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"IUE Observations of New A Star Candidate Proto-Planetary Systems"

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IUE Observations Associated With
"IUE Studies of New A Star Proto-Planetary Disk Systems"

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As a result of the detection of accreting gas in the A5e PMS Herbig Ae star, HR 5999, most of the observations for this IUE program were devoted to Herbig Ae stars rather than to main sequence A stars. For the first time, mid-UV emission at optical minimum light was detected for UX Ori (A1e), BF Ori (A5e), and CQ Tau (F2e). The presence of accreting gas in HD 45677 and HD 50138 prompted reclassification of these stars as Herbig Be stars rather than as proto-planetary nebulae. More detailed results are discussed below.

UX Ori: Comparison of IUE low dispersion spectra obtained during the 1992 August-September optical minimum for the Herbig Ae star UX Ori with data obtained when the star was visually brighter reveals the presence of large amplitude UV light and color changes similar to those reported in optical photometry. The spectra exhibit a pronounced change in character from a continuum spectrum characterized by strong, circumstellar absorption at maximum light, to prominent mid-UV Fe II and Mg II emission, and a pronounced flux excess at shorter wavelengths at minimum light. Despite the light variations, the IUE short wavelength data are consistent with a spectral type of A1-2 in all observations. Detection of emission at epochs when contemporary optical data indicate that the star is heavily obscured indicates that the UV emission originates in bipolar nebulosity. The lack of spatial extension at the resolution of the IUE is consistent with the emission originating within optical nebulosity extending up to 600-900 AU from the star. The IUE data are consistent with circumstellar extinction in the dense dust clouds responsible for the optical minimum with $R=7-8$. The optical maximum data, however, suggest $R=5.0$, indicating that the dense dust clouds are not only more opaque than the average circumstellar medium in the UX Ori disk, but are preferentially populated by larger grains. Detection of a pronounced short wavelength flux excess, which is independent of the inferred R values for UX Ori which becomes progressively larger as the star is obscured is consistent with the predictions of detection of a large dust-scattered light component at optical minimum. Optical spectra for this star obtained in coordination with the IUE observations and discussed in Grinin et al. (1994) show accreting gas similar to that seen toward β Pic, but significantly higher in column density. Collectively these data strengthen recent arguments by Grinin et al. (1994) that the dense dust clouds represent the comae of star-grazing comets. A paper detailing these findings has been submitted to Astronomy & Astrophysics and is currently being refereed.

Correlation of Mid-UV Emission with IR Excess: As the result of observations obtained

under this IUE observing program, the 16-17th episode continuations, and analysis of archival data supported by the PI's LTSA program (NASW 4756), we find that detection of prominent mid-UV Mg II and Fe II emission is not restricted to UX Ori, but is characteristic of the Herbig Ae/Be stars with sporadic, large amplitude light variations (greater than 1 magnitude) and increasing linear polarization with decreasing light. The luminosity of the mid-UV emission is correlated with the IR excess or mm and sub-mm flux, and thus provides a direct measurement of the current accretion rate, a proxy for the age of the system. Comparison of published optical spectra and data acquired in coordination with the IUE observations has shown that accreting gas is routinely present in these systems with velocities consistent with free-falling material. The available optical data in conjunction with more limited IUE high dispersion spectra show that the column density of the accreting gas is correlated with the system age. A poster paper was presented at the 1994 January AAS meeting in Crystal City. A more extensive discussion, including observations obtained during the 18th episode will be presented at the Meeting "Circumstellar Dust Disks and Planet Formation" to be held at the Institute d'Astrophysique in Paris from July 4-8, 1994. Preparation of a paper to be submitted to the refereed literature is in progress.

Publications:

- Grady, C.A., Pérez, M.R., Thé, P.S., Grinin, V.P., de Winter, D., Johnson, S.B., Yusef-Zadeh, F., Talavera, A., Blondel, P.F.C., Tjin A Djie, H.R.E., Calvet, N. 1994, *The β Pictoris Phenomenon Among Young Stars. II. Ultraviolet Observations of the Herbig Ae Star UX Orionis*, A&A (Submitted).
- Grady, C.A., Pérez, M.R., and Thé, P.S. 1994, "*HD 45677 and HD 50138: Identification of 2 B[e] Stars as Herbig Be Stars Viewed Through Their Circumstellar Disks*", editors, Thé, P.S., Pérez, M.R., and van den Heuvel, E. , ASP Conference Series Vol (62), (in press, publication expected for mid-1994), p. 409.
- Grady, C.A., Pérez, M.R., Talavera, A., Thé, P.S., de Winter, D., Grinin, V.P., Calvet, N. 1993, "*Iron Emission Lines in the Spectra of Herbig Ae/Be Stars Viewed Through Their Proto-Planetary Disks*", BAAS, 25, 1353.
- Grady, C.A., 1994 "*The Beta Pic Phenomenon among Herbig Ae/Be and Classical T Tauri Stars: UV Observations of Systems Viewed Through Their Circumstellar Dust Disks*" to be presented at Circumstellar Dust Disks and Planet Formation, July 4-8 1994 (in preparation).

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The β Pictoris Phenomenon Among Young Stars.

II. Ultraviolet Observations of the Herbig Ae Star UX Orionis *

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Abstract. Comparison of IUE low dispersion spectra obtained during the 1992 August-September optical minimum for the Herbig Ae star UX Ori with data obtained when the star was visually brighter reveals the presence of large amplitude UV light and color changes similar to those reported in optical photometry. The spectra exhibit a pronounced change in character from a continuum spectrum characterized by strong, circumstellar absorption at maximum light, to prominent mid-UV Fe II and Mg II emission, and a pronounced flux excess at shorter wavelengths at minimum light. Despite the light variations, the IUE short wavelength data are consistent with a spectral type of A1-2 in all observations. Detection of emission at epochs when contemporary optical data indicate that the star is heavily obscured indicates that the UV emission originates in bipolar nebulosity. The lack of spatial extension at the resolution of the IUE is consistent with the emission originating within optical nebulosity extending no more than 600-900 AU from the star. The IUE data are consistent with circumstellar extinction in the dense dust clouds responsible for the optical minimum with an equivalent $R=7-8$. The optical maximum data, however, suggest $R=5.0$, indicating that the dense dust clouds are not only more opaque than the average circumstellar medium in the UX Ori disk, but are preferentially populated by larger grains. Detection of a pronounced short wavelength flux excess, independent of the circumstellar extinction, which becomes increasingly prominent as the star is progressively obscured is consistent with the predictions of detection of a large dust-scattered light component at optical minimum. Collectively these data strengthen recent arguments by Grinin et al. (1994) that the dense dust clouds represent the comae of star-grazing comets.

* Based on observations made with the *International Ultraviolet Explorer* operated by NASA at Goddard Space Flight Center, Greenbelt, USA and by ESA at Villafranca de Castillo, Madrid, Spain

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Key words: Herbig Ae star – UV spectroscopy – spectral variation – bipolar flow – circumstellar extinction – proto-planetary disk system

1. Introduction

A number of recent studies of Herbig Ae/Be (HAeBe) stars have suggested that these Pre-Main Sequence (PMS) stars (Palla and Stahler 1993) possess large, viscously heated accretion disks which are potentially the evolutionary precursors of the β Pic disk (Hillenbrand et al. 1992; Lada and Adams 1992). This view is somewhat controversial for the HAeBe stars as a group, since the IR excess may come from material which is not intimately associated with the PMS star (Natta et al. 1993), and the outer envelopes of these stars may be more simply modelled using a spherical geometry (Hartmann et al. 1993; Berrilli et al. 1992). However, there is a population of isolated HAeBe stars for which polarimetric data sampling the material in the *immediate* vicinity of the star provide convincing evidence for the distribution of dust disks (Grinin et al. 1991), with our line of sight to the stars passing through the disk. This viewing geometry is especially favorable for line-of-sight studies of the circumstellar grains, using techniques developed for the interstellar medium, and also, when the star is heavily obscured, enables us to “view”, in the integrated light of the star, the effects of dust in close proximity to the star, and the presence of any gas associated with jets or outflows. Thus, PMS stars with disks oriented edge-on to our line of sight are superb laboratories for probing the physical and chemical evolution of the disk and the immediate stellar environment at the epoch when planetesimal formation is expected.

One of the best studied members of this class of Herbig Ae star is the isolated system UX Ori (A2IIIe, Tjin A Djie et al. 1984). The star exhibits large amplitude ($\Delta V=2.^m5$) light changes accompanied by spectacular color changes. Down to $V=10.^m3$, as the star light fades it becomes progressively redder (Bibo and Thé 1990; 1991). Below that magnitude and down to $V=11.3$ the stellar colors exhibit a large scatter, but do not show any systematic trends. Below $V=11.3$ the (B-V) colors become progressively bluer, and at minimum light may be as blue or bluer than at optical maximum light. The color-magnitude (C-M) changes are accompanied by progressively increasing polarization with decreasing light (Grinin et al. 1991;1993), prompting the suggestion that, as the star is progressively obscured by dust clouds acting as “natural coronagraphs”, we view a larger and larger fraction of light scattered into our line of sight by dust in close proximity to the star. The circumstellar material is apparently not merely passively orbiting the star. UX Ori exhibits accreting gas at both optical maximum and minimum (Grinin et al. 1994).

During August-September 1992 UX Ori went through a prolonged, deep optical photometric minimum. Optical photometry, polarimetry, and spectroscopy obtained during the minimum are discussed in Grinin et al. (1994). We present a discussion of IUE low dispersion spectra obtained during this minimum, together with the available archival UV data, and more recent observations obtained at brighter states.

Table 1. IUE Journal of Observations from 1981-January 1993. Where multiple, graded exposures were obtained on the same date, continuum measurements are tabulated for the spectrum with the best exposure in the wavelength of interest. IUE SWP data cover 1150-2000 Å. LWR/P data cover from 2000-3200 Å. The continuum flux units are $\text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$, RMS deviations in the intermediate band average fluxes typically account for 0.^m2, due to a mixture of noise and line structure in the IUE data. Columns (1) and (2) give the year and date of the observations. Column 3 gives the V magnitude derived from the IUE FES data. Columns 4 and 5 indicate whether Mg II and Fe II are in emission (em), or absorption (abs). Uncertain data are indicated by ..

