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A PHOTOMETRIC CATALOG OF HERBIG Ae/Be STARS AND DISCUSSION OF THE NATURE AND CAUSE OF THE VARIATIONS OF UX ORIONIS STARS

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ABSTRACT

UBVR photometric monitoring of Herbig Ae/Be stars and some related objects has been carried out at Maidanak Observatory in Uzbekistan since 1983. More than 71,000 observations of about 230 stars have been obtained and are made available for anonymous ftp. Virtually all Herbig Ae/Be stars observed are irregular variables (called "UXors" after UX Ori), but there is a wide range of amplitudes from barely detectable to more than 4 mag in V. Our data confirm the results of previous studies, which indicate that large-amplitude variability is confined to stars with spectral types later than B8. The distribution of variability ranges is quite similar to what is seen in classical T Tauri stars. A careful search has failed to reveal any evidence for periodic variations up to 30 days, which can be interpreted as rotation periods. This is a clear distinction between the light variations of low-mass and high-mass pre–main-sequence stars. The Herbig Ae/Be stars evidently do not possess either the large, stable cool spots or persistent hot spots associated with strong surface magnetic fields and magnetically funneled accretion in classical T Tauri stars. A wide variety of shapes, timescales, and amplitudes exists, but the most common behavior is well illustrated by the light curve of LkHα 234. There are two principal components: (1) irregular variations on timescales of days around a mean brightness level that changes on a much longer timescale (typically years), sometimes in a quasi-cyclic fashion, and (2) occasional episodes of deep minima, occurring at irregular intervals but more frequently near the low points of the brightness cycles. Our data suggest that many T Tauri stars of K0 and earlier spectral type share the same variability characteristics as Herbig Ae/Be stars and should be regarded as UXors. Two FU Orionis stars ("FUors"), FU Ori and V1515 Cyg, also have recent light curves that are similar, in some respects, to UXors. The most developed model to account for the variations of some large-amplitude UXors involves variable obscuration by circumstellar dust clumps orbiting the star in a disk viewed nearly edge-on. However, there are problems in extending this model to the entire class, which lead us to propose an alternative mechanism, i.e., unsteady accretion. Evidence favoring the accretion model over the obscuration model is presented. It is suggested that the thermal instability mechanism responsible for outbursts in interacting binary system disks, and possibly FUors, may be the cause of the deep minima in UXors.

Key words: stars: emission-line, Be — stars: pre–main-sequence — stars: variables: other

1. INTRODUCTION

Herbig Ae/Be (HAEBE) stars were originally identified by Herbig (1960) as possible higher mass analogs of the T Tauri stars, that is, pre–main-sequence stars with masses of $\sim 2\ M_{\odot}$ or larger. This hypothesis has generally been supported by a large number of subsequent studies (e.g., see Thé, Perez, & van den Heuval 1994), in particular by Strom et al. (1972) and Hillenbrand et al. (1992). Like the T Tauri stars, HAEBE stars have long been recognized as photometrically variable. However, the character of their light variations and its cause(s) remain somewhat enigmatic today. Whereas considerable progress has been made in understanding the variations of the classical and weak T Tauri stars (CTTSs and WTTSs, respectively), there are still large gaps in our knowledge of the circumstellar environments of HAEBE stars, which translate into fundamental uncertainties in accounting for their variations. It is probably not an exaggeration to say that the HAEBE stars are the only remaining class of variable stars with a substantial membership whose basic variability mechanism is still unclear.

Photometric variations of T Tauri stars can be divided into three types (Herbst et al. 1994 and references therein). Type I variations result from the rotation of a star with large cool spots. Type II variations are caused by changes in the observed pattern of hot accretion spots on a star's surface due to unsteady accretion and stellar rotation. Type III variations are the subject of this paper. Following Herbst (1994) we will refer to type III variables as "UXors". WTTSs display only type I variations. Because of the stability of their large cool spots on timescales of months to years (e.g., Herbst 1989; Grankin 1994) it is possible to obtain rotation periods for large numbers of WTTSs by photometric monitoring (e.g., Rydgren & Vrba 1983; Bouvier, Bertout, & Bouchet 1986; Grankin 1994; Choi & Herbst 1996). CTTSs display both type I and type II variations. The timescale for intrinsic changes in the hot spots can be comparable to or shorter than a rotation period, so it is often more difficult, but not necessarily impossible, to find rotation periods for CTTSs (e.g., Bouvier et al. 1993). Type I and II variations are well integrated into the general picture of T Tauri stars that has emerged from a broad spectrum of observational and theoretical studies (see, for example, Königl 1991; Shu et al. 1994; Mahdavi & Kenyon 1998). Namely, the stars have strong, bipolar magnetic fields that disrupt accretion disks within a few stellar radii and divert the infalling matter along flux tubes to accretion zones surrounding the magnetic axes (analogous to auroral zones on Earth). Some of the disk material does not accrete but is ejected along the magnetic axis creating bipolar jets and flows. Cool spots are associated with the "footprints" in the photosphere of the bipolar fields, and the hot spots are associated with the accretion zones in the CTTSs.

