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ASTRONOMY AND ASTROPHYSICS

The β Pictoris phenomenon among young stars

II. UV observations of the Herbig Ae star UX Orionis*

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Abstract. IUE spectra of the Herbig Ae star UX Ori reveal the presence of large amplitude light and color changes, which are an extension to shorter wavelengths of the "blueing" effect seen in the optical. At optical maximum the UV spectrum of UX Ori is dominated by heavy line blanketing from accreting circumstellar gas with velocities as high as +200 km s^{-1}. At minimum light, prominent mid-UV emission from Fe II and Mg II is present, and the overall spectrum closely resembles spectra of more heavily embedded Herbig Ae stars. Comparison of the UV and optical data for UX Ori suggest that single parameter ISM-like extinction curves do not fit the observed data near optical maximum light, when contamination by scattered circumstellar dust is minimized. The best fit to the UV color-magnitude diagram is for circumstellar extinction dominated by silicate grains with $a_{min} \geq 0.15$ μm, and with a power law distribution $n(a) = a^{-2}$, suggesting that both the particle size distribution and grain chemistry in the inner disk have evolved considerably from those characteristic of molecular clouds in the 2-3 Myr since the formation of UX Ori.

Key words: stars: pre-main sequence – circumstellar matter – accretion – line: profiles – stars: individual: UX Ori – ultraviolet: stars

1. Introduction

A number of recent studies of Herbig Ae/Be (HAeBe) stars have suggested that these Pre-Main Sequence (PMS) stars (Palla & Stahler 1993) possess large, viscously heated accretion disks which are potentially the evolutionary precursors of the β Pic disk (Hillenbrand et al. 1992; Lada & 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 in disks (Grinin et al. 1991), with our line of sight to the stars passing through the disk. This viewing geometry, and the accompanying occultation events are especially favorable for line-of-sight studies of the circumstellar gas and grains, using techniques initially developed for the interstellar medium, and more recently applied to β Pic. Optical studies of HAeBe stars have demonstrated that stars, which are known large-amplitude photometric variables, exhibit high velocity accreting gas in a number of spectral lines, including transitions of the Balmer series, Ca II H and K, Na I D, and O I λ7773 (Welty et al. 1992; Hamann & Persson 1992; and the data presented in Finkenzeller & Mundt 1984). For the brighter HAeBe stars, UV spectra demonstrate the presence of accretion (Grady et al. 1993a,b, 1994, 1995; Pérez et al. 1993). 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.

2. UX Ori

One of the best studied members of this class of Herbig Ae (HAe) stars is the isolated system UX Ori (A2-3 IIIe, Tjin A

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Djie et al. 1984). The star exhibits large amplitude (ΔV=2.^{m}5) light changes accompanied by spectacular color changes. Down to V=10.^{m}3, as the star light fades it becomes progressively redder (Bibo & Thé 1990, 1991; Herbst et al. 1994). 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. 1991,1994), with reproducible polarization position angles from optical minimum to minimum, and a wavelength dependence consistent with scattering of starlight by circumstellar dust in an axisymmetric structure, most probably a disk. These data have prompted 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. In tandem with the light and polarization changes they find systematic changes in the Hα emission profile from an inverse type III P Cygni profile at optical maximum to a single, narrow emission feature with broad, asymmetric wings. A similar profile in a previous optical minimum was reported by Kolotilov (1977).

Optical spectroscopy of UX Ori near maximum light demonstrates the presence of accreting gas with velocities as high as +200 km s^{-1} and pronounced variability from night to night (Grinin et al. 1994; de Winter et al. 1995). Grinin et al. (1995) note that Na I has a sufficiently short photoionization lifetime close to the star that essentially no high velocity feature should be detectable unless the gas is being produced *in situ* by the sublimation of refractory grains. The presence of this feature, which is frequently observed with absorption components similar to those seen in the spectrum of β Pic strengthens the parallel between this system and the more evolved β Pic disk with its evaporating, infalling bodies (Grinin et al. 1995; de Winter et al. 1995).

Over the past 14 years, UX Ori has been repeatedly observed by the International Ultraviolet Explorer (IUE) in its low dispersion mode, with data obtained at or near optical maximum on 3 dates, and optical minimum at 2 epochs. In addition, UX Ori was observed on 1994 October 1 in high dispersion, with an exposure optimized for the 2600-3000 Å region. These data extend the wavelength coverage and transitions available for studies of the accreting circumstellar gas, and also enable us to extend the color magnitude variability studies of Grinin et al. (1994) to shorter wavelengths.

3. Observations and data reduction

UX Ori has been comparatively well observed, for a moderately faint HAe star, by the IUE at irregular intervals from 1981 through 1994. A total of 27 spectra covering either 1150-2000 or 2000-3200 Å have been obtained, including observations on 10 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. Mean flux levels in two 50 Å bandpasses centered at 2950 and 1800 Å, located in portions of the spectrum with modest line blanketing, give some indication of the rms deviation of the continuum data near the camera sensitivity maxima. The rms deviations reflect the aggregate of noise sources in the IUE camera, particle radiation backgrounds, photon statistics and line blanketing.

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 et al. (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_y=10.065, with, however some large excursions night to night (Johnson et al. 1994). The 1993 October 8, November 18, and 1994 September 11 data 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}.

4. General characteristics of the spectra

The available IUE data cover essentially the entire optical photometric range of UX Ori from $9.7 \leq V_{FES} \leq 11.9$. From maximum to minimum light the IUE spectra exhibit changes in continuum light levels and UV colors, accompanied by a transition from a strong absorption spectrum at maximum light to prominent mid-UV emission at minimum light (Figs. 1-3). At minimum light, the mid-UV spectrum of UX Ori closely resembles more heavily embedded HAeBe stars such as Lk Hα25. Changes in the UV spectrum of a HAe star have not previously been reported, but have now been observed in 3 additional objects with optical color-magnitude diagrams similar to UX Ori (Grady et al. 1993c).