Year	Date	V _{FES}	Images	MgII	FeII	F ₁₈₀₀ x10 ¹³	F ₂₉₅₀ x10 ¹³	Comments
1981	29 Aug.	9.70	SWP 14857	...	...	...	...	saturated $\lambda \geq 1800\text{Å}$
1983	01 Apr.	10.91	LWR 15639, 15640	...	...	...	...	underexposed
			SWP 19605	...	...	...	...	underexposed
1983	30 Oct.	9.72	LWP 2179, 2180	abs.	abs.	...	2.24	slight saturation
			SWP 21406	...	...	1.35	...	
1984	09 Jan.	10.59	LWP 2580, 2585	abs.	abs.	...	0.71	
			SWP 21975, 21976	.....	0.55	...	...
1986	14 Nov.	10.91	LWP 9519	em.	em :	...	0.58	
			SWP 29676	...	...	0.54	...	
1990	01 Feb.	10.66	SWP 38105	...	...	0.61	...	
1992	05 Feb.	11.90	LWP 22337	em.	em.	...	0.25	
			SWP 43931	...	...	0.37	...	
	24 Sep.	11.90	LWP 23996	em.	em.	...	0.34	
	25 Sep.	11.90	SWP 45774	...	...	0.40	...	
1993	28 Jan.	10.07 :	LWP 24806	abs.	abs.	...	0.91	V estimated from optical data
	08 Oct.	10.90 :	LWP 26528	abs.	abs.	...	1.54	V _{FES} contaminated by stray light
			SWP 48770	...	...	1.48	...	
	18 Nov.	11.20	LWP 26772	em. :	abs.	...	0.32	
			SWP 49253	...	...	0.57	...	

2. Observations and Data Reduction

UX Ori has been comparatively well observed, for a moderately faint Herbig Ae star, by the IUE at irregular intervals from 1981 through 1993. A total of 23 spectra covering either 1150-2000 or 2000-3200 Å have been obtained, including observations on 8 dates with data for both cameras. The data reduction is summarized in Pérez et al. (1993). Due to the irregular photometric variability of the star, many of the available spectra are not optimally exposed. The journal of observations, together with comments on the exposure characteristics of the data, are given in Table 1.

Broad-band optical photometry using the IUE Fine Error Sensor (FES) data is available for all of the observations. Observations made prior to early 1993, have been transformed into V_J data using the calibration of Pérez and Loomis (1991), as described in Pérez et al. (1993). Since simultaneous color data were not available for these observations, we have made no color correction to the FES data. Neglect of color corrections can result in an error as large as 0.11 in V for the optical maximum data ((B-V)=0.38). For the observation of UX Ori on 1993 January 28 the angle of the telescope axis to the anti-solar point was sufficiently large that significant stray light contaminated the FES due to light leaks which have developed in the spacecraft baffles, resulting in unreliable photometry with the FES. Strömgren photometry obtained shortly after the observation showed $V_g=10.065$, with, however some large excursions

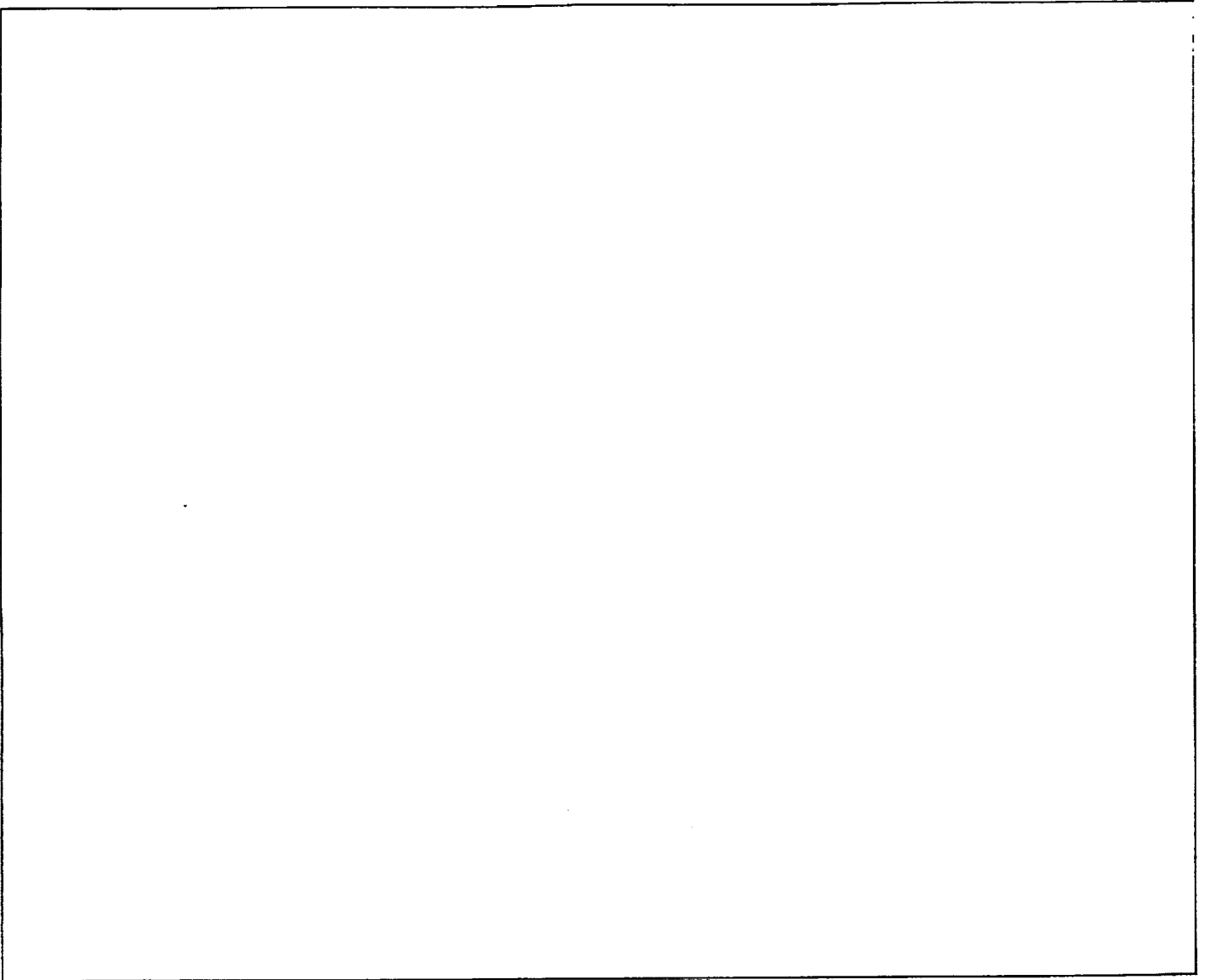


Fig. 1. The mid-UV spectrum of UX Ori as a function of V . a) Optical maximum ($V=9.7$), intermediate state ($V=10.07$), and optical minimum ($V=11.95$) mid-UV spectra of UX Ori. At optical maximum, the mid-UV spectrum of UX Ori is similar to other, bright Herbig Ae stars in showing strong absorption due primarily to Fe II, with Mg II filled in. At optical minimum, the spectrum shows a comparatively flat continuum with superposed emission in Fe II and Mg II. Intermediate state spectra show progressive filling in of the absorption with decreasing optical light. Leader lines indicate the location of transitions of Mg II (1) and Fe II multiplets 62, 63, and 1. b) Detail of the optical minimum spectrum.

night to night (Johnson et al. 1994). The most recent observations, on 1993 October 8 and November 18 have minimal contamination due to stray light. The 1993 November 18 observation was obtained with contemporary Strömgren photometry which is in good agreement with the $V(FES)$.

3. General Characteristics of the Spectra

As shown in Table 1, the available IUE data cover essentially the entire photometric range of UX Ori with data available between $9.7 < V(FES) < 11.9$. From maximum to minimum light, the IUE spectra exhibit both large

amplitude continuum light changes, changes in the absorption spectrum, and detection of an emission spectrum in the fainter UV observations (Figure 1). Changes in the character of the UV spectrum of a Herbig Ae star of this type have not previously been reported. The IUE data include observations on 2 dates when the star was close to optical maximum light (August 1981 and October 1983), with data covering the 2000-3200 Å range obtained only on 10/83. The August 1981 1150-2000 Å spectrum is heavily saturated longward of 1700 Å. The October 1983 SWP spectrum is severely underexposed shortward of 1800 Å. Comparison of the optical maximum SWP data suggests that both the continuum light levels and the amount of line blanketing in the spectrum may be variable, although the low S/N in the October 1983 spectrum precludes more detailed analysis.

3.1. Optical Minimum UV Observations

In 1992 two observation sets were made at $V=11.9$, on February 5, 1992 and on September 23/24 1992. The second of these observation sets corresponds in time to the end of the prolonged, deep optical minimum reported by Grinin et al. (1994) (figure 2). The overall character of these spectra are similar, with some weak absorption features (compared to the optical maximum data) present shortward of 2000 Å. In contrast to the optical maximum observation, which showed blended absorption in Fe II multiplets, and Mg II filled in to the local continuum level, the optical minimum observations show only a flat continuum with prominent *emission* in both Fe II and Mg II. An emission spectrum of this kind has previously been reported for the recently identified Herbig Be star, HD 45677 (Grady et al. 1993), and has not previously been reported for a Herbig Ae star showing absorption at maximum light.