The situation with regard to type III variables (hereafter UXors) and HAEBE stars is less satisfactory. It is clear that the nature of the variability and, by inference, the close circumstellar environment of more massive pre–main-sequence (PMS) stars differ from that of CTTSs. The change in variation characteristics occurs at a spectral type of about K0, with most, if not all, G-type and earlier PMS stars being UXors. Generally speaking, the timescale for their variations becomes longer than in the CTTSs, there can be more variation at V, R, and I wavelengths (relative to U and B), and the light curves switch from being "irregular" to being "quasi-Algol" (Shevchenko et al. 1994c) in the sense described below. Other differences include Hα equivalent widths (which correlate with brightness in type II but increase as the star fades in UXors) and color index (which reddens with decreasing brightness in type II but becomes bluer during the deep minima of UXors). Finally, the data of Grinin (1994) indicate that polarization increases substantially in at least some UXors during deep minima.

These changes in the character of the variations are undoubtedly connected in some way to the differences in the circumstellar environments of low-mass and intermediate-mass PMS stars. Unfortunately, whereas the accretion disk model with magnetic funneling is well supported for CTTSs, there is considerable debate about even the order of magnitude of accretion rates in HAEBE stars. Hillenbrand et al. (1992) interpreted the infrared excesses of HAEBE stars as accretion disk luminosity, by analogy with the CTTSs, and derived proportionally higher accretion rates. However, Hartmann et al. (1993) pointed out that the lack of evidence for accretion luminosity at shorter wavelengths (analogous to the blue "veiling continuum" in CTTSs) argues against large accretion rates and proposed an alternate model for the infrared excess, i.e., thermal emission from circumstellar grains not confined to a disk. The debate continues today (e.g., Böhm & Catala 1994; Miroshnichenko, Ivezic, & Elitzur 1997; Corcoran & Ray 1998) without definitive resolution.

In addition to the accretion rate, the question of the interface between an accretion disk (if there is one) and the star remains open. The large, cool, high-latitude spots on WTTSs (e.g., Herbst 1989) and CTTSs (e.g., Mahdavi & Kenyon 1998) demonstrate that strong, dipole magnetic fields can be generated in fully convective, low-mass PMS stars and these fields apparently control the inner accretion flows in CTTSs. The radiative envelopes of A and B stars might not be expected to support such strong, organized magnetic structures. The higher accretion rates derived by Hillenbrand et al. (1992) might also be expected to significantly reduce the size of or eliminate any magnetosphere. In that case, the accreting matter may not fall ballistically onto the surface of the star along field lines, creating hot spots and spectroscopic accretion signatures, but may "ease" onto the star through the viscous inner disk, or "boundary layer." It then becomes more difficult to distinguish accretion luminosity from stellar photospheric luminosity, since the temperatures of the inner disk and the star are comparable and the inner disk may actually be optically thick (Hartmann et al. 1993).

Whatever the cause, the nature of the photometric variations of PMS stars changes at a spectral type of about K0, and the purpose of this paper is to illustrate and describe the variations of the earlier type stars. The data contain clues to the nature of the circumstellar environments of stars a bit more massive than the Sun and allow us to test possible causes of the variations and propose a new one: unsteady accretion. In § 2 we describe the database on HAEBE stars, which is the basis for a discussion of the nature (§ 3) and cause (§ 4) of the variability.

2. OBSERVATIONS AND NOMENCLATURE

Some *UBVRI* data on HAEBE stars has been culled from the literature, but the great bulk of what is in our catalog comes from the ROTOR program carried out at Mount Maidanak Observatory (longitude: E4°27′35″; latitude: +38°41′.3; elevation: 2540 m) in Uzbekistan since 1983. A detailed description of the program has been given by Shevchenko (1989); here we briefly mention some salient facts. About 230 target stars have been chosen over the years, mostly from the list of Herbig & Bell (1988). Observing conditions at Mount Maidanak are such that clear skies prevail from May until October, with poorer conditions both for observing and living in the winter. During the summer, about 90% of the nights are photometric and skies are extremely dark, of course. Although it is not important for the work reported here, we note in passing that the average seeing at Mount Maidanak is better than 0″.7, making it one of the best sites on the planet. It was selected as a principal site for development during Soviet times but has suffered from lack of funding during the post-Soviet era. Observations for the ROTOR program are obtained on three different 0.6 m telescopes using photomultiplier tubes. The *UBVR* (Johnson) system is employed. Standards and extinction stars are observed each night. The data are reduced with standard techniques at the Tashkent Astronomical Institute. From there they are copied to disks and transported to Wesleyan University where they are incorporated into the ftp-accessible database of *UBVRI* photometry of PMS stars described by Herbst et al. (1994).