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 the 1983 October observation. 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.

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Table 1. IUE Journal of Observations from 1981-1994. Where multiple, graded exposures were obtained on the same date, measurements are tabulated for the spectrum with the best exposure at the wavelength of interest. The continuum flux units are erg cm^{-2} s^{-1} Å^{-1}, and exposure times are given in minutes. 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 (62,63) are in emission (em), or absorption (abs). Uncertain data are indicated by :. Notes: 1:spectrum saturated longward of 1650 Å, 2: spectrum has low S/N due to underexposure, 3: spectrum has high particle-radiation induced background, 4: a few pixels saturated near 2800 Å, 5: saturated from 2600-2800 Å 6: V_{FES} is uncertain due to straylight contamination, 7: V estimated from contemporary optical data, 8: high dispersion spectrum with exposure optimized for 2800 Å

Year	Date	V_{FES}	Images	Exp.	Mg II	Fe II	F_{1800} x10^{13}	F_{2950} x10^{13}	Notes
1981	29 Aug.	9.7	SWP 14857	147	...	...	...	...	1
1983	01 Apr.	10.9	LWR 15639	10	...	...	...	...	2,3
			LWR 15640	20	...	...	...	...	2,3
			SWP 19605	10	...	...	...	...	2
	30 Oct.	9.7	LWP 2179	10	filled	abs.	...	2.00±0.30	4
			LWP 2180	20			...	...	5
			SWP 21406	10	...	...	1.53±0.23	...	
1984	09 Jan.	10.6	LWP 2580	20	filled	abs.	...	0.80±0.15	
			LWP 2585	48		abs.	...	0.71±0.08	
			SWP 21975	20	...	...		...	
			SWP 21976	30	...	...	0.64±0.07	...	
1986	14 Nov.	10.9	LWP 9519	20	em.	em:	...	0.56±0.05	
			SWP 29676	50	...	...	0.63±0.07	...	
1990	01 Feb.	10.7	SWP 38105	30	...	...	0.63±0.12	...	
1992	05 Feb.	11.9	LWP 22337	22	em.	em.	...	0.25±0.04	
			SWP 43931	90	...	...	0.37±0.03	...	
	24 Sep.	11.9	LWP 23996	48	em.	em.	...	0.34±0.02	
	25 Sep.	11.9	SWP 45774	180	...	...	0.46±0.03	...	
1993	28 Jan.	10.1:	LWP 24806	30	filled	abs.	...	0.91±0.08	6
	08 Oct.	10.9:	LWP 26528	12	filled	abs.	...	1.54±0.17	7
			SWP 48870	20	...	...	1.48±0.22	...	
	18 Nov.	11.2	LWP 26772	35	em.:	abs.	...	0.40±0.01	
			SWP 49253	90	...	...	0.58±0.02	...	
1994	11 Sep.	9.9	LWP 29150	15	filled	abs	...	1.16±.14	3
			SWP 52088	20	...	...	1.09±.19	...	
	21 Sep.	10.0	LWP 29212	15	filled	abs	...	1.58±0.15	3
			SWP 52168	25	...	...	1.69±0.13	...	
	01 Oct.	9.8	LWP 29278	400	filled	abs	...	1.99±0.06	8

4.1. 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) (Fig. 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 which are tentatively identified as absorption due to Fe II, C I, and Al II. The mid-UV spectrum shows a flat continuum with no detectable absorption, together with prominent emission in the stronger Fe II multiplets such as UV(62,63) and Mg II (1), 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. 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

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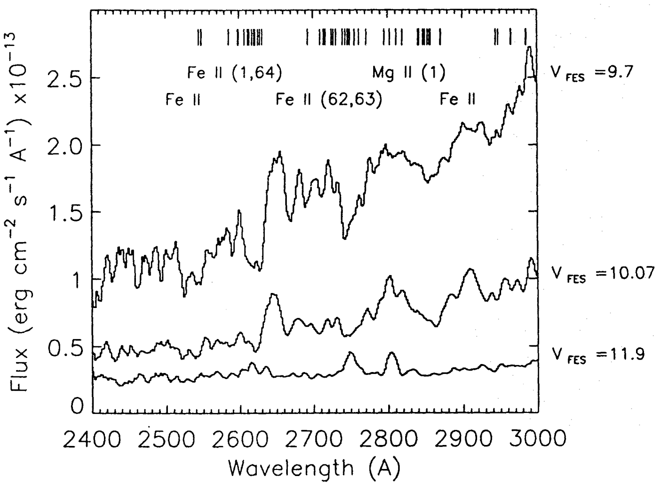

Fig. 1. The mid-UV spectrum of UX Ori as a function of V. a) Optical maximum (V=9.7), intermediate state (V=10.1), and optical minimum (V=11.9) mid-UV spectra of UX Ori. At optical maximum, the mid-UV spectrum of UX Ori is similar to other, bright HAe stars with strong absorption due primarily to Fe II, and 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

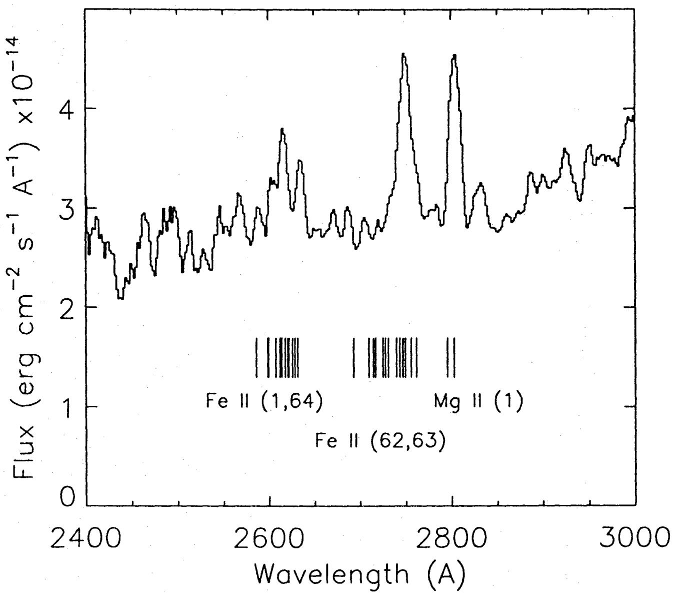

Fig. 2. Detail of the optical minimum mid-UV spectrum showing the prominent Mg II and Fe II emission

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 multipets 62,63.