3.2. UV Spectral Type

As noted by Heck (1987), the most important spectral class criterion for A stars is the slope of the continuum, especially in the 1250-2000 Å region covered by the IUE SWP camera. This wavelength range for A stars is characterized by a sharp drop in the overall flux level with decreasing wavelength, and by prominent photoionization edges near 1560 Å (A1-3) and 1700 Å (A5-A7). The drop in the flux distribution is sufficiently rapid and sensitive to T_{eff} or spectral class that to first order the effects of extinction can be ignored for stars of approximately solar composition. Comparison of the UX Ori optical minimum data, particularly the higher S/N observation made during the September 1992 deep optical minimum with normal A standard stars (Wu et al. 1982), shows a good match in the overall spectral energy distribution and the relative prominence of the 1560 Å photoionization edge to a spectral type of A1-2. Similar conclusions can be reached in comparison with the minimally reddened Herbig Ae star HD 163296. The same spectral type range was inferred by Tjin A Djie et al. (1984) from the optical maximum data (SWP 14857).

A number of mechanisms have been proposed for the large amplitude light variations of Herbig Ae stars including stellar activity, obscuration of the star by circumstellar dust clouds, and binarity. The aperiodic nature of the optical minima argues against binarity in itself being responsible for the variability of the star. For classical T Tauri stars, Herbst et al. (1986) argued that the light variations may be due to long-duration stellar activity cycles, changes in

the mass accretion rate affecting the luminosity of the boundary layer or to flaring. All of these mechanisms can be expected to modulate the FUV flux of the star, either by varying the fraction of the stellar surface which is covered by active regions, or the emission measure of any variable hot plasma component. The IUE data for UX Ori do not suggest any significant change in the stellar spectral class, despite a $\Delta V = 2.7^m$, behavior which is most consistent with variable extinction of the star.

4. UV Intermediate-Band Photometry

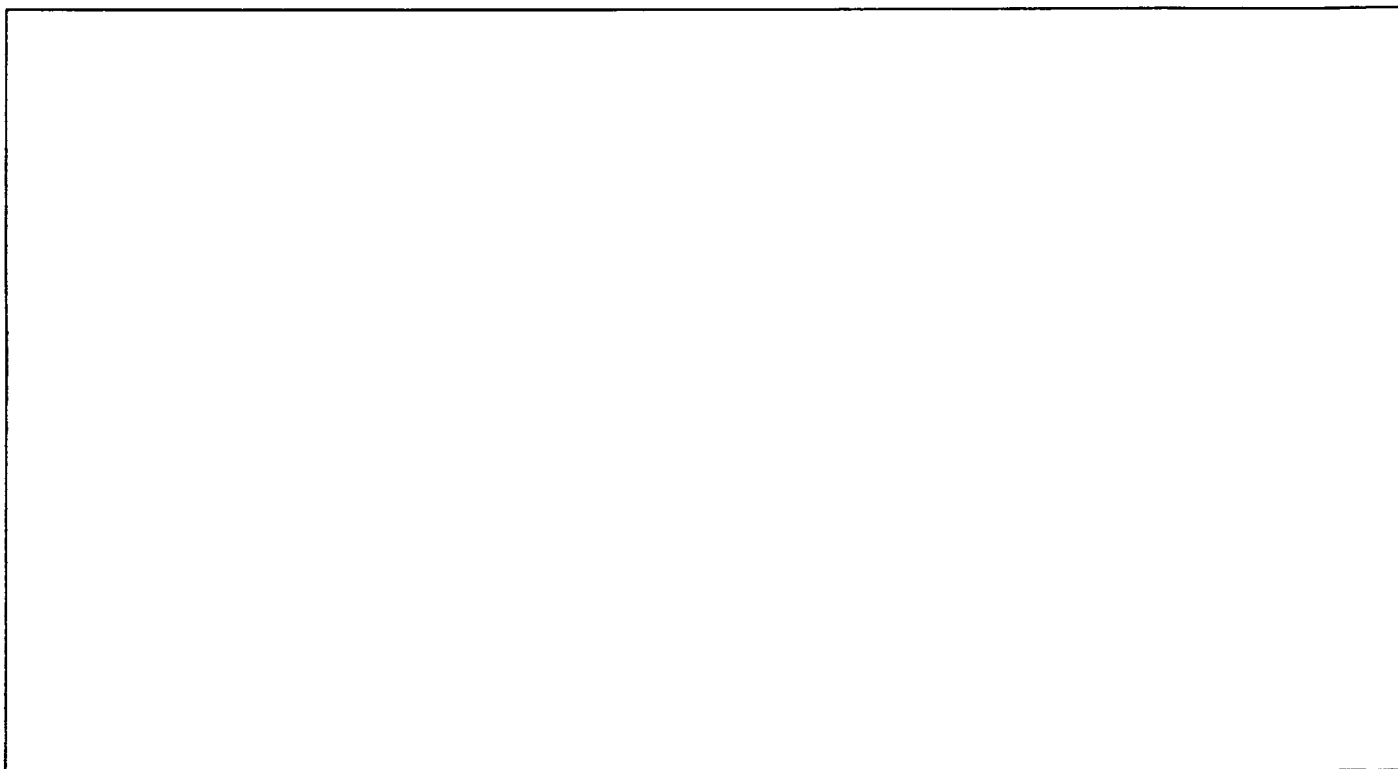


Fig. 2. UV intermediate band C-M diagram for UX Ori compared with data from Grinin et al. (1994). The IUE data do not show the turnaround in the stellar colors typical of the longer-wavelength optical colors.

Optical photometry of UX Ori shows a well-developed “hockey-stick” C-M curve (Grinin et al. 1994). As bandpasses at shorter wavelengths are considered, the ΔV below optical minimum at which the curve changes from reddening to blueing decreases. We have binned the IUE data into 50 Å bandpasses centered at 2950 and 1800 Å where line blanketing is minimal in most of the spectra, and where the camera sensitivity is comparatively high, excluding the observations with saturation, severe underexposure, or spacecraft microphonics contamination (Table 1). We find, in contrast to the optical data, no indication of a reddening branch of the C-M diagram in the UV. Instead, we find a trend of progressively bluer colors with decreasing light. This result from the binned data is immediately apparent from the change in slope of the UV spectra from optical maximum to minimum from the mid-UV to the FUV at 1500 Å (Figure 1).

Changes in the circumstellar line-of-sight extinction, while capable of changing the slope of the UV spectral energy distribution, tend to preferentially attenuate the shorter wavelengths. Variable extinction, by itself is not able to produce a systematic blueing of the stellar colors with decreasing optical light. Given the isolated location of UX Ori (Grinin et al. 1991), and the lack of any indication, from the optical photometry, of regular variability which might indicate a companion, we conclude that we have detected light from the early Ae star UX Ori in all of the IUE observations. The only model suggested which can account for both the large amplitude light and polarimetric changes, and a trend to bluer colors at minimum light, is that proposed by Grinin et al. (1991). In this model the photometric variability is due to occultation of the star by a dense, circumstellar dust cloud. With the star obscured, material in the vicinity of the star becomes detectable in the integrated light of the system via scattering by dust in close proximity to the star. For such scattering, the fraction of scattered light in the integrated light of the system should increase rather steeply with decreasing wavelength. This behavior is consistent with the lack of a "turnaround" in the UV photometry.

5. UV Line Veiling

The optical maximum IUE spectra of UX Ori exhibit pronounced absorption in singly ionized metals (predominantly Fe II). At the resolution of the IUE long wavelength spectrograph, the optical maximum spectrum is indistinguishable from that of HD 163296, a bright Herbig Ae star with little foreground reddening, and no indication of large amplitude light variations. Absorption in the Fe II multiplets is substantially weaker, relative to the local continuum level at $V=10.5$, and is not detectable in the spectra, with adequate S/N, at $V \geq 10.9$. In the FUV, a similar weakening of the absorption is visible in the fainter IUE spectra, and also in the brighter of the 2 optical maximum spectra compared to the October 1983 observation.

Comparison of the HD 163296 and UX Ori low dispersion data with main sequence standard stars shows that both systems exhibit stronger than expected mid-UV Fe II absorption than is consistent with any A spectral type (Wu et al. 1983), and which is substantially stronger than the absorption seen in the majority of bright, A-shell stars (Slettebak and Carpenter 1983). Similar absorption features are seen in low dispersion spectra of other, bright Herbig Ae stars such as HR 5999 (Pérez et al. 1993). For HD 163296, higher resolution IUE data demonstrate that the bulk of the Fe II absorption originates, not in photospheric absorption, or even in a "shell" at the stellar radial velocity, but in a strong, dense stellar wind. In the case of HR 5999, higher resolution IUE spectra demonstrate that the bulk of the Fe II absorption originates in a strong, dense accretion flow. Since optical observations of UX Ori have demonstrated the presence of accreting gas, rather than a strong wind in our line of sight, it is likely that the bulk of the *absorption* in this system is also produced in an accretion flow. Independent support for this interpretation is provided by the decrease in absorption with decreasing system light, suggesting that the lines are "veiled" because the light component passing directly through the disk is a smaller fraction of the system light at optical minimum than contributions scattered into our line of sight.

6. The Optical Minimum Data

The most distinctive feature of the IUE observations of UX Ori is the detection, in the fainter mid-UV observations, of emission in both Mg II and Fe II. Both observations made at $V=11.9$ show prominent Mg II emission, as well as emission in Fe II multiplets 62, 63 and 1. Fixed-pattern and extraction noise in the current IUE data processing preclude firm detection of emission in Fe II multiplets in less sensitive parts of the IUE LWP camera; we anticipate that these features will be detected with the IUE final archive processing (Nichols-Bohlin et al. 1994). The higher S/N observation at $V=10.9$ also shows Mg II emission with a marginal detection of Fe II multiplets 62,63.