The data are available for anonymous ftp through the Web page of the Wesleyan Astronomy Department.[1] Files are named for the stars and stored in subdirectories that were established by spectral characteristics as follows: HAEBE (B, A, and F types), GTTS (G and K0 types), CTTS (K1 and later types with $W_{H\alpha} > 10$ Å), and WTTS (K1 and later types with $W_{H\alpha} < 10$ Å). A few FU Orionis stars ("FUors") are included in their own subdirectory. These categories follow standard terminology in the field, except for the GTTSs. G- and K0-type T Tauri stars like CO Ori or SU Aur are often called CTTSs, but their photometric variations and other aspects of their nature are not consistent with the "typical" CTTS, which is of later type. Herbst et al. (1994) used the designation ETTS (for early-type T

[1] www.astro.wesleyan.edu.

TABLE 1

SUMMARY OF DATA ON HAEBE STARS

File Name	JD (min)	JD (max)	N	Range	V (average)	$U-B$	$B-V$	$V-R$
abaur.dat	44837	50760	932	0.25	7.05	0.05	0.12	0.20
aksco.dat	43350	46254	47	0.83	9.00	0.17	0.62	...
as310.dat	46262	48163	341	1.11	12.45	−0.01	1.07	1.17
as441.dat	46257	50045	588	1.49	11.85	0.12	0.52	0.60
as442.dat	45879	50791	1301	1.06	11.01	0.30	0.67	0.72
bd41d3731.dat	45489	46801	179	0.16	9.89	−0.45	0.08	0.15
bd65d1637.dat	45505	50753	1188	0.71	10.18	−0.37	0.45	0.52
bd9d880.dat	46052	46782	15	0.18	9.89	0.01	0.08	0.17
bfori.dat	44845	50764	700	3.05	10.41	0.35	0.32	0.32
bhcep.dat	46984	50723	965	2.81	11.16	0.21	0.63	0.53
bnori.dat	46047	49987	123	0.49	9.67	0.12	0.47	0.46
bocep.dat	46998	50723	1155	0.50	11.60	−0.03	0.56	0.54
cqtau.dat	47505	50760	149	2.24	10.27	0.45	0.76	0.74
cquma.dat	49883	49943	13	0.03	6.28	0.02	0.06	0.08
cucha.dat	42800	46226	65	0.09	8.46	0.22	0.36	...
elias1.dat	46333	46706	2	0.15	15.24	...	1.48	2.13
euser.dat	46289	48894	424	1.29	13.74	0.50	0.78	0.75
hd150193.dat	45879	49919	289	1.28	8.64	0.14	0.51	0.49
hd163296.dat	46632	49949	375	0.42	6.88	0.09	0.10	0.11
hd200775.dat	45888	50724	1147	0.18	7.37	−0.38	0.40	0.53
hd250550.dat	45665	48935	267	2.32	9.54	−0.27	0.07	0.22
hd259431.dat	45649	50764	256	0.35	8.73	−0.58	0.27	0.53
hd53367.dat	45665	50044	137	0.47	7.00	−0.59	0.44	0.53
hkori.dat	45971	50764	397	0.71	11.71	0.04	0.52	0.70
ilcepa.dat	45880	50305	656	0.44	9.28	−0.23	0.73	0.75
kkoph.dat	45881	50672	530	3.83	11.45	0.47	0.66	0.84
lkha112.dat	46254	49945	296	0.65	9.82	−0.60	0.25	0.49
lkha115.dat	45903	49949	294	1.45	11.96	−0.18	0.41	0.58
lkha118.dat	45879	49951	312	0.92	11.20	−0.22	0.87	1.02
lkha119.dat	45879	49951	300	1.49	12.15	0.26	0.85	0.90
lkha131.dat	46255	50045	371	1.78	13.72	0.04	1.06	1.06
lkha132.dat	46259	50019	34	0.29	15.23	0.09	1.15	1.06
lkha134.dat	45888	50724	1088	0.68	11.35	0.13	0.67	0.79
lkha135.dat	46255	50019	358	0.76	11.02	0.27	0.72	0.78
lkha147.dat	50007	50017	2	0.07	14.45	...	1.50	1.61
lkha167.dat	46257	50019	14	1.52	15.34	−0.26	1.93	1.85
lkha168.dat	46255	50017	56	0.21	13.48	1.05	1.25	1.21
lkha169.dat	46046	50030	307	0.52	10.53	0.03	0.69	0.70
lkha176.dat	46613	50044	432	0.75	12.13	0.25	0.77	0.88
lkha183.dat	46619	50745	326	0.80	11.92	−0.45	0.58	0.75
lkha192.dat	46612	50018	200	0.46	14.35	0.08	1.28	1.50
lkha193.dat	46612	50018	168	0.37	13.78	0.02	0.76	0.75
lkha194.dat	46618	50019	62	0.67	13.87	−0.06	0.76	0.84
lkha198.dat	45879	50020	519	0.72	14.18	0.40	0.96	1.24
lkha201.dat	46257	47835	241	1.29	13.64	0.16	1.21	1.25
lkha208.dat	45665	50045	274	0.85	11.65	0.31	0.42	0.46
lkha215.dat	45665	50024	215	0.89	10.54	0.05	0.52	0.69
lkha218.dat	46047	50044	153	1.39	11.87	0.26	0.42	0.49
lkha220.dat	46047	50045	168	0.62	11.81	−0.09	0.28	0.40
lkha233.dat	45497	47887	514	1.08	13.56	0.68	0.85	0.92
lkha234.dat	45505	50753	1188	1.48	12.21	0.13	0.88	0.98
lkha257.dat	45879	50740	808	1.61	13.35	0.71	0.73	0.67
lkha259.dat	46382	46739	10	1.08	15.02	0.20	1.53	1.68
lkha324.dat	49938	50020	14	0.04	12.65	0.64	1.12	1.08
lkha339.dat	46335	46340	2	0.02	13.66	0.22	0.87	0.89
lkha341.dat	46335	50024	94	0.79	13.39	−0.07	0.96	0.96
lkha350.dat	46259	47521	154	1.30	14.04	0.45	1.93	1.85
macch12.dat	46681	46714	2	0.74	16.76	0.07	0.50	0.19
mwc1080.dat	45648	50725	1594	0.76	11.52	0.14	1.36	1.54
mwc137.dat	47110	50044	160	0.48	12.00	−0.56	1.31	1.87
mwc297.dat	45903	49960	570	0.65	12.28	0.84	2.12	2.66
mwc342.dat	47446	49647	718	0.66	10.61	−0.22	1.24	1.74
mwc930.dat	48055	49993	240	2.20	12.60	1.27	2.61	2.52
mxori.dat	50005	50022	6	0.02	9.91	0.16	0.73	0.64
nvori.dat	50009	50022	5	0.16	9.90	0.15	0.46	0.44