Optical minimum light observations of HAe stars are now available for 2 additional large-amplitude variables with extensive optical photometric and polarimetric monitoring, BF Ori (A5 IIIe), and CQ Tau (F2 IIIe), as well as HD 45677 (B2[e]). At maximum light, these stars show prominent mid-UV absorption spectra similar to UX Ori. At minimum light, emission in Fe II is seen in HD 45677 and BF Ori, but not in CQ Tau (Grady et al. 1993c). The overall prominence of the Fe II emission appears to be correlated with the stellar spectral type. All three of these stars have an inferred viewing geometry similar to UX Ori (Schulte-Ladbeck et al. 1992; Grinin et al. 1991). Similar emission is present in mid-UV spectra of HK Ori, KK Oph, RR Tau which have been observed only when heavily obscured (Grady et al. 1993d). All three of these objects, like the known large amplitude variables show accreting gas in their optical spectra. The data collectively suggest that the optical minimum spectra of UX Ori are representative of at least 27% of the HAeBe stars, and all of those which have polarimetric signatures of a system inclination similar to β Pic.

4.2. 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 and modest ($A_V \leq 2$) extinction. For larger A_V and normal (R=3.1) extinction, preferential attenuation of the shorter wavelengths occurs; this effect is greatly reduced for grayer extinction. 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. 1983), 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 HAe star HD 163296. The same spectral type range was inferred by Tjin A Djie et al. (1984) from the optical maximum data (SWP 14857).

5. UV intermediate-band photometry and veiling

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. As shown in Fig. 3, the binned UV data are consistent with either a progressive trend to bluer colors with decreasing light, or no systematic color change down to V=11.0 (ΔV=1.3), followed by progressive blueing. We do not find any clear indication of a reddening branch in the C-M diagram, in contrast to the optical data. This result from the binned data is immediately apparent from the change in slope of the UV spectra from optical

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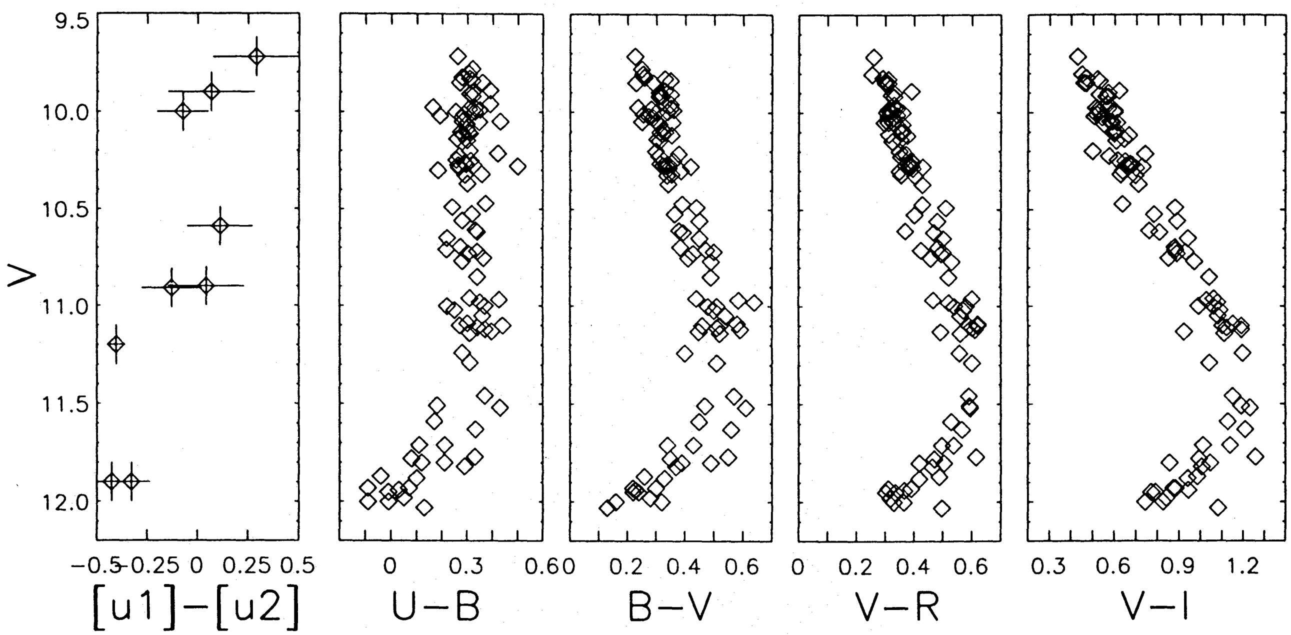

Fig. 3. UV C-M diagram for UX Ori compared with optical photometry from Grinin et al. (1994). The IUE data do not show the turnaround in the stellar colors typical of the longer-wavelength optical colors

maximum to minimum from the mid-UV to the far-UV at 1500 Å (Fig. 1).

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 HAe star with little foreground reddening, and no indication of large amplitude light variations. Both stars exhibit enhanced Fe II absorption relative to main sequence standard stars (Wu et al. 1983) and a lack of the expected Mg II absorption, at the resolution of the IUE low dispersion data. Absorption in the Fe II multiplets is substantially weaker, relative to the local continuum level at V=10.5, and is undetectable in the spectra, with adequate S/N, at V$\geq$10.9. In the far-UV, 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. The IUE data are therefore consistent with maximum veiling of the absorption spectrum at minimum light and maximum blueing.