The firm emission line detections occur in spectra with large ΔV compared to optical maximum, at points when the optical photometry and spectroscopy (Grinin et al. 1994) lead us to believe that the star and innermost disk is heavily obscured. The emission features, therefore, must originate in a region lying above or below the dust disk. All of the available IUE data are consistent with the source being an unresolved point source ($\text{FWHM}=3''$) in both the lines and continua. The IUE data suggest, therefore, that the Fe II and Mg II emission line regions can extend no further than $1.5''$ from the star. Grinin et al. (1994) note the presence of spatially extended Na I emission with a $\text{FWHM}=3-4''$, consistent with the limits provided by the IUE data. If we adopt a distance of 450 pc for UX Ori, the IUE and optical data are consistent with a nebula which is preferentially oriented above/below the circumstellar disk plane and extending no more than 600-900 AU from the star. Additional, high resolution imagery or long slit spectroscopy are needed to better constrain the orientation of the nebula with respect to the dust disk. This interpretation is supported by the detection of $H\alpha$ emission at optical minimum which is apparently centered on the system velocity (Grinin et al. 1994). Together with the orientation constraints provided by the polarimetry, these data suggest that we have detected a bipolar emission line region which may be either a jet or a disk wind similar to that recently imaged around the T Tauri system DG Tau (Kepner et al. 1993). The similarity of the emission spectrum to the lines seen in absorption toward HD 163296 and other minimally obscured Herbig Ae stars suggests that we have detected, from the side, a strong, dense outflow.

7. Constraints on Extinction At Optical Minimum

Previous assessments of the extinction toward UX Ori have either relied on the reddening portion of the optical light curve or have assumed that UX Ori exhibited the same intrinsic spectral energy distribution as a main sequence star of the appropriate spectral type or a suitably chosen Kurucz (1979) model atmosphere (Bibo and Thé 1990). As noted by Sitko et al. (1993), comparison of spectra obtained at optical maximum and at minimum light for the same disk system can provide a more direct assessment of the extinction in the dust clumps responsible for the deep photometric minima, *provided* that the illuminating geometry is the same for all observations. In particular, this approach, which has the advantage of eliminating the effects of foreground extinction, assumes that a scattered light component to the integrated light be present at the same relative strength in both the maximum and minimum light data. The IUE

data for UX Ori suggest that some scattered light contribution is present in all spectra obtained below the optical maximum, and may even affect some of the optical maximum data. While we, therefore, cannot reliably *derive* an UV extinction curve for UX Ori independently of a model for the scattered light, we can use the available data to constrain the nature of the circumstellar extinction.

We assume that all of the UX Ori spectra are composites of a stellar spectrum reddened by passage through the circumstellar dust disk and a component scattered into our line of sight by grains in the disk and elsewhere in the immediate vicinity of the star. At optical maximum (October 1983) we assume that only extinction by the average circumstellar medium and a small scattered light component modify the stellar spectrum. At optical minimum we assume that circumstellar extinction is provided by the dense dust cloud in addition to the extinction seen in the optical maximum spectrum. We can place constraints on the extinction *due to the dense dust cloud* by reddening the optical maximum data with extinction laws with plausible R values and $E(B-V)$, and requiring that this model spectrum not exceed the observed data which the optical photometry indicates (Grinin et al. 1994) should have a substantial scattered light component at the time of the 9/92 IUE observation.

Choice of Extinction Model: The photometry of Grinin et al. (1994), with an extrapolation of the reddening portion of the light curve from optical maximum to $V=11.9$ suggests that the optical minimum data can be characterized by $A_V=2.2$ and $E(B-V)=0.3-0.35$, due entirely to the circumstellar envelope. These data would imply, in the absence of a scattered light component to the integrated system light, $6.3 \leq R \leq 8.3$. Detailed studies of circumstellar extinction associated with proto-planetary disks are still in their infancy. As a result, there are no available UV extinction studies for $R \geq 5.5$. Since, however, the parameterization of Cardelli, Clayton, and Mathis (CCM, 1989) has been quite successful in describing the extinction up to such R values, we have chosen to use extrapolations of the CCM curves with a grid of R values.

Figure 3 shows the results of our reddening the optical maximum spectrum by different R values in comparison to the September 23/24 1992 optical minimum spectrum. Extinction curves typical of the diffuse ISM are clearly inconsistent with the data, since they significantly overestimate the flux levels at 3000 \AA . Extrapolations of the CCM (1989) extinction parameterizations need to have $R \geq 5.5$ in order to reproduce the observed flux level at 3000 \AA , thus providing a lower bound to the R value since the optical photometry and polarimetry (Grinin et al. 1994) require the presence of a significant scattered light component at optical minimum. Selective extinction in the range $7 \leq R \leq 8$, which is consistent with the reddening portion of the optical C-M diagram (Grinin et al. 1994) is plausible, and is consistent with the bulk of the light detected in the optical minimum spectra being dust-scattered light. Both the optical data and the IUE observations suggest that the grains associated with the deep minima are substantially larger than those typical of the interstellar medium, and may be significantly larger than those characteristic of the ISM in star formation regions.

As an alternate to the CCM extinction curves, we have explored grey extinction. Using the $\Delta A_V=2.2$ inferred from the V(FES) data, we find that grey extinction by itself reproduces the flux level at 3000 \AA but does not account

for the color change in the optical data. We conclude, therefore that the grains in the dust cloud associated with the deep minimum have a distribution which is significantly skewed toward grains larger than those typical of the ISM or most star formation regions, but which are not all uniformly large. Interestingly, independent of the assumed R value used to redden the optical maximum data, we find pronounced flux excesses at the shorter wavelength in the IUE data, suggesting that at optical minimum the observed light of the UX Ori system is dominated by the dust-scattered component.

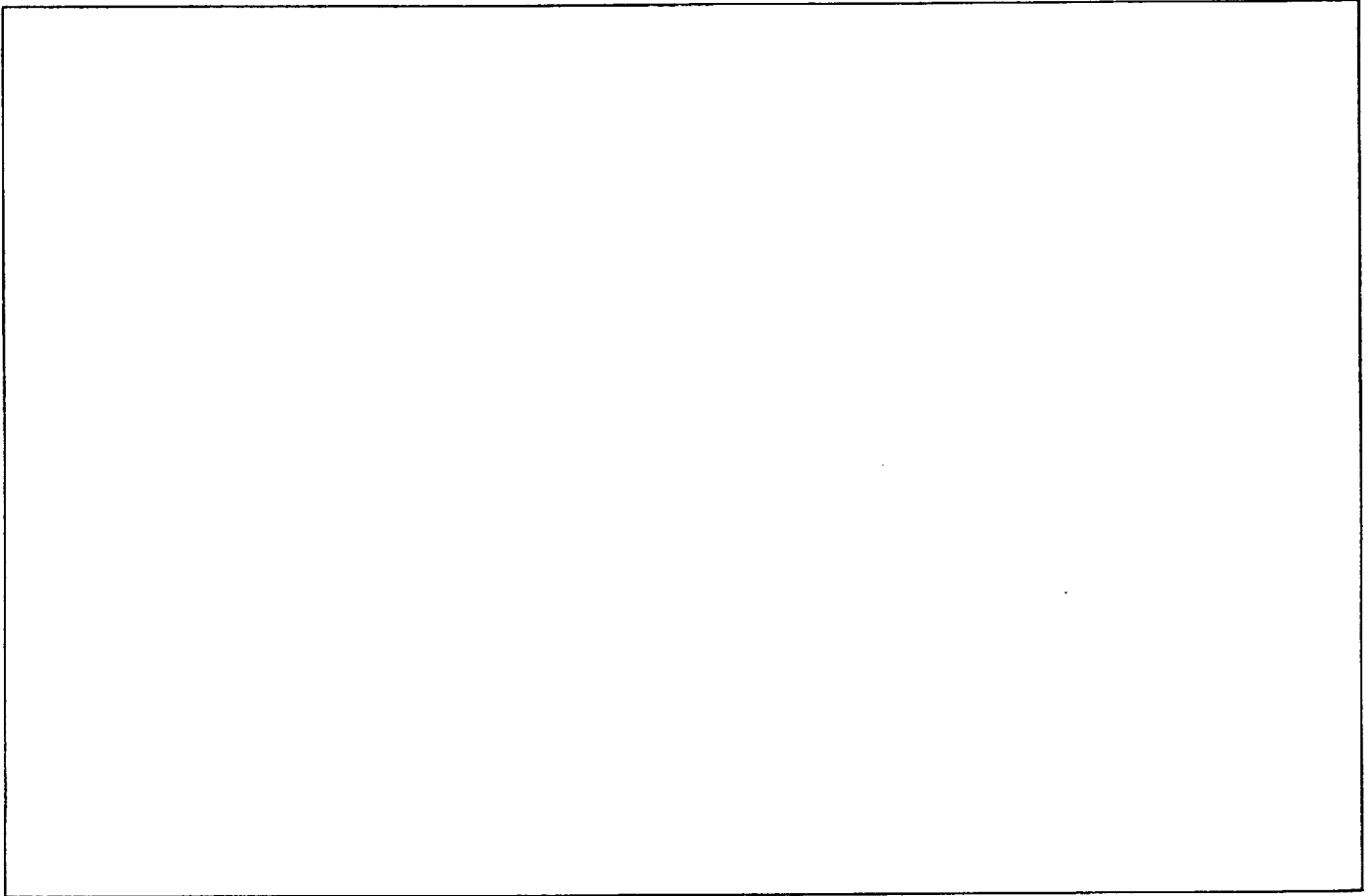


Fig. 3. Comparison of the UX Ori 1992 September optical minimum data with reddened optical maximum spectra. In panel a) the optical maximum data have been reddened using the Cardelli, Clayton, and Mathis (1989) parameterization with ratios of total to selective extinction, R , ranging from 3.1, 5.0, 5.5, 6.0, 7.0, and 8.0. In panel b) the optical maximum spectrum reddened using grey extinction is displayed. In all cases a pronounced excess of the observed flux compared to the reddened optical maximum spectrum is observed for $\lambda \leq 2600 \text{ \AA}$. Ratios of total to selective extinction, $7.0 \leq R \leq 8.0$ produce sufficiently large flux excesses to account for the observed color changes.

