84	12.57
	LWP 12013	2,447,110	4500	Imhoff	13.80	12.45
V1057 Cyg......	LWP 12012	2,447,110	30,900	Imhoff	16.61	15.32

suggest either that accretion has significantly modified the structure of the underlying pre–main-sequence stars, possibly by expanding the photosphere or by spinning up a radiative photosphere close to breakup velocity, or that the standard thin disk assumptions break down near the surface of the accreting star.

II. ULTRAVIOLET OBSERVATIONS

Various ultraviolet spectra of FU Ori have been collected with *IUE*, and a log of the low-resolution observations used in this paper is presented in Table 1. This table also lists the observed continuum magnitudes, $m_\lambda = -2.5 \log F_\lambda - 21.1$, in 30 Å bandpasses centered at 2700 Å and at 3100 Å. There is no evidence for large variations ($\gtrsim 0.2$ mag) in the UV flux of FU Ori, and the observed changes in m_{2700} probably are not real. Several very short ($\lesssim 15$ minute) exposures also were taken with *IUE*, but these spectra are very noisy and will not be discussed here.

The useful short ($\lesssim 2$ hr) exposures have been weighted by their exposure times and co-added to produce the spectrum shown by the solid line in Figure 1. Prominent features on the spectrum are the Mg II emission line at 2800 Å, deep absorption bands at 2750, 2860, and 2930 Å, and the 2650 Å continuum break. The very long exposure in this series (LWR 16704) is overexposed longward of ~2800 Å; data for shorter wavelengths are plotted as the dotted line in the figure. (These data have been displaced downward for clarity). The overexposed spectrum confirms the depth of the 2650 Å break and several other absorption features in the region where the coadded spectrum is not well exposed.

The 2650 Å break appears to be the most temperature-sensitive ultraviolet absorption feature among A–G supergiants; other absorption lines either are too weak for spectral classification or are not very sensitive to temperature. This feature is very small in early A supergiants and increases in strength until about F5 I (see Figs. 2 and 4). The break weakens in late F and early G stars, because absorption in the interval 2650–3200 Å increases more rapidly as temperature decreases than does the absorption at shorter wavelengths. Although two spectral types can be assigned for a given depth of the 2650 Å break, the "continuum" slope between 2650 Å and 3200 Å is significantly flatter for supergiant stars earlier than about F5 than for stars later than about F5. Thus, the spectral type can be assigned from the depth of the 2650 Å break and the slope of the 2650–3200 Å continuum.

The FU Ori spectrum has been dereddened by $A_V = 2.2$ mag

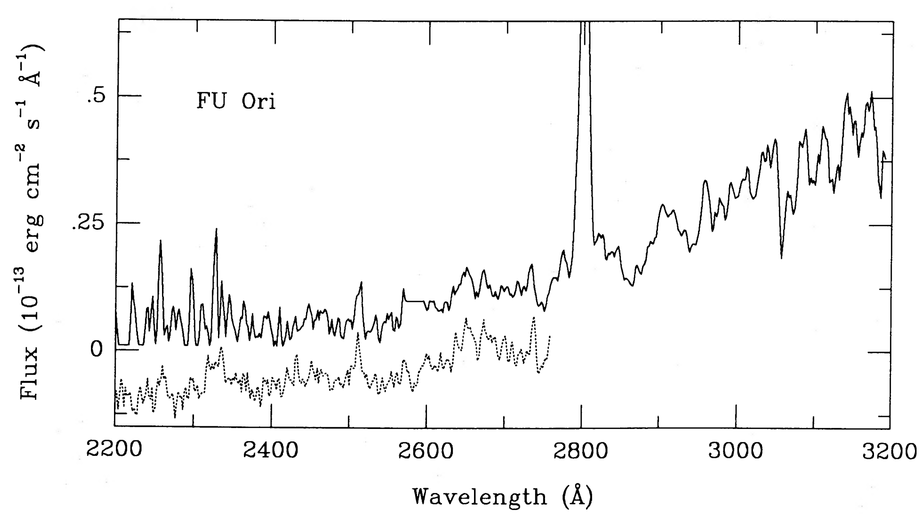

FIG. 1.—Ultraviolet spectra of FU Ori obtained with *IUE*. The solid line shows the coadded spectrum produced from short exposures summarized in Table 1. The dotted line is the spectrum resulting from LWR 16704; these data have been displaced downward for clarity.