Herbst et al. (1994) have reviewed a number of mechanisms for the large amplitude light variability in UX Ori and similar objects. They conclude that the model proposed by Grinin et al. (1991; 1994), involving occultation of the star by a dense, circumstellar dust cloud is the most plausible. The UV data presented here strengthen the case for this interpretation since the large amplitude UV light variations which are correlated with the optical light level are inconsistent with the alternate mechanisms proposed for T Tauri stars.

Herbst et al. (1994) suggest that the occultation events occur, not in the circumstellar disk, in close proximity to the star, as suggested by Grinin et al. (1994), but due to occultation of the star by dust clouds infalling from the circumstellar envelope onto the disk. This suggestion is not consistent with the IR data, which demonstrate an increase in the 2-10 μm IR excess as the star is occulted implying, instead, that the optical minima are accompanied by an increase in the number of warm (T$\geq$300 K) grains in in close proximity to the star (Hutchinson et al. 1994). Coupled with the detection of high levels of polarization at optical minimum, the IR data suggest that our line of sight to UX Ori passes through a substantial portion of the circumstellar disk.

6. Accreting gas in the mid-UV spectrum of UX Ori

Our mid-UV high dispersion, large aperture spectrum of UX Ori, LWP 29278, was obtained at V_{FES}=9.8, close to optical maximum light. While signifcantly lower in continuum S/N than observations of brighter HAeBe stars in this dispersion, the S/N=8-12 over 2800-3000 Å is sufficient to detect a prominent absorption spectrum in transitions of Fe II, Mn II, Mg I, and Mg II. The Fe II transitions are sufficiently strong, numerous, and closely spaced in wavelength that quantitative analysis of single line profiles for the higher oscillator strength transitions, which have the most secure atomic data, is challenging. The strongest diatomic molecular band in the wavelength range covered by our spectrum, due to OH (0,0) at 3080 Å is not detected in either emission or absorption, in common with other HAe stars and β Pic. The absence of this band suggests that the bulk of the circumstellar gas is atomic or more highly ionized.

6.1. Detection of accreting gas

In contrast to well-studied HAe stars such as HD 163296 (for a review see Catala 1994), the bulk of the line blanketing in

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LWP 29278 is produced by absorption from neutral and singly ionized gas (especially Fe II) which is preferentially redshifted with respect to the IUE wavelength scale (Fig. 4). The strength of the absorption is sufficient, when the spectrum is degraded to the resolution of the IUE low dispersion data, to account for the stronger-than-expected Fe II absorption in the mid-UV spectrum. Absorption can be followed without a comparison spectrum to at least +150 km s^{-1} (figure 4, 5) If a comparison source, such as HD 30739 (A1 Vn) is used, enhanced absorption can be seen in the UX Ori spectrum out to +200-230 km/s, assuming that both stars are similarly centered in the IUE large aperture and have similar radial velocities. We note that there are no independent measurements of the radial velocity of UX Ori. Given the relatively low S/N of this spectrum compared either to the HR 5999 (Pérez et al. 1993) or β Pic (Kondo & Bruhweiler 1985) data, our data are consistent with Fe II absorption extending over essentially the same velocity range as for β Pic. Fe II transitions with lower levels in high lying metastable levels are considerably stronger, relative to transitions to the ground configuration than is seen in HR 5999 (A5e, Pérez et al. 1993), or β Pic (Boggess et al. 1991). It is uncertain whether this reflects overall higher ionization/excitation of the accreting gas toward UX Ori, consistent with its earlier spectral type, or the presence of incipient emission filling in the lowest velocity portions of the transitions to the ground configuration (plausible given the optical minimum behavior of UX Ori).

6.2. *Mg II*

Imhoff (1994) noted that for the majority of HAeBe stars, the Mg II profile is similar to Hα. Hα in UX Ori at optical maximum exhibits either a type III P Cygni profile or an inverse type I profile. Our data show, instead of the prominent net emission seen toward other HAe stars (Imhoff 1994), a rather structured spectrum with peak flux close to the local continuum level, and with a complex absorption feature extending from -50 to +100 km s^{-1}. The best fit to the UX Ori spectrum in regions of minimal line blanketing is provided by comparatively rapidly rotating A1 stars (which have rather featureless mid-UV spectra). Given the comparatively low v sin i=70 km s^{-1} (Böhm & Catala 1994) for UX Ori, our data suggest that there is some line veiling in the mid-UV. The high dispersion data demonstrates that the absence of Mg II absorption in the low dispersion data is due to filling in by circumstellar emission. With subtraction of an assumed photospheric spectrum, the UX Ori data are consistent with asymmetric Mg II emission with a type III profile, but with the red emission component more prominent than the violet component. The low S/N of the data and presence of other strong circumstellar lines in the vicinity of the Mg II resonance doublet makes it uncertain whether the change in profile asymmetry from that characteristically observed at Hα is real, or an artifact of the heavy line blanketing in the UV. However, our data suggest Mg II emission extending over essentially the same velocity range as for Hα, and in particular, extending to higher negative velocities than positive velocities. The IUE data are consistent, therefore, with the highest velocity portions of the

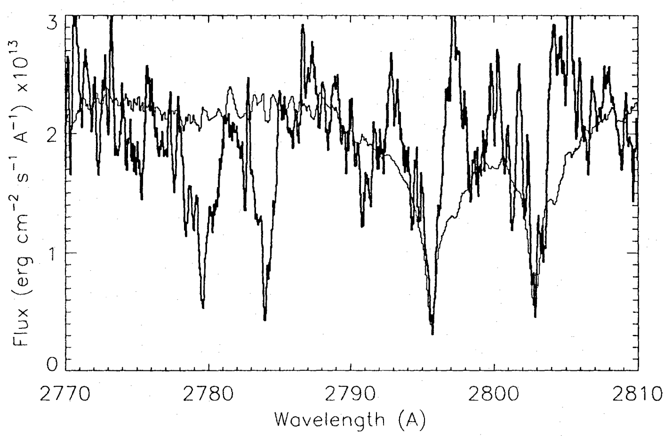

Fig. 4. Region surrounding the Mg II resonance doublet in UX Ori (bold) and an A1 comparison star, HD 30739, scaled to the UX Ori continuum flux. Relative to the comparison star, UX Ori exhibits filling in of the Mg II photospheric absorption, together with prominent absorption in Fe II transitions which is predominantly redshifted relative to heliocentric wavelengths

Mg II and Hα line formation regions coinciding. If the Type III profile is interpreted conventionally, as emission produced in a rotating disk viewed at close to the equatorial plane (plausible in view of the geometry inferred from the linear polarimetry), the primary difference between Hα and Mg II occurs in the low velocity portions of the profile which are formed at greatest spatial extent from the star.