8. Extinction at Optical Maximum

Light curves for UX Ori (Bibo and Thé 1990, 1991; Grinin et al. 1994; Johnson et al. 1994) suggest that the star is usually at or only slightly below its optical maximum light level. The optical maximum spectra are likely, therefore, to be representative of the average circumstellar medium in the UX Ori disk. We have explored the extinction toward

UX Ori in the optical maximum observations using HD 163296 as a comparison source. This Herbig Ae star has a similar spectral type to UX Ori, a slightly larger IR excess, and hence only slightly larger mass accretion rate, if the model proposed by Hillenbrand et al. (1992) is correct, is comparatively bright ($V=6.8$), and minimally reddened by the foreground interstellar medium ($E(B-V)=0.03$, with $R=3.1$). An extensive selection of IUE low dispersion spectra are available, as a by-product of several high dispersion monitoring campaigns. At optical maximum, UX Ori has $(B-V)=0.38\pm 0.03$ (Tjin A Djie et al. 1984), with at most $(B-V)_o=0.06$ expected for A2 III (Schmidt-Kaler 1982). Studies of nearby stars suggest that $E(B-V)=0.06$ may be due to the foreground ISM (Tjin A Djie et al. 1984), leaving a circumstellar $E(B-V)_{CSM}=0.26$. These data suggest a larger reddening than proposed by Bibo and Thé (1990) from single extinction parameter fits of optical data to Kurucz (1979) model atmospheres.

After de-reddening both the optical maximum UX Ori data and the HD 163296 observations (SWP 6556, LWP 11813) to correct for our assumed foreground extinction, we compared the UX Ori data with HD 163296 observations reddened using a grid of R values with the CCM (1989) extinction curve parameterizations. We find that the UX Ori optical maximum data are inconsistent with reddening by $R=3.1$. Good fits to the UV spectral energy distribution are found for $R=5.0\pm 0.2$, with the HD 163296 fluxes a factor of 3.4 brighter than the UX Ori data. If we correct for both foreground interstellar and the circumstellar extinction in the UX Ori system at optical maximum, $V_0=8.11$. Under the assumption that UX Ori and HD 163296 have identical spectral energy distributions which can be normalized at V , this implies that UX Ori lies a factor of 1.78 beyond HD 163296. Thé et al. (1985) have inferred a distance of 150pc for HD 163296, implying that UX Ori lies some 268pc away, or in front of the Orion star formation region. This accounts for a factor of 3.19 in the flux difference. The remainder is likely to represent small differences in the luminosities of the 2 stars, which are apparent in the 0.22 magnitude difference in the IR excess at 12 microns. Our inferred optical maximum R value is in agreement with the value derived by Bibo and Thé (1990). Selective extinction in this range is not only consistent with values typical of star formation regions but is distinctly smaller than the range of plausible R values needed to describe the deep optical minimum.

9. Discussion

Some physical insight into the grain population of the inner UX Ori system can be provided by comparison of the observations with the model of Voschinnikov (1989) and Voschinnikov et al. (1988) which has been used successfully to account for the optical polarization data. The model assumes a homogeneous, ellipsoidal dust envelope with semi-axes with ratio $A/B=3$. The scattering particles are modelled using a Monte Carlo code assuming single Mie scattering, with interstellar chemical composition, $N(\text{Si})/N(\text{C})=1.07$, and the Mathis, Rumpl, and Nordsieck (MRN) (1977) particle size distribution $n(a)=a^{-q}$ with $q=3.5$. The presence of silicate dust in the UX Ori system, inferred from the optical polarization by Grinin et al. (1991), is supported by detection of prominent $9.7\ \mu\text{m}$ emission by Wooden (1994). Previous studies of the optical data have suggested that the inferred optical polarization, extinction, and integrated system light are comparatively insensitive to the maximum particle size, which we assume to have the MRN value

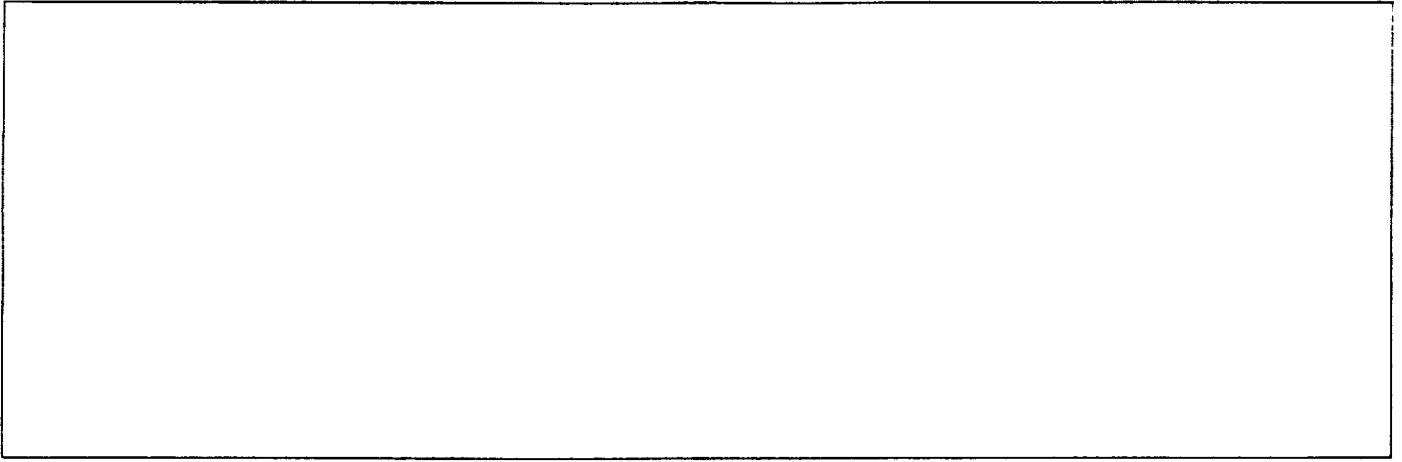


Fig. 4. Extinction toward UX Ori at Optical Maximum: We have derived the circumstellar extinction toward UX Ori using the pair method (Savage 1978) with HD 163296 as the comparison Herbig Ae star, and having corrected UX Ori and HD 163296 for assumed foreground extinction with $R=3.1$ of $E(B-V)=0.03$ and 0.06 , respectively. We find generally good agreement of the reddened HD 163296 spectrum with the October 1983 UX Ori observations for $R=5.0\pm 0.2$.

of $0.25 \mu\text{m}$. With these assumptions, the remaining free parameters are the optical depth at the U band (3650 \AA), and the minimum grain size. Voschinnikov et al. (1988) found that models with interstellar a_{min} values did not reproduce the wavelength dependence of the optical polarization. Such models exhibit pronounced absorption at the 2200 \AA bump, which is inconsistent with *all* UV observations of UX Ori. Previous optical studies have suggested that $a_{\text{min}}=0.04$ and $\tau(U)=0.5$ can reproduce both the wavelength dependence of the optical polarization and the polarization level at optical minimum. Preliminary comparison of these models, convolved with a $T_{\text{eff}}=9000 \text{ K}$, $\log(g)=4.0$, solar composition Kurucz (1991) model suggests that either a smaller optical depth or a larger minimum particle size is needed to produce scattered light levels at or below the continuum flux in the IUE optical minimum spectra. Since comparatively high optical depths are required in the optical to produce the observed polarization level (4% at the time of the 1992 September IUE observation, Grinin et al. 1994), the IUE data suggest that the minimum grain size may be larger than has previously been considered. If supported by more detailed modelling, these data suggest that the average circumstellar grains in the UX Ori envelope are comparable in size to those responsible for the polarization in the β Pic disk (Gledhill et al. 1991). The extinction constraints on the dust clouds responsible for the optical minima suggest that these grains are still larger. The IUE data, while limited in number, also suggest that the dust-scattered light component may be highly variable (e.g. 1993 November 18, see figure 2), implying that the dust optical depth in the inner portions of the UX Ori system is unlikely to be homogeneous. Additional observations will be required to determine whether changes in the scattered light fraction are correlated with the variable Mg II flux, or with changing column densities of accreting gas.

Previous studies of circumstellar extinction associated with HAeBe stars have noted the apparent deficit of small grains relative to the larger grains (Grinin et al. 1991; Steedman and Thé 1990). Steedman and Thé (1990) interpreted the deficit as indicating removal of the small grains by a number of mechanisms, all of which ultimately depend upon

the grains not being heavily shielded from the UV radiation field of the PMS star. If grain removal processes dominate the evolution of the circumstellar grain population in the UX Ori system, we would expect to find smaller grains associated with the more radiation-shielded conditions of the deep optical minimum. This is not observed. Instead, the IUE data provide convincing evidence that the dust cloud associated with the deep optical minimum in August-September 1992 is associated with a larger a_{min} than the grain population sampled at optical maximum. A trend of increasing grain size with increasing optical depth is seen in molecular clouds and star formation regions, and has been suggested as a signature of active grain agglomeration, although the inferred a_{min} in the UX Ori system is significantly larger than that typical of star formation regions or molecular clouds. Large, circumstellar grains have been reported for other HAeBe stars, notably HD 45677 (Sitko et al. 1994; Brown et al. 1994) and WW Vul (Friedemann et al. 1993). Variations in the extinction curves associated with optical minima have been reported for WW Vul, an A1e star with an IR excess similar to that of UX Ori (Friedemann et al. 1993). The data for WW Vul suggest significant departures from interstellar grain compositions for at least one of the minima (Voshchinnikov 1993), in addition to size evolution of the grain population. It remains to be seen whether such progressive grain agglomeration, and signatures of chemical fractionation of the circumstellar dust are characteristic of the more opaque dust clouds in the disks of most Herbig Ae/Be stars, or whether these effects become apparent only for the older systems. However, the available data support the suggestion of Grinin et al. (1991; 1994) that the dust clouds responsible for the optical minima closely resemble comae of star-grazing comets and expectations for young planetesimals. If supported by studies of additional systems, these data indicate that planetesimal formation is a common process in the disks of PMS stars.