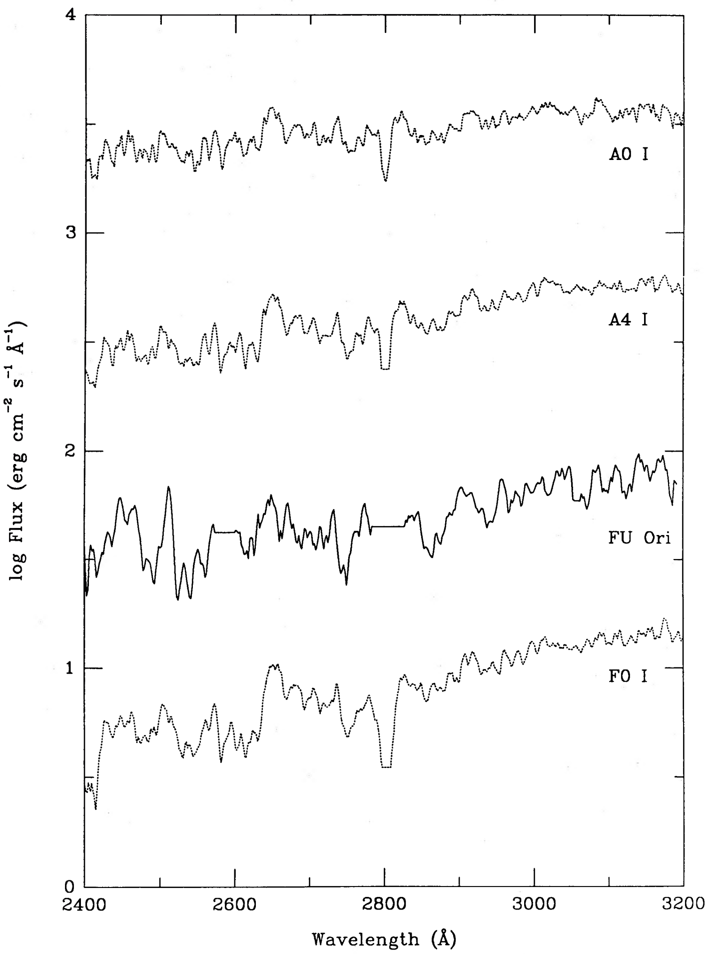

FIG. 2.—Comparison of FU Ori ultraviolet spectrum with spectra of normal supergiant stars from Wu *et al.* (1983). The FU Ori data have been dereddened by $A_V = 2.2$ mag using the Savage and Mathis (1979) reddening law. FU Ori displays absorption features commonly observed in A-F supergiants, and the depth of the 2650 Å continuum break indicates a spectral type of A5 I.

(KHH, Fig. 2) using the Savage and Mathis (1979) reddening curve and the result is presented along with spectra of standard supergiant stars in Figure 2. To avoid confusion, the Mg II features and several reseau marks have been eliminated from these data. The 2650 Å break suggests spectral types of roughly A5 I or G5 I, but the dereddened continuum is more consistent with the earlier classification. The ultraviolet continuum is similar to that of a middle G star only if the reddening correction is very small ($A_V \lesssim 0.2$ mag; for a normal reddening law) or if the reddening is gray. Various studies of interstellar reddening have shown that the 2500–3200 Å extinction is highly correlated with optical reddening (e.g., Meyer and Savage 1981), and Herbig and Goodrich (1986) found a near-normal UV extinction law was appropriate for the Taurus cloud. FU Ori is located in B35, a region of low-mass star formation similar to Taurus, so a gray extinction in this region seems unlikely. We conclude that the ultraviolet spectral classification is A5 I with an estimated error of a few spectral subclasses. This result is close to the F0 I Ewald, Imhoff, and Giampapa (1986) estimated from *IUE* spectra and is somewhat earlier than the F2 I spectral type inferred from blue optical spectra by Herbig (1966, 1977).