6.3. *Velocity structure in the accreting gas*

Intercomparison of the magnesium and iron line profiles (Fig. 5) show a trend of progressively increasing ionization/excitation with increasing radial velocity. The Fe II 2783.6 Å profile and similar transitions show a prominent absorption component which is displaced some 20 km s^{-1} redward of the absorption feature in Mg I 2852 Å and 30 km s^{-1} redward of the absorption component visible in Fe II 2599. The velocity offset of this feature from the centroid of the neutral gas is similar to the offset reported by de Winter et al. (1995) in Na I. Overall, the accreting gas profiles from neutral and singly ionized species in the mid-UV are similar to the Na I profiles observed by de Winter et al. (1995), and are likely to have a similar origin. The IUE data strengthen the conclusion of de Winter et al. (1995), that refractory-rich planetesimals appear to be common in a PMS system no older than 2-3 Myr.

The presence of Mg II (3) absorption immediately redward of this feature, together with the pronounced "shoulder" seen in the Fe II 2783.6 feature is similar to HR 5999, and suggests that much of the higher velocity gas is collisionally ionized into higher ionization stages. If correct, prominent, redshifted absorption should be visible in Al III, Fe III (34), and possibly C IV, and this absorption should map the highest velocity ranges of UX Ori's accreting circumstellar gas. Unfortunately due to the comparative faintness of UX Ori, HST GHRS or STIS spectra will be required to test this hypothesis.

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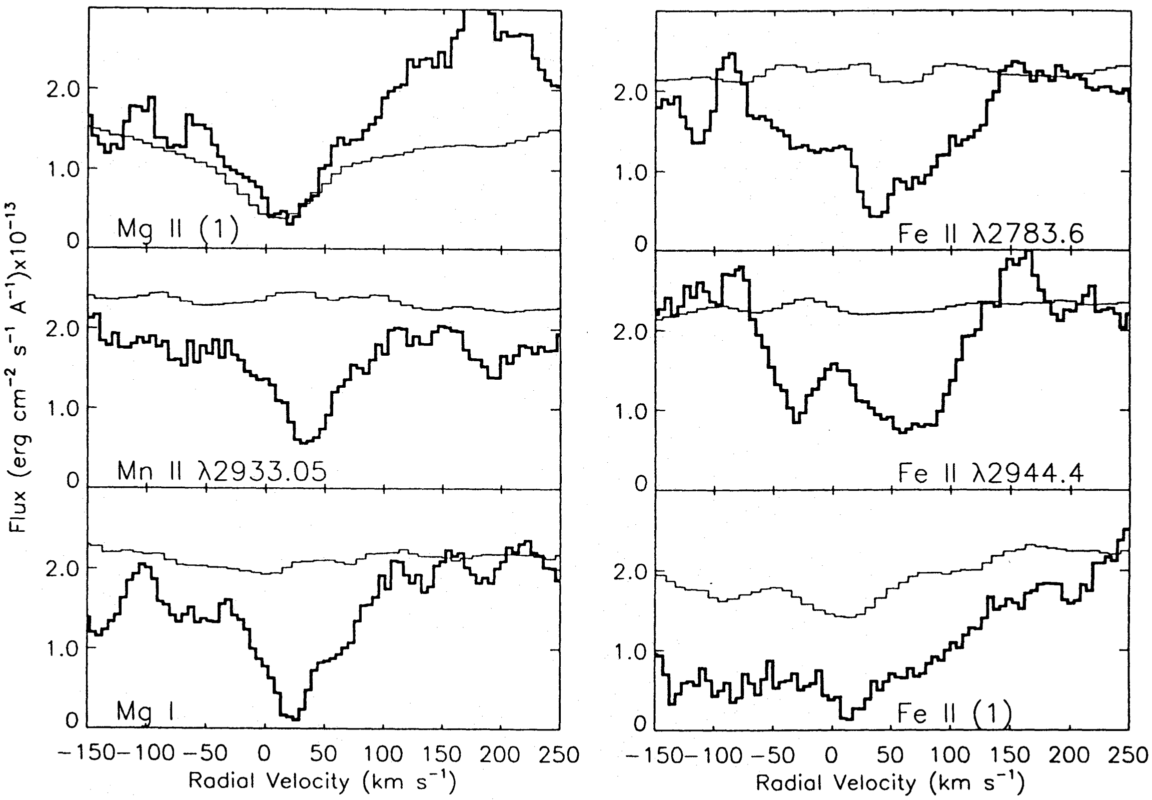

Fig. 5. Selected mid-UV line profiles for UX Ori near optical maximum light (bold) and HD 30739 normalized to the continuum flux of UX Ori (light). Prominent circumstellar absorption is visible in Mg I, Mg II, Fe II, and Mn. Comparison of the Fe II 2599 Å profile with HD 30739 suggests that high velocity gas is present in absorption out to 200-230 km s^{-1} in UX Ori

7. Extinction at optical maximum

The low dispersion UV spectra of UX Ori enable us to indirectly probe the solid material in the circumstellar disk, using techniques originally developed for studies of the interstellar medium, but more recently extended to other proto-planetary disk systems (Sitko et al. 1994).