TABLE 1—*Continued*

File Name	JD (min)	JD (max)	N	Range	V (average)	$U-B$	$B-V$	$V-R$
p2599.dat	48533	50764	114	0.08	8.86	0.11	0.10	0.12
p2649.dat	48551	48954	18	2.04	13.67	1.03	1.42	1.43
rmon.dat	46375	50024	72	0.94	12.15	−0.36	0.66	0.96
rcra.dat	44112	48838	240	4.47	12.20	0.11	0.84	1.20
rrtau.dat	39739	50764	578	4.25	12.08	0.37	0.63	0.71
svcep.dat	46985	50723	912	1.46	10.98	0.26	0.39	0.40
tcra.dat	45888	48838	111	1.89	12.86	0.41	1.01	1.08
tori.dat	45963	50764	317	5.70	10.63	0.48	0.53	0.61
tcha.dat	47655	48042	26	2.04	10.97	0.78	1.26	...
tycra.dat	43346	49225	544	1.34	9.37	0.14	0.56	0.66
uxori.dat	44934	50749	592	2.93	10.40	0.34	0.37	0.41
v1318cyg.dat	46345	50710	34	8.55	16.85	−0.32	1.79	2.04
v1578cyg.dat	45868	50026	592	2.43	10.13	0.21	0.40	0.46
v1685cyg.dat	46611	50022	843	1.43	10.69	−0.28	0.79	1.06
v1686cyg.dat	46263	51042	897	4.67	14.07	0.84	1.36	1.42
v351ori.dat	49944	49987	18	0.25	8.95	0.24	0.38	0.36
v376cas.dat	46258	49954	47	2.23	15.55	0.59	1.05	1.27
v380ori.dat	43780	50044	584	1.76	10.49	−0.20	0.56	0.83
v451ori.dat	46061	47798	139	0.45	9.55	−0.22	0.13	0.19
v517cyg.dat	45880	50045	449	2.11	12.41	0.47	0.62	0.58
v586ori.dat	46779	50046	295	1.77	9.75	0.16	0.16	0.19
v590mon.dat	46335	50024	72	0.35	12.77	−0.09	0.16	0.31
v594cas.dat	45490	50045	882	0.74	10.58	−0.26	0.55	0.76
v645cyg.dat	46609	48954	606	2.43	13.47	0.27	1.08	1.19
vvser.dat	44763	50011	937	1.91	11.92	0.44	0.96	1.08
vxcas.dat	44774	50045	792	1.19	11.28	0.32	0.32	0.32
vymon.dat	46335	50024	131	2.00	13.47	0.89	1.62	1.83
vymong2.dat	46739	46739	1	0.00	18.75	−1.87	0.77	2.17
wwvul.dat	46645	50046	863	2.15	10.74	0.41	0.41	0.40
xyper.dat	46305	50046	628	0.90	9.21	0.47	0.49	0.49
zcma.dat	44939	50045	459	1.61	9.46	0.57	1.25	1.22