Several *IUE* spectra of Z CMa have been acquired by other investigators, and pertinent details for these data are listed in Table 1. The coadded spectrum is displayed in Figure 3. It is apparent that Z CMa possesses many spectral features observed in FU Ori (compare with Fig. 1), although Mg II is a weaker emission feature. Spectra of F and G supergiants from the *IUE* spectral atlas are displayed together with Z CMa in Figure 4. The 2650 Å break is much stronger in Z CMa than in an F0 supergiant and is comparable in depth to the break observed in an F5 supergiant. This feature gets weaker in G supergiants, so we estimate a spectral type of F5 I is appropriate for Z CMa at 2650 Å. This spectral type is essentially identical with the optical classification assuming an error of several subclasses in optical and ultraviolet spectral types (see the discussion in Hartmann *et al.* 1989).

A single double-shift exposure of V1057 Cyg was made with *IUE* to search for the UV continuum of this object. The spectrum has very low signal to noise, and a real continuum is

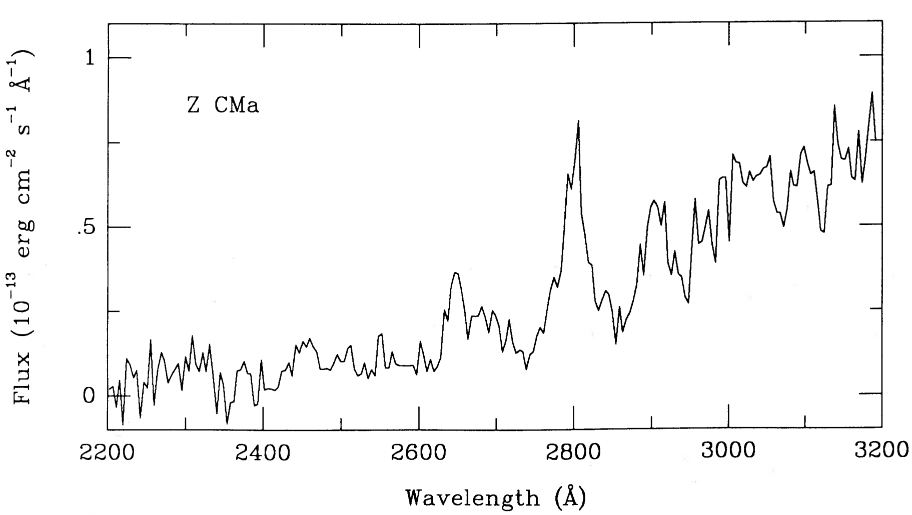

FIG. 3.—Co-added ultraviolet spectrum of Z CMa. Information concerning the two exposures used to produce this spectrum is summarized in Table 1.