7.1. Foreground extinction estimates

Light curves for UX Ori (Bibo & 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 HAe 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. The star 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±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 & Thé (1990) from single extinction parameter fits of optical data to Kurucz (1979) model atmospheres.

7.2. Best fits to ISM-like extinction curves

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 Cardelli et al. (1989, hereafter CCM) extinction curve parameterizations. The most distinctive features of the UX Ori spectrum, either when compared with a reddened HD 163296 spectrum, or when normalized by HD 163296, following Voshchinnikov & Karjukin (1994), is the absence of the 2200 Å bump, and the comparative flatness of the spectral energy distribution down to at least 1500 Å. The S/N of the existing UX Ori data are insufficient for us to extend the analysis to shorter wavelengths. We find that the UX Ori optical maximum, and all spectra with V$\leq$10.0 are inconsistent with reddening by average ISM extinction curves with R=3.1, or indeed with any curve having a prominent 2200 Å bump. Reasonable fits to the UV spectral energy distribution are found for

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R≥5.0±0.2. Our inferred optical maximum R value is in agreement with the value derived by Bibo & Thé (1990). More recent optical photometry from Grinin et al. (1994) is consistent with R=4.1±0.5. As discussed by CCM, ISM-like extinction curves up to R=5.5 can be characterized by the value of the ratio of total to selective extinction in the optical. The discrepancy between the inferred optical maximum extinction for UX Ori and the optical data strongly suggests that the circumstellar extinction in this, and potentially other HAeBe stars, may depart strongly from an ISM-like wavelength dependence.

8. Comparison with models

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 & Thé 1990). Voshchinnikov & Karjukin (1994) note, however, that the presence of appreciable amounts of scattered light in the integrated light of a star+disk system can appreciably distort the appearance of the spectral energy distribution, particularly for pole-on systems where the scattered light appears as a "UV-excess". For disk systems viewed more nearly edge-on, the scattered light can mimic the appearance of a flat extinction curve, particularly in the UV, thus limiting the applicability of the pair method and its extensions (Sitko et al. 1994) to the regions of the color-magnitude diagram near optical maximum light.

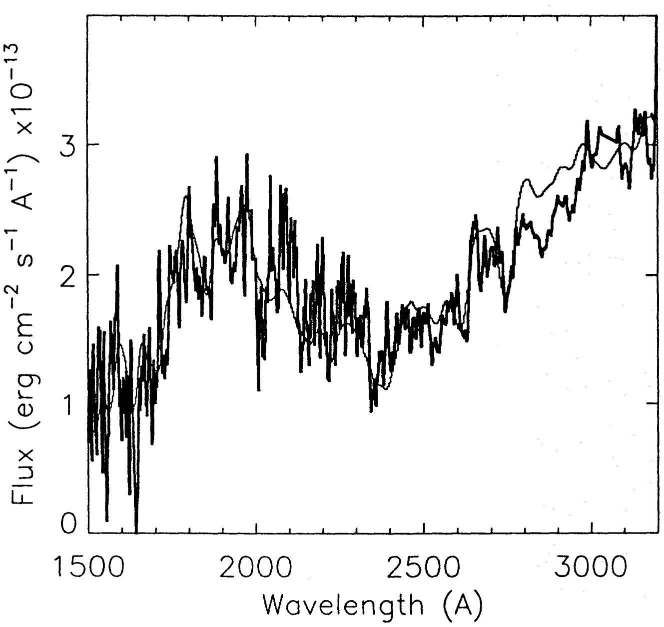

Fig. 6. Comparison of UX Ori at optical maximum with the spectrum of HD 163296 reddened using a CCM R=5.0±0.2 curve. Both spectra have been corrected for assumed foreground extinction with R=3.1 and E(B-V)=0.06 (UX Ori) and E(B-V)=0.03 (HD 163296)

We can use the optical polarization data for the epoch of the 1992 September IUE observation to estimate the degree of attenuation of stellar light in the absence of the circumstellar disk. If we follow Grinin (1992) and assume that $P_{obs}(\Delta m)=P_{IS}+P_{CS}(0)10^{0.4\Delta m}$, with P_{IS}=0 and P_{CS}=0.5%, the observed polarization at V of 4% corresponds to Δm=2.72, in the absence of a disk. If we assume R=5.0, we would then predict ΔE(B-V)=0.55. Using a CCM extinction curve to approximate the circumstellar extinction, we find that the attenuated, but unscattered stellar light accounts for no more than 25% of the optical minimum signal at 3000 Å, and 8% or less from 1500-2000 Å. Thus, to first order, we can assume that the optical minimum IUE spectra are dominated by the light scattered within the circumstellar disk.

8.1. Model parameters

Conventional parameterizations of extinction for the ISM beginning with Mathis et al. (1977) have assumed that the optical and UV extinction can be described by a mixture of silicate and graphite grains characterized by silicate/graphite ratio, minimum grain size (a_{min}), maximum grain size (a_{max}), with the grain population modeled as $n(a)=a^{-q}$. More recent studies of the ISM have suggested that characterization of the particle size distribution by a power law with a minimum grain size is simplistic (Kim et al. 1994; Kim & Martin 1994), however for our purposes, the simpler parameterization is sufficient to explore the ways in which circumstellar grains around a young PMS star such as UX Ori differ from those in molecular clouds or in more diffuse portions of the ISM. We note that the UV data are insensitive to maximum grain size, but are quite sensitive to minimum grain size and q.

8.2. Models to date

Voshchinnikov et al. (1988) modeled the available optical polarimetry and photometry using single Mie scattering models. They found good fits to the broad-band optical colors and polarization using ISM-like models with $q = 3.5$, and $n(Si)/n(C) = 1.07$, circumstellar envelope semi-axis ratios A/B=3.0-4.0, and a_{min}=0.04-0.5. Extension of this model into the wavelength range covered by the IUE produces I_{tot}/I_* with a weak 2200 Å bump in absorption, and comparatively flat ratio of ≈60%. The scattered light component shows a prominent peak of 35% at 2200 Å, with the far-UV substantially weaker than the scattered mid-UV component.