TABLE 2

Summary of Data on GTTSs

File Name	JD (min)	JD (max)	N	Range	V (average)	$U-B$	$B-V$	$V-R$
bd-224059.dat	47670	49201	165	0.24	10.17	0.34	0.84	...
coori.dat	44881	49647	536	2.71	10.67	0.52	1.06	0.95
cvcha.dat	45741	48033	89	0.40	10.98	0.05	1.05	...
dicep.dat	43686	50045	310	0.40	11.42	−0.04	0.89	0.85
doar9.dat	46955	49884	265	0.88	12.85	0.81	1.13	0.92
ezori.dat	49965	50022	8	0.24	11.70	0.28	0.86	0.78
gwori.dat	45733	50764	628	0.63	9.87	0.28	0.98	0.94
hd283572.dat	45614	47229	111	0.15	9.03	0.36	0.81	...
hiori.dat	49959	50021	11	0.54	13.60	...	1.30	1.21
hm13.dat	44289	48042	107	0.13	10.71	0.60	1.16	...
hptaug2.dat	45995	46009	17	0.10	11.07	0.92	1.40	...
ixoph.dat	48032	49994	18	0.55	11.12	0.84	1.30	1.13
lkha209.dat	49976	50044	22	0.05	11.86	0.19	0.82	0.80
lkha321.dat	49938	50020	14	0.09	12.32	0.37	1.25	1.18
rox8.dat	45510	45745	15	0.33	13.94	1.21	2.18	...
rylup.dat	43349	48042	154	2.52	11.21	0.77	1.13	...
rytau.dat	37672	49644	1503	2.29	10.27	0.49	1.02	1.07
suaur.dat	39095	50760	1129	1.54	9.20	0.43	0.90	0.82
sz41.dat	47656	48033	11	0.12	11.62	0.74	1.13	...
szcha.dat	47656	48042	16	0.83	12.37	0.85	1.23	...
tap31.dat	49936	50046	55	0.10	8.97	0.30	0.75	0.68
ttau.dat	37675	50725	1357	0.95	9.95	0.51	1.18	1.12
v1331cyg.dat	46612	49994	740	1.40	12.03	0.42	1.08	1.05
v521cyg.dat	46609	50753	887	1.77	13.74	0.58	1.25	1.18
v649ori.dat	47031	50021	262	0.79	12.09	0.41	1.12	1.08

TABLE 3
SUMMARY OF DATA ON FUORS

File Name	JD (min)	JD (max)	N	Range	V (average)	$U-B$	$B-V$	$V-R$
fuori.dat..........	44934	50046	550	1.16	9.39	0.82	1.36	1.19
v1057cyg.dat......	45489	51042	999	1.95	11.64	1.12	1.78	1.62
v1515cyg.dat......	45489	50022	1114	1.15	12.28	1.18	1.61	1.40

Tauri star) to distinguish them and to link them with HAEBE stars, but we now feel that G-type T Tauri star is, perhaps, more appropriate. Tables 1–3 summarize our data bank for HAEBE stars, GTTSs, and FUors. We turn now to a description of the type III variables—UXors—which includes all of the stars in the HAEBE and many of those in the GTTS categories.

3. DESCRIPTION OF TYPE III VARIABILITY

3.1. *Range of Variation*

Virtually all of the HAEBE stars in the catalog are variable at some level. Figure 1 shows their V magnitude range as a function of average brightness in V. Different symbols are used for the different spectral classes of PMS stars. Only among the HAEBE stars is there any trend of increasing range with decreasing brightness. This reflects the facts that the very brightest HAEBE stars are of early B spectral type and that HAEBE stars of that type are known to be low-amplitude variables (Finkenzeller & Mundt 1984). There is no apparent correlation between average brightness and range evident in the GTTS, CTTS, or WTTS classes.

In Figure 2 we show histograms of V magnitude ranges for each of the four spectroscopic classes of PMS stars. Only stars with more than 20 V magnitude measurements are included in the plots. The smaller ranges of the WTTSs are well known (e.g., Herbst et al. 1994) and evident. They reflect a relatively low amount or absence of variable accretion luminosity in these stars. The GTTSs, CTTSs, and HAEBE stars have many more examples of large-amplitude variation. Particularly interesting is the similarity in the histograms for the HAEBE stars and CTTSs. In both cases, the most common range is small (0.5–1 mag), but some stars