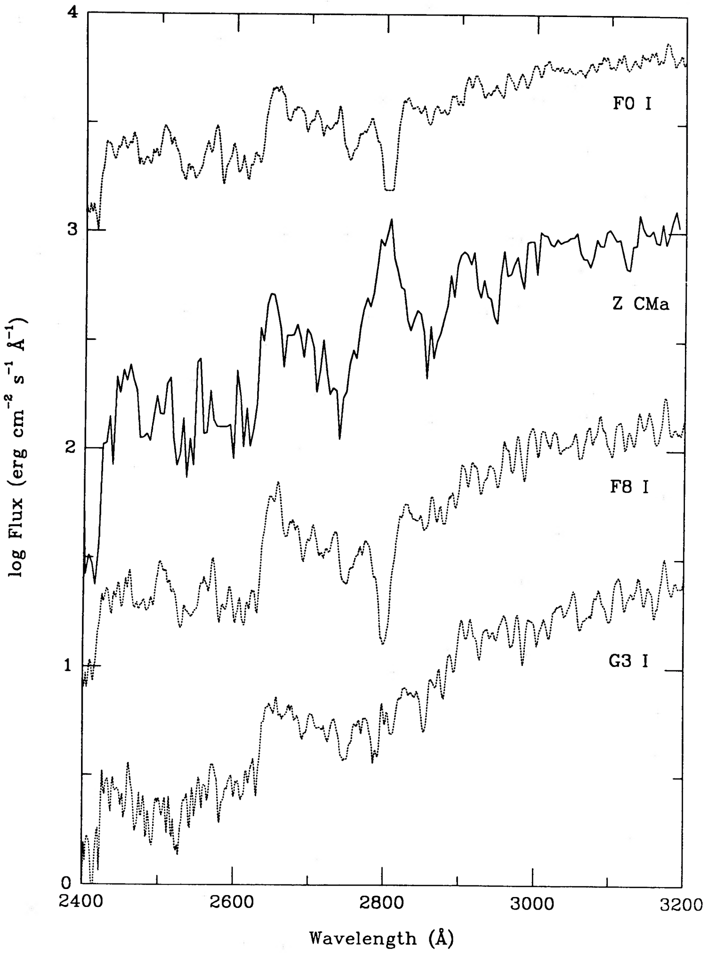

FIG. 4.—Comparison of the observed Z CMa ultraviolet spectrum with spectra of supergiant comparison stars. The Z CMa data have *not* been dereddened. The depth of the 2650 Å continuum break suggests a spectral type of F5 I.

present only above 2700 Å. We summed the data in 30 Å bins and present this result in Figure 5. A weak Mg II emission line appears as a 2 σ feature above the continuum; the lack of definite absorption features in the original spectrum precludes any estimate of an ultraviolet spectral type for V1057 Cyg.

III. ANALYSIS

a) Comparison of Disk Model Predictions with Observations

One of the original motivations for applying the accretion disk model to FU Orionis objects was the variation of spectral type with wavelength observed in the optical and infrared. The radial decrease of temperature in a viscous disk naturally explains this behavior; the F- or G-type absorption lines are produced in warm, inner disk regions, while cooler, outer disk material is responsible for M-type features observed in the infrared. KHH found that a disk model in which the innermost annulus has a temperature of $T_{max} \sim 7200$ K (corresponding to an F2 I star) gave the best fit to observations of FU Ori. A slightly cooler model with $T_{max} \sim 6600$ K accounted for the available V1057 Cyg data. Optical line profiles of Z CMa are consistent with the predictions of the "FU Ori model," but the unusual energy distribution of this object does not allow a unique fit to a standard, steady state disk model (see Hartmann *et al.* 1989).

Our *IUE* results for FU Ori suggest that the variation of spectral type with wavelength continues to $\sim$2650 Å. The adopted spectral type of A5 I is slightly earlier than the F2–3 I predicted from an analysis of the continuum energy distribution and optical absorption line profiles, suggesting that the inner disk regions are somewhat hotter than $T_{max} \sim 7200$ K. This difference should not be viewed as significant, because the predicted temperature in the inner disk is uncertain[4].

We find no evidence for a variation of spectral type with wavelength in Z CMa. The F5 I classification assigned to the ultraviolet spectra is indistinguishable from the optical spectral type, F6–F7 I, estimated by Hartmann *et al.* (1989).

To compare the disk model with our *IUE* observations in more detail, we have synthesized ultraviolet spectra following methods outlined in KHH. The disk is assumed to consist of concentric annuli which are assigned a temperature, T_d, according to the α-model developed by Shakura and Sunyaev (1973). Each annulus is further assumed to emit radiation as if it were a star having an *effective* temperature, T_d, and the total emitted flux is determined by summing the weighted contribu-

[4] The standard steady disk model predicts that the disk temperature approaches zero at the stellar surface (see Pringle 1981), which probably is unphysical.