When the UX Ori maximum and minimum light spectra are normalized by HD 163296, reddened for the increment in foreground extinction and scaled by the flux ratio inferred from the difference in V magnitudes between the two stars, Fig. 7 results. Independent of the normalization factor between HD 163296 and UX Ori, the slope of the scattered light spectrum differs significantly from the model predictions, particularly in the far-UV from 2000 to at least 1500 Å. The absence of the 2200 Å bump and the rise in the far-UV, indicating the presence of grains with significantly higher albedo than graphite suggests

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that either the disk grain chemistry, minimum particle size, or power law differ from the values considered by Voshchinnikov et al. (1988). As noted by Voshchinnikov & Karjukin (1994) and Voshchinnikov et al. (1995), multiple Mie scattering models for A/B ratios consistent with the polarimetry for UX Ori require $a_{min} \geq 0.1\mu$m to totally eliminate the 2200 Å feature from either the total light spectrum or the scattered light spectrum. Thus the single and multiple scattering models suggest that the grains in the UX Ori system may be comparable in size to both interplanetary dust particles and to grains in the β Pic system (Gledhill et al. 1991).

While model C-M diagrams based on either silicate or graphite grains with q = 3.5 produce reasonable agreement with the optical photometry for UX Ori for $a_{min} \geq 0.05$ μm (amorphous silicates modeled with obsidian), or 0.03 μm (graphite), the agreement with the UV C-M diagram is less good. Graphite models do not produce the observed "blueing", while obsidian models with a_{min} =0.05 μm become very blue within 0.5 magnitudes of optical maximum light, showing no further color evolution down to optical minimum light with q = 3.5. Obsidian models with a_{min} =0.15 μm and q = 3.5 show reddening beginning at 1 magnitude below optical maximum light, in disagreement with the data. The best fit obtained to date to the UX Ori data are for obsidian grains with a_{min}=0.15 μm and q = 2, e.g. a grain population which not only has a minimum grain size 30 times that of the ISM, but which has relatively fewer small grains than are seen in the diffuse ISM or in molecular clouds (Fig. 8), although the optical minimum UV data are considerably bluer than the model predictions. IR data for UX Ori (Hutchinson et al. 1994; Wooden 1994) demonstrate that submicron-sized silicates are certainly present in the UX Ori disk, so modeling of the near-stellar dust by large silicate grains is reasonable. More extensive modeling with more plausible grain chemistry is clearly needed, however, to refine these estimates. UV spectropolarimetry will also be invaluable in constraining the disk orientation and nature of the scattering.

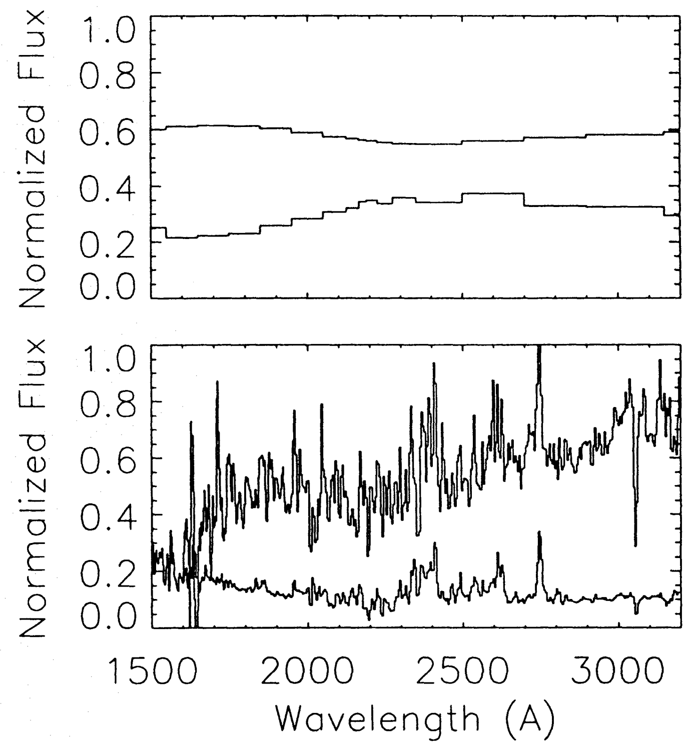

Fig. 7. Total (I_{tot}/I_*) and scattered (I_{scat}/I_*) light components in the mid-UV following Voshchinnikov & Karjukin (1994). (upper) The single Mie scattering model of Voshchinnikov et al. (1988) which successfully described the optical light and color changes in UX Ori. (lower) I_{tot} is estimated from the optical maximum UX Ori spectra, and I_{scat} from the optical minimum data. For I_* we have used the HD 163296 spectrum normalized by the difference in stellar V magnitudes following reddening of the HD 163296 spectrum by the difference in foreground extinction in the two lines of sight. In constrast to the UX Ori data which show a systematic decrease in I_{tot}/I_* with decreasing wavelength, and a systematic increase in I_{scat}/I_* with decreasing wavelength, the model of Voshchinnikov et al. (1988) predicts a comparatively flat I_{tot}/I_* and I_{scat}/I_* decreasing with decreasing wavelength

8.3. Variability at optical minimum

At optical minimum, UX Ori exhibits significantly more scattered light in the UV that is predicted by simple models containing only a star, dust cloud, and a homogeneous circumstellar dust disk responsible for the scattered light, with the same dust in the cloud and the disk. Detection of species such as Na I with accretion velocities of several hundred km s^{-1} (Grinin et al. 1994; de Winter et al. 1995), and detection of increased mid-IR continuum emission together with enhanced silicate emission at optical minimum suggests that the dust cloud responsible for the deep minimum of 1992 was very large and located comparatively close to the star. In this case, the scattered light from the single cloud could well be comparable to the average scattered light from the disk. Mid-IR spectra of the 9.7 μm silicate feature at both optical maximum and minimum light will be particularly helpful in determining whether the increase in emission in the silicate feature noted by Hutchinson et al. (1994) is due to an increase in small grains, or in number of larger grains (Pollack et al. 1994). Observations of additional optical minimum episodes are also desireable to enable us to separate the average disk contribution from the scattered and polarized light contribution originating in the dust coma of the infalling body.