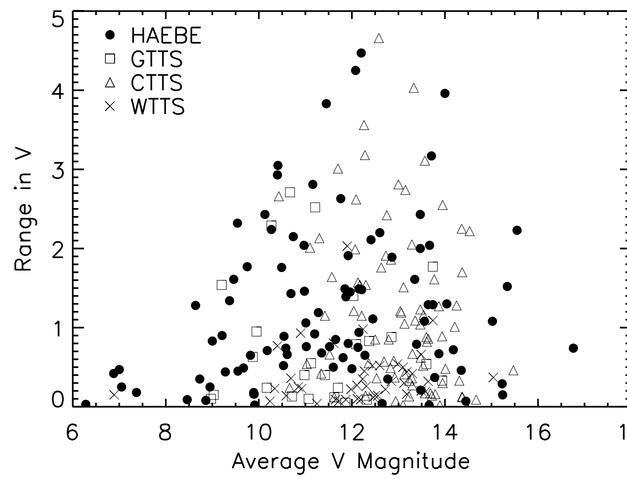

FIG. 1.—Range in V vs. average V magnitude for stars in the four spectroscopic classes of PMS stars defined in the text.

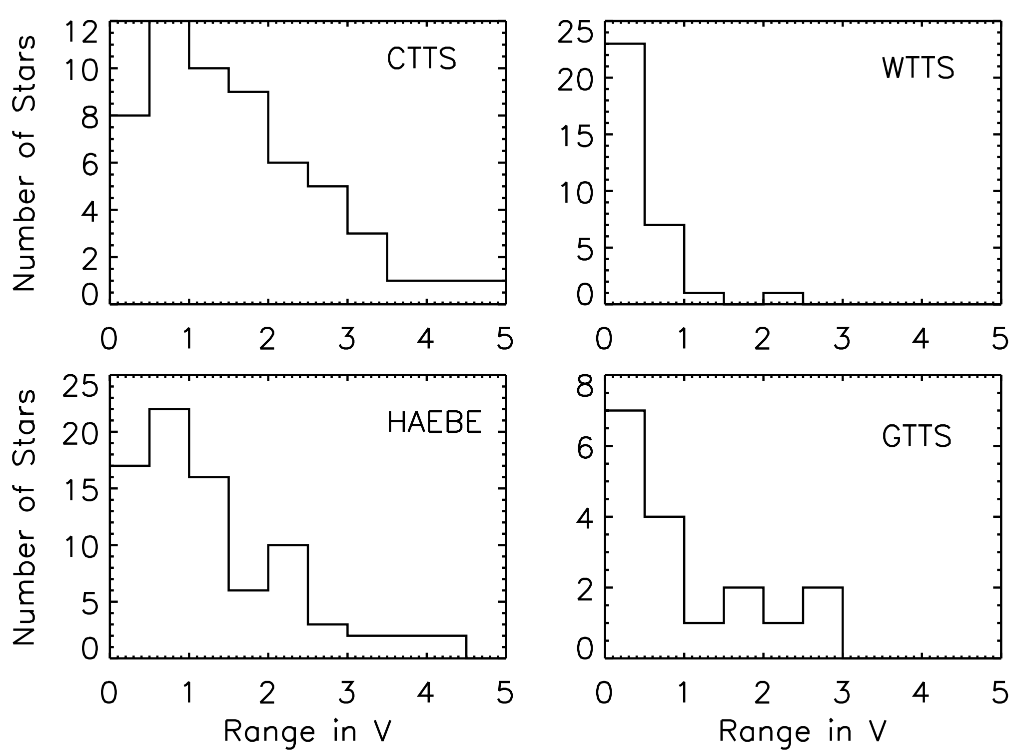

FIG. 2.—Histograms of V magnitude ranges for stars in the four spectroscopic classes of PMS stars defined in the text

exhibit much larger variability, extending up to about 4 mag in V. In the most extreme cases, there is a relatively small number of discordant measures that could be dismissed as accidental errors of the photometry but may also be real, so we have not discarded them. If the average deviation is used in place of the range, as a more robust measure of the degree of variability, the general picture remains unchanged. The largest amplitude HAEBE stars are T Ori, R CrA, and RR Tau, all exceeding a 4 mag range in V. The largest amplitude CTTSs in the catalog are DK Tau and GI Tau, which both exceed 4 mag. The only WTTS with a variation exceeding 2 mag is cD $-35°10525$, which has $W_{H\alpha} = 2.8$ Å but is classified as a tt star by Herbig & Bell (1988). The only other WTTS exceeding 1 mag in variation (barely) is V370 Ori.

In Figure 3 we plot the average deviation of variation in V versus spectral type for the HAEBE stars in our catalog. Again, we have limited the sample to stars with more than 20 V magnitude measurements. The discovery reported in earlier studies (Finkenzeller & Mundt 1984; Bibo & Thé 1990) that large-amplitude variation is confined to stars of B8–A0 spectral type or later, is confirmed by our data. None of the 19 stars with spectral types B7 or earlier have average deviations in V exceeding 0.2 mag. In contrast, more than a third of the 41 HAEBE stars with spectral type B8 or later do exceed that limit. Any explanation of the variations of HAEBE stars should account for this striking fact and for the similarity in variability ranges between the HAEBE stars and CTTSs displayed in Figure 2. We return to these issues in the discussion section of the paper.