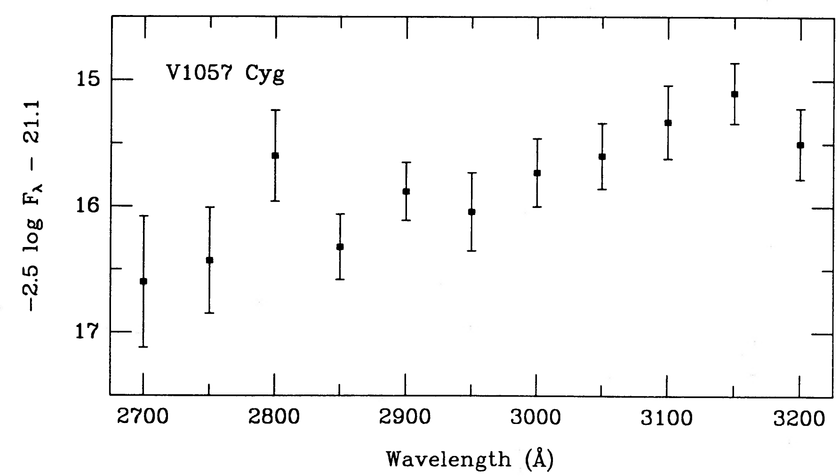

FIG. 5.—Ultraviolet spectrophotometry of V1057 Cyg. The original spectrum was summed in 30 Å bins separated by 50 Å; this result is plotted in the Figure along with 1 σ error bars.

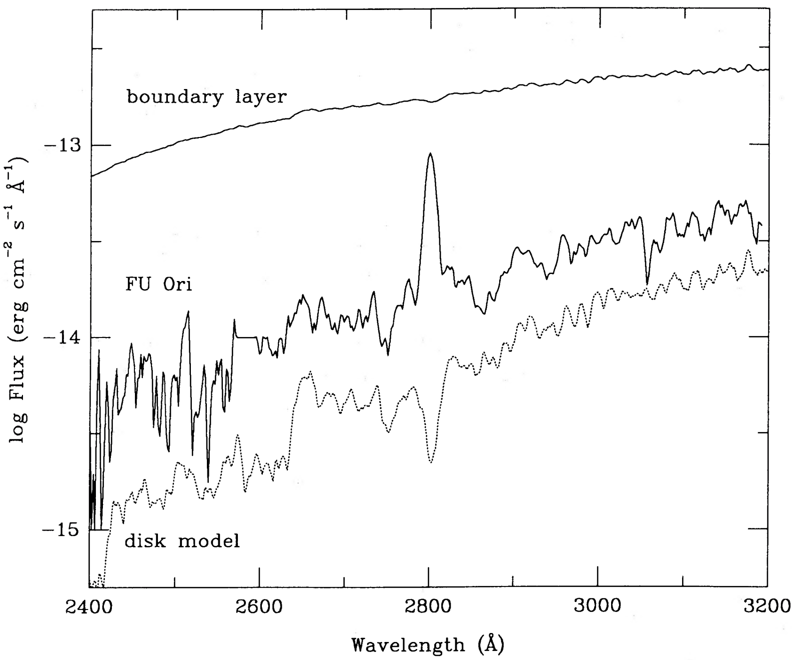

FIG. 6.—Comparison of the observed FU Ori spectrum with a synthesized disk spectrum reddened by $A_V = 2.2$ mag. The co-added FU Ori data have been smoothed over 3 pixels for $\lambda < 2600$ Å. A model including boundary layer emission is shown by the solid line at the top of the panel. The disk model provides a reasonable "fit" to the data, although the predicted depth of the 2650 Å continuum break is larger than observed.

tions from individual annuli (see Tables 3 and 4 in KHH). The local gravity in the disk "photosphere" varies from $\log g \sim 2$ at the inner edge of the disk to $\log g < 0$ at large distances from the central star, so emitted fluxes from supergiant stars are a reasonable first approximation to the spectra of disk annuli. Normalized *IUE* observations of supergiants from Wu *et al.* (1983) served as input spectrophotometry for the model calculations.