Mid-UV spectra in observations with $V \geq 10.9$ reveal the presence of Fe II and Mg II emission line regions which are normally obscured by the light of the star, as modified by the gas and dust in the disk. The IUE data suggest that these emission lines are produced in a bipolar nebula extending no more than $1.5''$ from the star, consistent with the detection of extended Na I emission by Grinin et al. (1994). Intercomparison of the optical minimum and $V=11.2$ observations suggests that the Mg II and Fe II emission vary by 50%. If we assume that the luminosity of these lines are powered by accretion onto UX Ori, the IUE data suggest that the accretion is unsteady. Unsteady accretion has been suggested by Graham (1992) and Pérez et al. (1993) to account for line profile variations in R CrA and HR 5999 respectively. If supported by higher S/N and resolution data, the UX Ori data provide the first indication that the mass return from a Herbig Ae/Be star to the ISM is variable. Such variability in the mass loss rate has been inferred for classical T Tauri stars to account for structure and knots in spatially resolved bipolar flows and jets (Ray and Mundt 1992). Our data suggest that the same phenomena may occur for older, intermediate mass PMS stars.

Acknowledgements. Support for this study was provided by the NASA Long-Term Space Astrophysics Program contract NASW-4756 and the NASA IUE Guest Observer Program under PO S-14605-F to the Applied Research Corporation. We wish to thank the IUE project scientist, Dr. Yoji Kondo, and the staff of the IUE Observatory for enabling us to obtain our target-of-opportunity observations of UX Ori during the deep optical minimum. IUE data analysis was carried out at the IUE Data Analysis Center at NASA/GSFC. This study has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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Figure 1 a, b

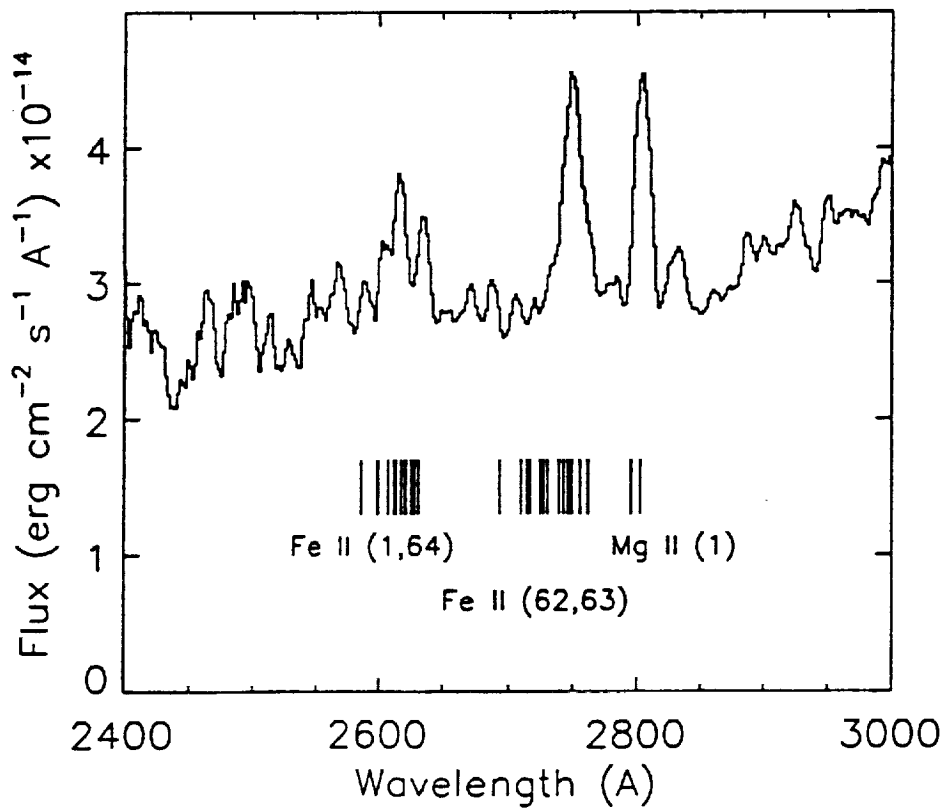
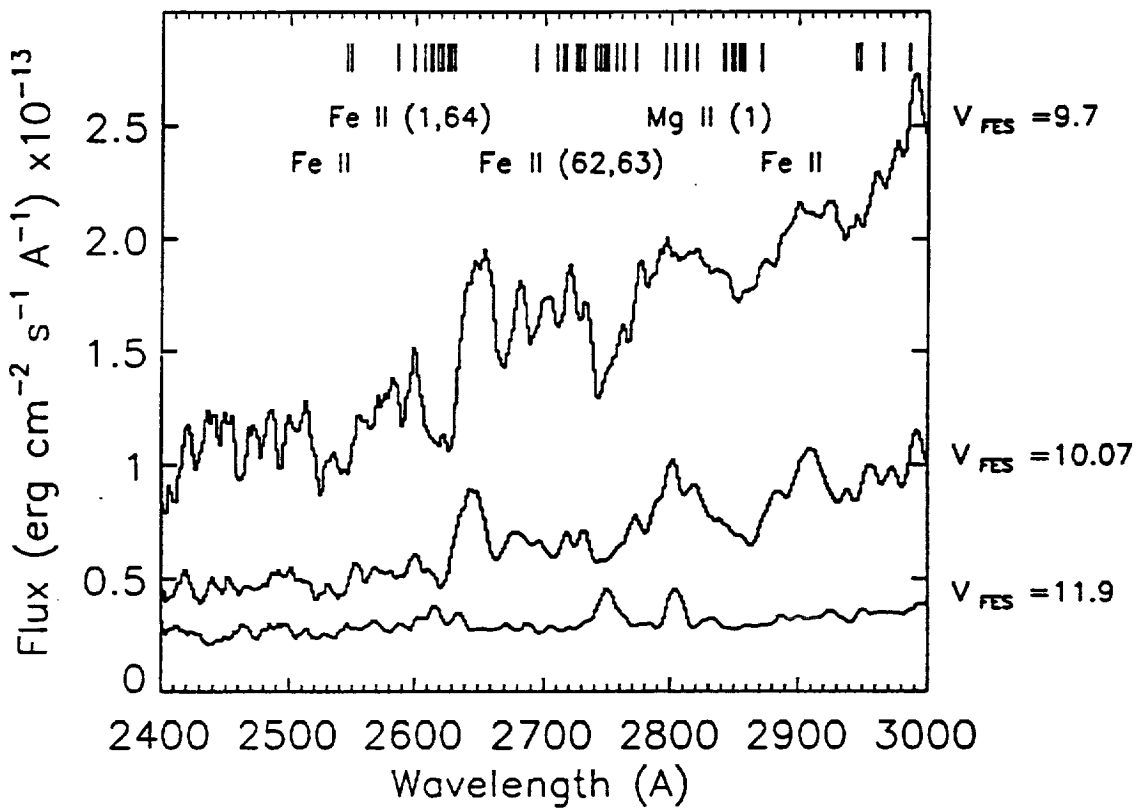