9. Discussion

Combined IUE low and high dispersion spectra of the HAe star UX Ori demonstrate that large amplitude, photometrically variable HAe stars undergo striking changes in the nature and color of their UV spectra in tandem with similar changes reported for the optical. While UX Ori has the most extensive UV dataset of any of the large amplitude variables, similar changes have been documented for CQ Tau (F2e), and BF Ori (A5e). The overall character of the mid-UV spectrum in this star at optical minimum is similar to heavily obscured HAeBe stars and to objects which have only been observed in the UV when well below maximum light. Thus, large amplitude light changes and

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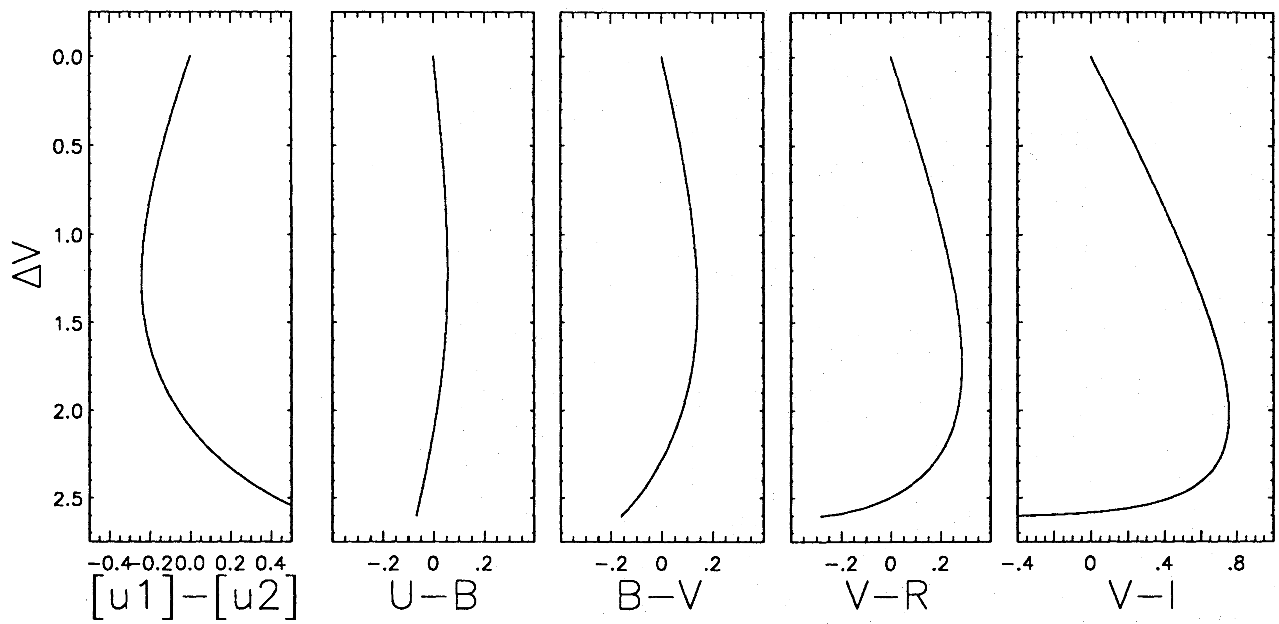

Fig. 8. Theoretical color magnitude diagram for amorphous silicates (obsidian) with a_{min}=0.15 μm and q = 2. The model is calculated for magnitudes below optical maximum, and assuming all colors are zero at optical maximum

changes in the nature of the UV spectrum appears to be characteristic of the 27% of HAeBe stars which are large amplitude variables (Bibo & Thé 1991), and must be accounted for in any models for these objects.

The correlation of increased line veiling, and progressive blueing of the light with decreasing optical light and increasing optical polarization is consistent with increasing visibility of a circumstellar disk as the star is progressively occulted by debris clouds in the disk. Other models which have been proposed for either HAe or classical T Tauri stars predict maximum veiling at optical maximum light, which is not observed.

Our high dispersion mid-UV spectrum of UX Ori demonstrates that the prominent UV line blanketing apparent in the low dispersion data is due to accreting circumstellar gas, rather than to outflowing material such as is seen toward the non-photometrically variable HAe stars such as HD 163296 (Catala 1994). The combination of accreting gas in a star for which the optical polarimetry indicates the presence of a circumstellar dust disk suggests that this and similar stars are not only the evolutionary precursors of systems like β Pic, but also share a similar disk orientation on the plane of the sky. The species sampled in the accreting gas toward this system, as for the β Pic system, are consistent with the dissociation products of silicate grains.

Comparison of the low dispersion spectra with model predictions for the circumstellar extinction and scattered light suggest that the grains in the UX Ori disk may be as much as 30 times larger than those characteristic of the diffuse ISM, and significantly larger than those typical of molecular clouds. Additional data, particularly IR spectra, and UV spectropolarimetry will be needed to test the suggestion that the particle size distribution in the UX Ori disk is further skewed from interstellar values to one with q = 2. In any event, the UV data for UX Ori suggest that the grains in this disk are comparable in size to interplanetary dust particles, and those in the β Pic disk. Our observation of variable scattered light levels at optical minimum, together with the observation of Hutchinson et al. (1994) of variable silicate emission near optical minimum light suggests that the near-stellar dust grains in the UX Ori system are frequently replenished by sublimation of the bodies responsible for the optical minima. The available data for UX Ori suggest that bodies resembling both the evaporating, infalling bodies suggested for the β Pic system and solar system comets are well-developed by 2-3 Myr.

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