Observed spectra of FU Ori are compared with disk model predictions in Figure 6. Several reseau marks and the Mg II emission feature have been truncated in the FU Ori spectrum, and these data also have been smoothed over 3 pixels for $\lambda < 2600$ Å. The agreement between the two spectra is quite good between 2650 Å and 3200 Å, although several absorption features in FU Ori (e.g., λ2875) are noticably stronger than in the disk model. FU Ori also has a weak 2650 Å break, which corresponds in strength to that of an A5 I star rather than the F2–F4 I stars characteristic of the inner annuli of the accretion disk model. In this respect, the observations indicate a slightly hotter disk in FU Ori than is predicted by the model developed in KHH.

The disk model predictions for FU Ori are compared with the observed spectrum of Z CMa in Figure 7. As with FU Ori, several absorption features are stronger than predicted by the model, as well as the continuum breaks at 2650 and 2420 Å. The strong absorption bands can be associated with Fe II multiplets, and these might be produced in a stellar wind from the disk or an extended disk photosphere (see below). The agreement between the model and the data is otherwise quite good over the entire wavelength range, and the differences in the continuum breaks probably are not significant in view of the signal-to-noise of the data.

Ultraviolet spectra of V1057 Cyg are too noisy to compare with disk model predictions in detail, but a simple check on the calculations in KHH can be made with the observed continuum fluxes. The model presented in Table 3 of KHH predicts dereddened continuum magnitudes of $m_{2700} = 11.01$ and $m_{3100} = 10.11$, while the observed magnitudes are $m_{2700} = 9.40 \pm 0.52$ and $m_{3100} = 9.80 \pm 0.29$. In view of the large reddening corrections, $A_{2700} = 7.2$ mag and $A_{3100} = 5.5$ mag, and the poor signal-to-noise of the spectrum at 2700 Å, the data are in reasonable accord with the predictions. Higher signal-to-noise spectra of V1057 Cyg are required for more comprehensive tests of the disk model.

b) *Boundary Layer Emission*

The model spectra and energy distributions discussed in this paper and in KHH have assumed that the sole energy source in FU Orionis variables is disk accretion, and have ignored radiation from the *boundary layer*, where material at the inner edge of the disk falls onto the stellar photosphere. Theoretical analyses of this region are very uncertain (see Lynden-Bell and Pringle 1974; Pringle 1977; Pringle and Savonije 1979; Tylenda 1977, 1981; Regev 1983; and references therein), so simple energetic arguments are used to constrain the radiation emitted by the boundary layer.

If the accreting star rotates at a small fraction of its breakup velocity, then inner disk material rotating at the Keplerian velocity must lose kinetic energy to land on the stellar surface. The luminosity of the boundary layer, $L_{\rm bl}$, is then comparable to the disk luminosity, $L_{\rm disk}$. To compute the predicted spectral energy distribution from the boundary layer, it is usually assumed that this region can be approximated as a constant temperature, annular ring with thickness fR_* surrounding an accreting star of radius R_*. The boundary layer surface temperature, $T_{\rm bl}$, is set by the blackbody relation: $\sigma T_{\rm bl}^4 = L_{\rm bl}/4\pi f R_*^2$. Various prescriptions for estimating the value of f yield $f \sim 0.01$–0.1, and $f \sim 0.02$–0.03 has been adopted in several studies of boundary layer emission in T Tauri stars (Kenyon and Hartmann 1987; Bertout, Basri, and Bouvier