Figure 2

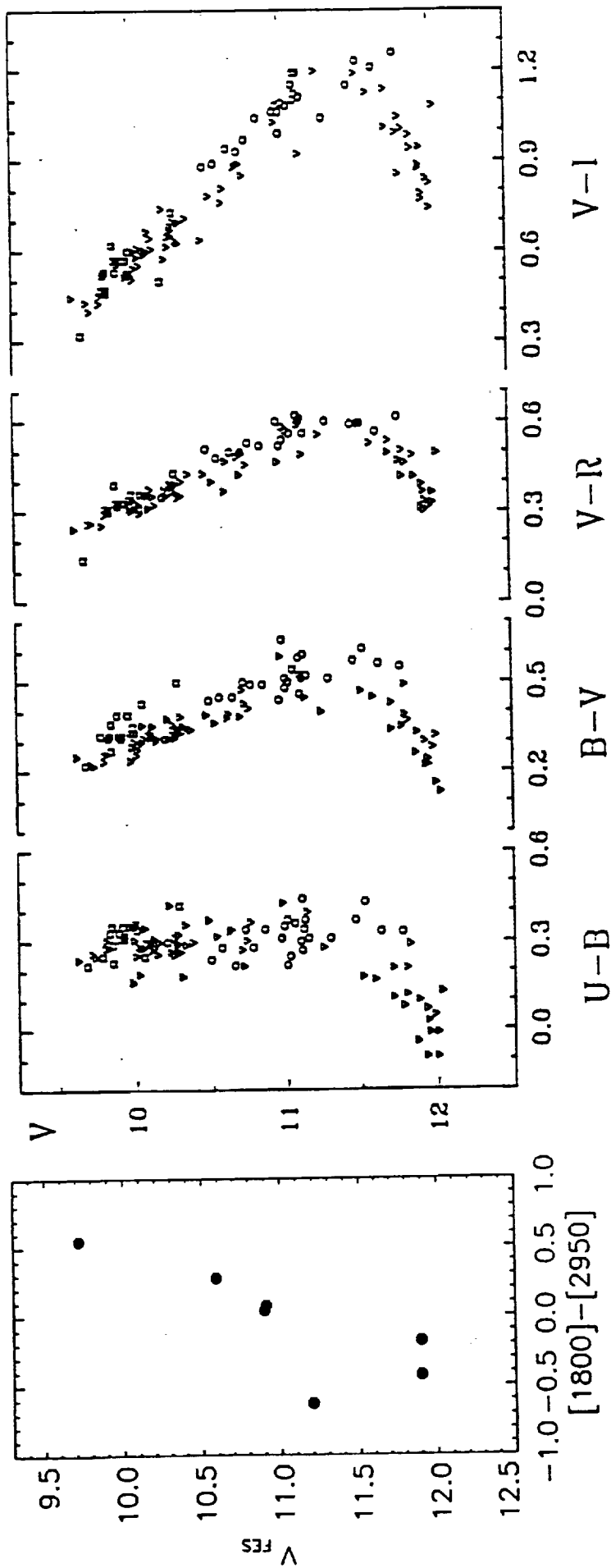


Figure 3a, b

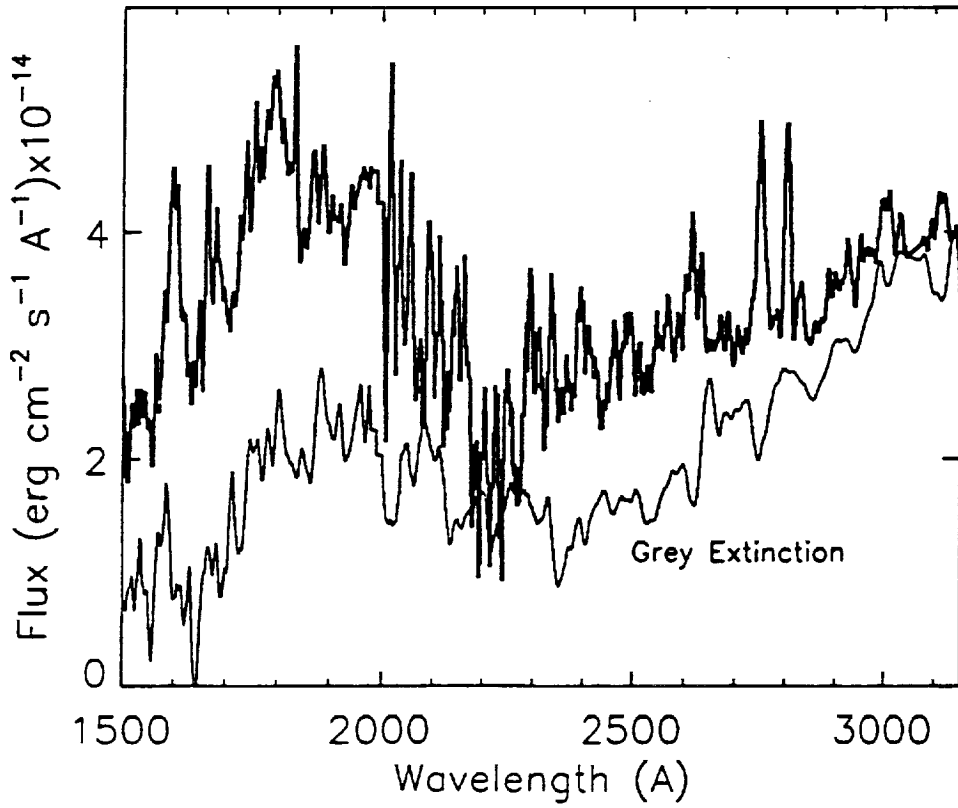
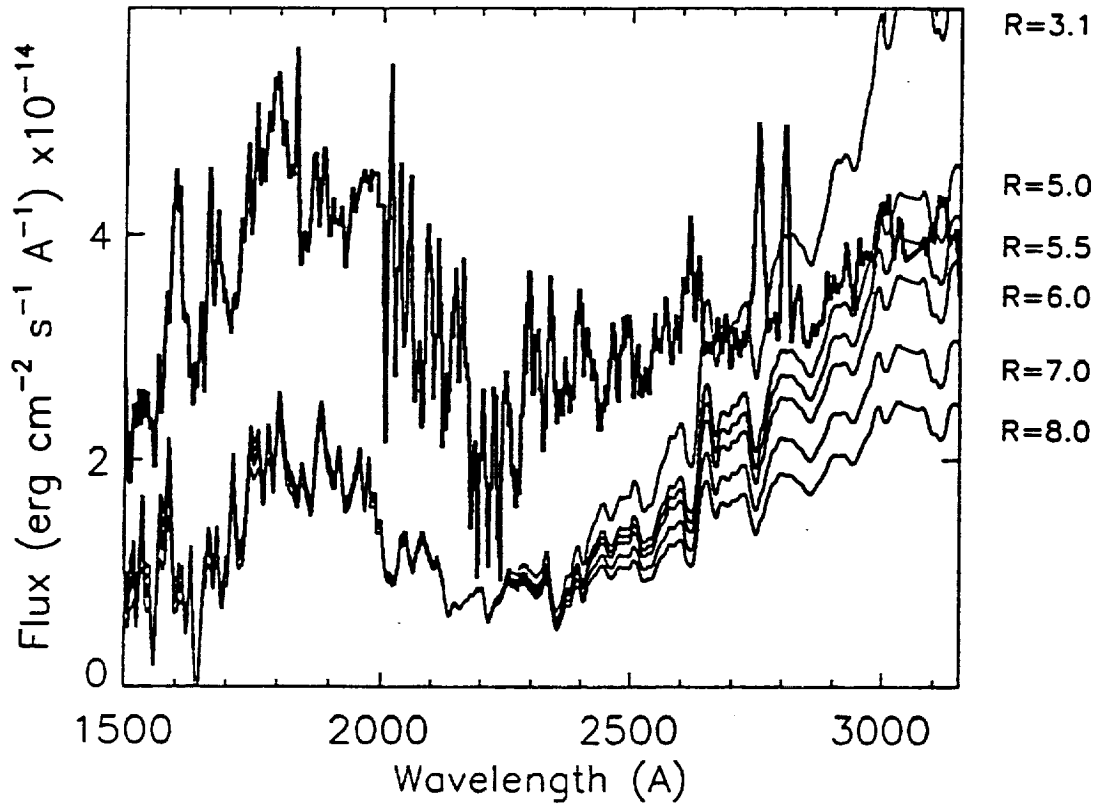
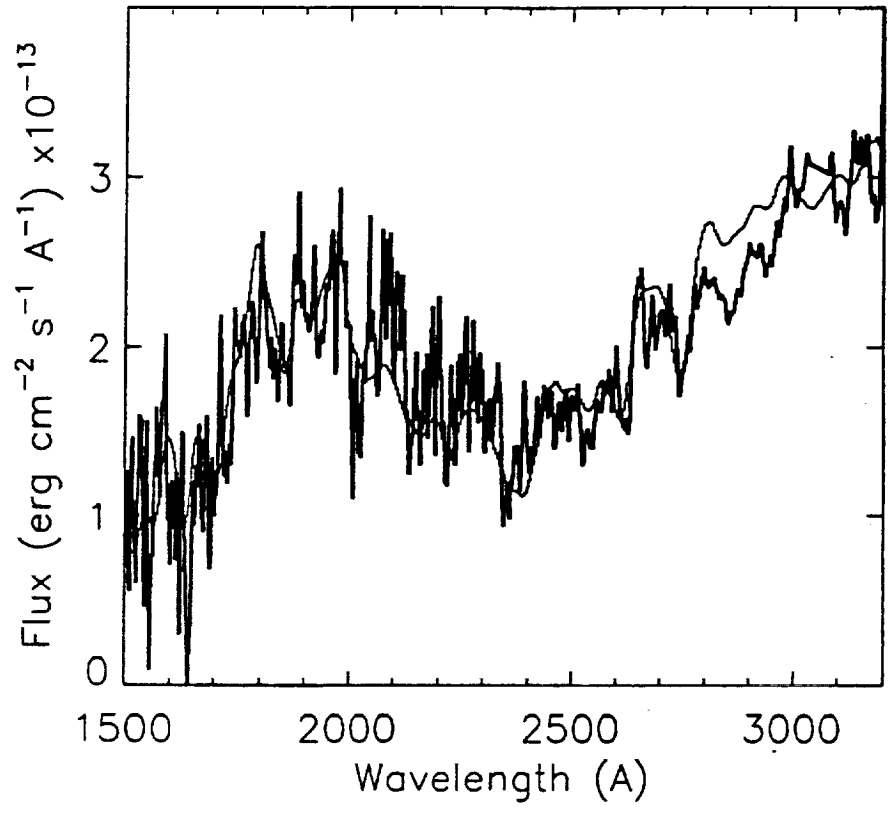


Figure 4



Resolution CO Vibrational Overtone Spectroscopy of YSO Disks

(UC Berkeley), A. Glassgold (NYU)

CO lines which form in warm (several 1000 K) dense (> 10¹⁰ cm⁻³) ... such as the near IR vibration-rotation bands of CO are in principle powerful diagnostics of the inner regions of YSO disks and winds.

In a collaboration with J. Carr, F. Shu, and A. Tokunaga, we have obtained high resolution (R = 20,000) spectra of the CO vibrational overtone emission in a small sample of embedded YSOs and TTSs using the cryogenic echelle spectrograph at the IRTF (CSHELL). Thus far, several of the objects studied at high resolution show evidence for emission from rotating disks.

Recently, we have obtained high S/N spectra of both the CO(v=2-0) and CO(v=5-3) bandhead regions in 1548C27. The additional information provided by the CO(v=5-3) bandhead region is particularly valuable because lines from the CO overtone transitions also fall in this spectral region.

These observations constitute some of the most direct evidence to date for the existence of inner disks around YSOs and provide important constraints on basic physical properties of YSOs and their surrounding disks.

Coronagraphic Survey for Circumstellar Disks

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We present results from a coronagraphic survey at visible wavelengths for circumstellar disks. Candidates include both main-sequence and pre-main-sequence stars selected on the basis of proximity, infrared excess, submillimeter emission, or spectral features indicative of solid, circumstellar material.

ST observations of the gas around J Pictoris: additional evidence for outflowing evaporating bodies

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Spectroscopic studies of the circumstellar (CS) gas around J Pictoris since 1984 have led to the detection of strong short-term variations in the CS lines of ionized species (see for instance Ferlet et al., 1987, A&A 185, 267, and Lagrange et al., 1992, A&A 264, 637 for the visible data and Lagrange et al., 1991, A&A 190, 275 for the UV data), tentatively attributed to evaporation from

solid, cometary-like bodies falling on the star. Detailed simulations of such a scenario have been developed and reproduce the medium resolution UV as well as the high resolution visible data available so far (Beust et al., 1990, A&A 236, 202; 1991, A&A, 241, 488; Beust and Tagger, 1993, Icarus, in press). In this poster, we will present high resolution UV spectra obtained in December 1992 with the Hubble Space Telescope GHRS. These data (Vidal-Madjar et al., 1993, A&A, to be submitted) enable us to confirm the presence of very ionized species around J Pictoris such as C IV, already proposed by Deleuil et al. (1993, A&A 267, 187) from IUE data, but also to detect unambiguously the molecular species CO. The variable parts of other CS lines (e.g., Fe II, Mg II, Al III), observed with unprecedented high resolution and high signal-to-noise, also bring strong support to the evaporating infalling body scenario.