3.2. *Rotation Periods and Quasi-Periodicity*

Rotation periods have been found for many TTSs by periodogram analysis of their light curves. While strict periodicity is not always found at every epoch, since the cool and hot spots that cause them can be short-lived, the extensive data set on HAEBE stars available for analysis here makes it easy to determine if their variations are periodic in the same ways as the WTTSs or CTTSs. To search for periodicity, we used the Scargle (1982) technique, as implemented by Horne & Baliunas (1986). The entire catalog was examined for periods between 2 and 30 days. Because of "beating" with the diurnal cycle, we believe that any periodic star would be detected by this process, even if the period were less than 1 day. Certainly stars with periods between 1 and 2 days would be easily detected, although distinguishing true periods from aliases might prove difficult. Data on each star were divided into epochs of one observing season duration, and all epochs with more than 20 nights of data were searched for substantial peaks in the periodogram. Also, an average periodogram for all observing seasons was formed, and a search for significant peaks carried out. The disappointing result was that only two HAEBE stars, BO Cep and MWC 1080, were found to have statistically significant peaks in their periodograms at $\sim 1\%$ or less false alarm probability. An additional three stars, Parenago 2599, V376 Cas, and WW Vul, had possible evidence of periodicity. In the remaining 75 HAEBE stars with enough data covering at least one epoch, no evidence for periodicity was found. This is in striking contrast to the situation for TTSs. An identical search among the WTTSs in our catalog revealed 23 definite and five possible periods out of 32 stars. For the CTTSs, the numbers were 16 definite and nine possible periods out of 53 stars. There were also seven definite and two possible periods out of the 16 GTTSs. To summarize, whereas $\sim 50\%$ of the CTTSs and $\sim 90\%$ of the WTTSs show evidence of periodicity, only $\sim 6\%$ of the HAEBE stars do the same.

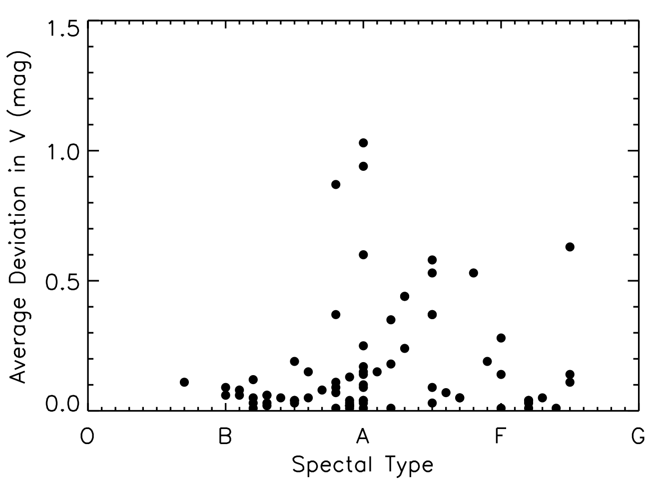

FIG. 3.—Average deviations in V for HAEBE stars as a function of spectral type

Furthermore, when cases of definite or possible periodicity among HAEBE stars are examined in detail, it becomes clear that it is not caused by the rotation of a spotted star as in WTTSs or CTTSs. The best evidence for real periodicity in a HAEBE star is found in MWC 1080 (V628 Cas; Fig. 4, *top left*), which has been discussed by Grankin et al. (1992) and Shevchenko et al. (1994a). They conclude that MWC 1080 is a close binary system with an orbital period of 2.8869 days. The periodicity in the light curve is attributed to an eclipse, not to the rotational modulation of a spotted star. The other HAEBE star with significant evidence of periodicity, BO Cep, is also probably a binary star (Shevchenko et al. 1993) with a period of 10.658 days. Its light curve (Fig. 4, *top right*) shows very deep minima, which occur periodically or nearly periodically, but not during every cycle. This is very unlike the behavior of spotted TTSs, and the period clearly has no relationship to the rotation of the star. We conclude that the periodic, rotationally driven modulation of brightness characteristic of lower mass PMS stars is simply not seen among the HAEBE stars, from which we infer that they do not have the surface cool spots or hot spots characteristic of WTTSs and CTTSs. This, in turn, suggests that the magnetically channeled accretion model may not apply to HAEBE stars, although it does not prove it. One could imagine, for example, that strong surface magnetic fields do exist on the HAEBE stars but do not cause cool spots since energy transport in these early-type atmospheres is primarily radiative. One could further imagine that the luminosity of the accreted matter is not significantly large, compared with the stellar luminosity, to reveal itself.