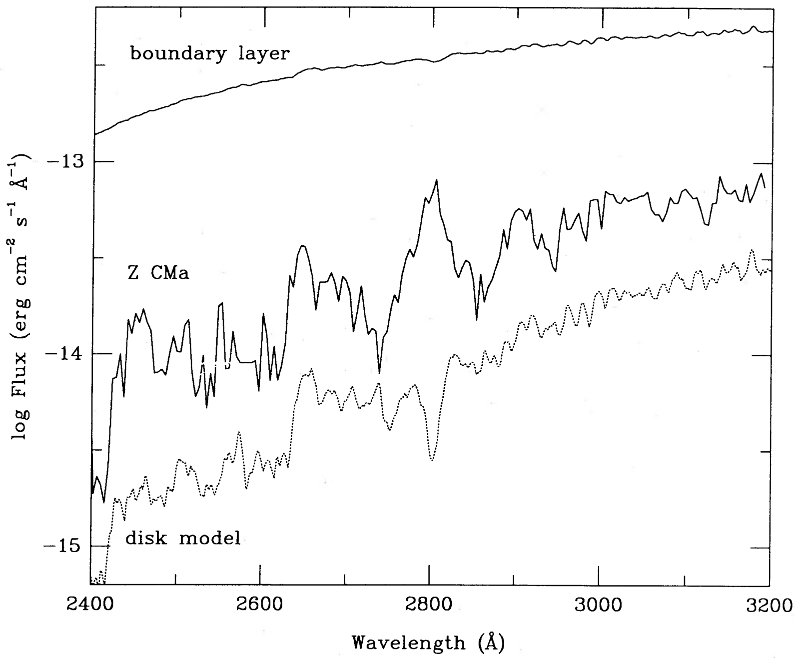

FIG. 7.—Comparison of the Z CMa spectrum with synthetic "FU Ori" spectra from Fig. 6. Aside from the stronger 2650 Å break in Z CMa and the larger apparent 2850 Å absorption feature, the disk model spectrum adequately reproduces the observations. Emission from a hot, optically thick boundary layer greatly overestimates the observed continuum flux and cannot account for the presence of the deep absorption features characteristic of the inner disk.

1988). For $f \sim 0.02$–0.03, $T_{bl} \sim 4T_{max}$, the maximum temperature in the accretion disk. Our disk models have $T_{max} \sim$ 6500–7200 K for FU Ori and V1057 Cyg, so $T_{bl} \sim 2$–3 $\times 10^4$ K. In this approximation, the boundary layer flux should dominate disk emission at ultraviolet wavelengths: the simple models described in KHH and Kenyon and Hartmann (1987) predict that ~80%–90% of the ultraviolet continuum flux in the region 2600–3200 Å should be produced by the boundary layer, as shown by the solid line in Figure 6 and Figure 7.

The detection of strong absorption features on ultraviolet spectra of FU Ori and Z CMa places strong constraints on the nature of possible boundary layer emission in either object. In Z CMa, the 2650 Å continuum break is as strong (perhaps stronger) as is observed in any supergiant star, which suggests that there is little radiation from a hot boundary layer in this system. It is possible that a boundary layer continuum could cause the weak 2650 Å break in FU Ori, but other absorption features on our co-added spectrum have not been obviously veiled by an extra continuum source (see Fig. 2). We estimate that perhaps ~10%–20% of the observed continuum flux in both FU Ori and Z CMa could be emitted by a boundary layer without seriously affecting the strengths of the ultraviolet absorption features. This radiation is a factor of ~10 lower than predicted by standard boundary layer models; thus, it appears that *boundary layer emission is not important in FU Ori and Z CMa.*

Theories for boundary layer emission are very crude, but it seems unlikely that reasonable modifications of the parameters can change the basic conclusion. The only way the observed ultraviolet spectra can be reconciled with the presence of a boundary layer with $L_{bl} \sim L_{disk}$ is if T_{bl} is significantly larger than ~30,000 K. However, such a region would produce copious amounts of H- and He-ionizing photons and form an extended H II region around the system. Strong H I and He I emission lines are not observed in FU Ori objects, and Croswell, Hartmann, and Avrett (1987) showed that the winds of these systems are predominantly neutral. Thus, a very hot boundary layer is not consistent with the observational data.