41.09

Iron Emission Lines in the Spectra of Herbig Ae/Be Stars Viewed Through Their Proto-Planetary Disks

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Recent studies of Herbig Ae/Be stars suggest that the systems with large amplitude photometric variability coupled with polarimetric variations are PMS stars viewed through their circumstellar disks, with essentially the same orientation as for the J Pic system. Irregular, Algol-type photometric minima have been interpreted in terms of intermitted obscuration of the star by dense, circumstellar dust clouds acting as "natural" coronagraphs. UV observations, made when the star is heavily obscured provide an unparalleled opportunity to probe the immediate vicinity of a number of systems which are too faint for conventional coronagraphic studies with current or planned instrumentation.

41.10

The Growth of Solids and Radiation Shielding in the Young Stellar Disk of HD 45677

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To investigate the properties of a probable proto-planetary system, HD 45677, we acquired FUV spectra from the ASTRO-1 and IUE space missions of two Herbig Be stars: HD 45677 and HD 200775 - young B2 Ve and B3 Ve stars with circumstellar disks. HD 45677 is viewed edge-on through the disk, while the HD 200775 sight-line apparently avoids the disk. After correcting for interstellar extinction and absorption toward both stars, we use HD 200775 as a comparison to HD 45677 in order to derive the HD 45677 disk absorption and to place an upper limit on the molecular hydrogen [N(H₂) < 10¹⁹ cm⁻²] through the HD 45677 disk. We also measure N(HI) = 2.5 x 10²¹ cm⁻² through the HD 45677 disk.

THURSDAY

HD 45677 AND HD 50138: IDENTIFICATION OF 2 B[E] STARS AS
HERBIG BE STARS VIEWED THROUGH THEIR CIRCUMSTELLAR
DISKS

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ABSTRACT Approximately 27% of the better-studied Herbig Ae/Be (HAeBe) stars exhibit large amplitude light changes consistent with aperiodic obscuration of the star. Polarimetric studies of several of these stars indicate that much of the circumstellar dust is distributed in disks. Photometric surveys have suggested that the systems with large amplitude light variations are found only for spectral types $\geq B8$, which is inconsistent with the disk models. We compare UV and optical data for 2 B[e] stars, HD 45677 (B2[e]) and HD 50138 (B8[e]), with the available data on HAe stars with Algol-like photometric minima. The available data for the 2 B[e] stars suggest a strong similarity to the known HAeBe stars viewed through their disks. These data suggest that the deficit of photometrically variable HBe stars earlier in type than B8 is a classification selection effect.

INTRODUCTION

Several recent studies have found that some Herbig Ae/Be (HAeBe) stars have IR excesses consistent with the presence of large, viscously heated accretion disks (Hillenbrand et al. 1992; Lada and Adams 1992), which are potentially the evolutionary precursors of the β Pic disk. Within the past year, it has become clear that HAeBe stars with large amplitude light and polarization changes are the stars viewed through their disks. This conclusion is supported by detection of accreting gas toward these stars, and not toward the less heavily obscured HAeBe stars. Finkenzeller and Mundt (1984) and more recently, Bibo and Thé (1991) have noted an apparent deficit in HAeBe stars with these characteristics with spectral types earlier than A0. Since there is no reason that the orientation of a disk system should depend upon the stellar spectral type, determining whether

or not the deficit is real is an important test of accretion disk models for these PMS stars.

REVIEW OF HERBIG AE STARS WITH ALGOL-LIKE MINIMA

Approximately 27% of the HAeBe stars in the Finkenzeller and Mundt (1984) catalog exhibit large amplitude light variations consistent with occultation of the star by circumstellar debris or dust clouds (Bibo and Thé 1991). Several of these stars have been the subjects of detailed polarimetric studies. Typically, as the star fades, the linear polarization increases (Grinin et al. 1991). A number of these stars have also been followed spectroscopically; the stars with the large amplitude light changes tend to exhibit accreting gas with velocities in the range 100-200 km s⁻¹ in either the Balmer lines (Hamann and Persson 1992; Finkenzeller and Mundt 1984) or transitions of Ca II and O I, in contrast to the photometrically less active systems which typically show spectroscopic signatures of outflowing material.

High dispersion UV studies of these stars are limited to the brighter members of the class. At IUE low dispersion resolution, these stars exhibit a number of common features. At optical maximum light the spectra show pronounced mid-UV and FUV absorption due to Fe II which is typically stronger than is consistent with any B or A spectral type, independent of luminosity class. Inspection of the high dispersion data for HR 5999 (Pérez et al. 1993) indicates that the bulk of this absorption is characterized by saturated absorption at low velocities with rather blocky line profiles and pronounced, red-asymmetric absorption wings extending to 250-300 km s⁻¹, reminiscent of similar features in β Pic, but much higher in column density. At optical minimum, or in several cases in IUE spectra obtained at or just below the V magnitude corresponding to the "turn-around" in the C-M diagram (see Bibo and Thé 1991), the spectrum changes character and exhibits Fe II and Mg II emission superposed on a comparatively featureless continuum. The available data (Grady et al. 1994) suggest that the emission increases with increasing IR excess.

HD 45677

HD 45677 is a comparatively bright B2[e] star with a long history of optical and IR observations. Light variations covering $7.55 \leq V \leq 8.69$ have been monitored since 1958, with minimal changes in the stellar colors. Combined UV and optical polarization data (Schulte-Ladbeck et al. 1992) suggest that the star is viewed essentially edge-on through a dust disk. The star exhibits increasing polarization (Gnedin et al. 1989; Coyne and Vrba 1976) with decreasing light, similar to that seen in the Herbig Ae/Be stars with Algol-like minima. As noted by Grady et al. (1993), the IR colors for HD 45677 are similar to those of 51 Oph, and are consistent with detection of an isolated, young star.

The similarity to the large amplitude variable HAeBe stars extends into the UV. The IUE data, particularly those obtained near the optical minimum in the late 1970s and early 1980s, show pronounced mid-UV emission due to Fe II and Mg II. The prominence of the emission has decreased with increasing system light (Pérez et al. 1993). Accreting gas has been detected in all IUE

high dispersion spectra, with velocities as large as $+400 \text{ km s}^{-1}$ (Grady et al. 1993)

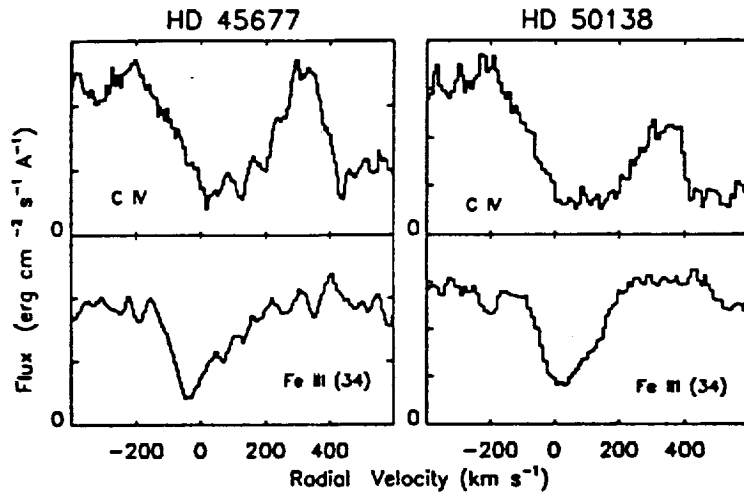


Figure 1: Representative C IV $\lambda 1548.188$ and Fe III (34) $\lambda 1895.456$ absorption profiles for HD 45677 and HD 50138. Accreting gas can be followed in both stars to $300\text{-}400 \text{ km s}^{-1}$.

HD 50138

A number of authors, including Jaschek et al. (1992), have noted the similarity of HD 50138 to HD 45677 in the optical and visual near-IR. Despite a lack of recent optical photometric variability (Halbedel 1991), the UV data suggest 30 changes in the continuum level (Savage et al. 1978) with the IUE data covering $6.58 \leq V \leq 6.80$. Some fraction of the variability may be associated with changes in the Fe II line blanketing. The average optical polarization toward HD 50138 is similar to HD 45677 in the brighter observations (Bjorkman 1993). The IR colors of HD 50138 are similar to HD 45677.

Like HD 45677, HD 50138 also shows Fe II emission in the high dispersion spectra. The emission is most apparent in the IUE spectra with minimal line blanketing, and is sufficiently weak that it is not detectable at the resolution of the low dispersion data. Hutsemékers (1985) noted the detection of red-shifted absorption in C IV and Si IV. Accreting gas is also visible in Fe III (34), confirming the presence of high-density circumstellar accreting gas. Like HD 45677, 51 Oph, and β Pic, there is a trend of increasing ionization of the gas with increasing velocity (Figure 1). The presence of C IV and Si IV in the spectrum of a B8[e] star is inconsistent with photoionization by the stellar radiation field (Bruhweiler et al. 1989), and indicates the presence of collisionally ionized gas, much as for β Pic. Accreting gas is also seen low ionization, optical lines (Jaschek et al. 1993).

DISCUSSION

Accreting gas is atypical of the bulk of classical Be stars (Grady et al. 1987; 1989), which generally show strong, high velocity outflows characterized by

highly variable discrete absorption profiles. Circumstellar dust signatures, particularly in the near IR are also atypical of classical Be stars (Dougherty et al. 1991). Evolved systems, such as post-AGB stars are expected to have 2-component stellar winds, rather than signatures of clumpy accretion. The available data for these two B[e] stars suggests a striking similarity to the Herbig Ae stars with Algol-like photometric minima. In combination with the polarimetric data, the spectroscopic data suggest a similar origin for the light variations in these systems, and further imply that the apparent deficit in photometrically variable Herbig Be stars noted by Finkenzeller and Mundt (1984) and Bibo and Thé (1991) is a selection effect.

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