If the boundary layer is not a source of emission in FU Ori objects, then some mechanism must allow material to accrete onto the central star without radiating a significant fraction of its kinetic energy. Hartmann and Kenyon (1985) suggested that accretion at rates $\sim 10^{-4}\ M_\odot\ yr^{-1}$ might expand the stellar photosphere and rob the boundary layer of thermal energy, and hydrodynamic calculations reported by Prialnik and Livio (1985) have shown that substantial increases in the stellar radius, roughly a factor of 2 or more, can occur when a large fraction of the boundary layer energy is deposited into the outer envelope of the accreting star. It is difficult to estimate how much boundary layer energy might have been used to expand the central stars in Z CMa and FU Ori, because their preoutburst radii are not known. Nevertheless, Hartmann *et al.*'s (1989) result for *Z* CMa, $R_* \sim 9$–15 $R_\odot$, might be a clue that accretion of ~0.01–0.1 $M_\odot$ in the past century has substantially increased the radius of its stellar photosphere. The situation for FU Ori is more ambiguous, because less than ~10% of the boundary layer energy is sufficient to expand a typical T Tauri star to its current dimensions, $R_* \sim 4$–5 $R_\odot$ (KHH; Prialnik and Livio 1985).

A second possible reason for the observed lack of boundary layer emission is that the central stars have been spun up close to the critical rotational velocity by the accretion of ~0.01 $M_\odot$. Accretion of ~20% of the total stellar mass from a Keplerian disk is needed to spin up a completely convective star to breakup (e.g., Kenyon and Hartmann 1987), so an FU Ori event lasting ~100 yr is not sufficient to increase the rotational velocity a significant amount. However, the Prialnik and

Livio (1985) calculations showed that a convective star develops a radiative envelope in response to accretion at a rate $\sim 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$. Angular momentum transport is less efficient in radiative regions than in convective layers, so it is conceivable that accretion initially affects the radiative envelope rather than the entire star. This mechanism would make it possible to increase the surface rotational velocity with considerably less disk accretion and reduce the boundary layer luminosity.

Finally, it is plausible that the lack of boundary layer emission results from a breakdown of the standard thin disk assumptions near the accreting star. Calculations by Lin and Papaloizou (1985) suggest that the height of the disk photosphere above the midplane might increase from $H \sim 0.01$–$0.05R_*$ to $H \sim 0.3R_*$ when accretion rates reach $10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$. If disk material near the accreting star expands out of the midplane in FU Ori systems, then the boundary layer cannot be approximated as a thin ring surrounding the stellar equator. Pringle (1977) argues that the radial extent of the boundary layer, δR, should be comparable to the scale height of the inner disk. A boundary layer with $\delta R \sim R_*$ is expected to have $T_{\mathrm{bl}} \sim T_{\mathrm{max}}$ and produce absorption features similar to those formed in the inner disk regions. As we stated above, the ultraviolet spectra are not consistent with a large amount of "extra" radiation from the boundary layer, but T_{bl} might be reduced even further if a significant fraction of the boundary layer energy goes into driving a wind (see Croswell, Hartmann, and Avrett 1987; Pringle 1989) or into spinning up or expanding the star. The observations are compatible with both of these possibilities and are not sufficient to distinguish between them.

IV. SUMMARY

We have presented low-resolution, ultraviolet spectrophotometry of the pre–main-sequence objects Z Canis Majoris, V1057 Cygni, and FU Orionis. Prominent absorption features observed on our spectra indicate spectral types of $\sim$A5 I for FU Ori and $\sim$F5 I for Z CMa. A very weak, featureless continuum was detected on the V1057 Cyg spectrum, so an ultraviolet spectral type cannot be estimated for this object.

Ultraviolet spectra of Z CMa and FU Ori are in reasonable agreement with predictions of simple accretion disk models. The absence of strong veiling of the ultraviolet absorption features indicates that any possible emission from a hot boundary layer between the disk and the star contributes less than 10%–20% of the disk luminosity. We suggest two possibilities for the elimination of boundary layer emission in both objects: (i) accretion of $\sim 0.01\ M_\odot$ has spun up a radiative envelope or increased the radius of the stellar photosphere, and (ii) expansions of the bounday layer out of the disk midplane reduces its temperature below the temperature of the inner disk.

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A. CASSATELLA: *IUE Observatory*, *IUE*-VILSPA, Apartado 54065, E-28080 Madrid, Spain

L. HARTMANN AND S. J. KENYON: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

C. L. IMHOFF: Code 684.9/*IUE*, Goddard Space Flight Center, Greenbelt, MD 20771