Generally speaking, the periodograms of HAEBE stars are featureless in the range up to 30 days, but the average power rises in direct proportion to the period. This ν^{-1} noise is characteristic of random, "shot" noise. Some stars show broad features in their periodogram, especially at long periods, which could be interpreted as "quasi periodicity." Outstanding examples of this phenomenon and a detailed discussion of it are given by Shevchenko (1989, 1994), Shevchenko et al. (1993, 1994b, 1994c), and Melnikov (1997).

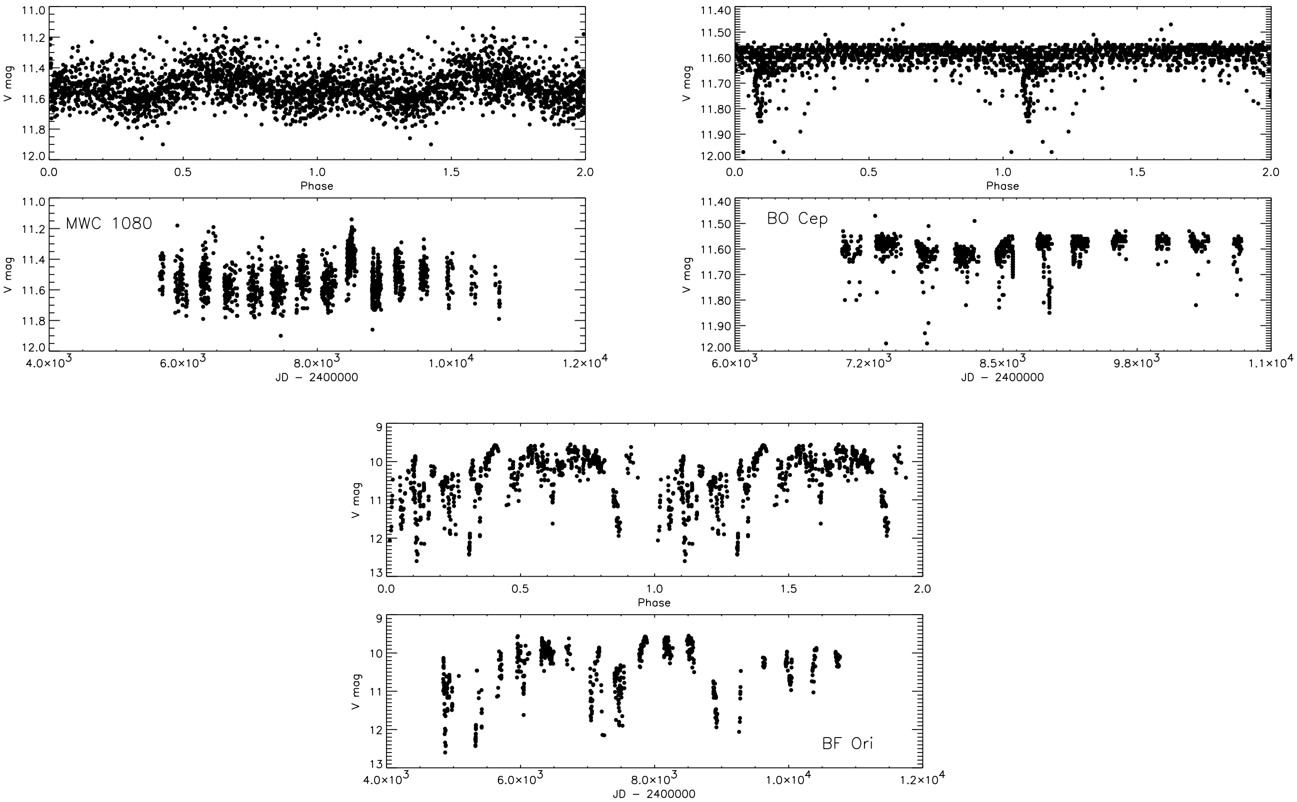

FIG. 4.—Light curves of three possibly periodic UXors. *Top left*, MWC 1080, with a period of 2.8869 days; *top right*, BO Cep, with a period of 10.658 days; *bottom*, BF Ori, with a possible cycle time of 6.32 yr. In each case, the top panel shows the folded light curve over two cycles and the bottom panel shows the actual light curve.

They distinguish three types of cyclic or quasi-cyclic behavior based on timescale and amplitude: long-term (years to decades, 0.4–4.0 mag range), intermediate-term (10–100 days, 0.05–0.5 mag range), and short-term (<10 days, 0.05–0.5 mag range). An example of long-term cyclic behavior, BF Ori, is shown in Figure 4 (*bottom*). The bottom panel shows the light curve over 17 yr, and the top panel shows the folded light curve with a cycle period of 6.32 yr. It is, of course, hard to establish the statistical significance of such lengthy periods since the number of elapsed cycles is small. However, the apparently cyclic or quasi-cyclic nature of HAEBE light curves on long timescales is quite a common feature of the class and will be evident in additional examples of light curves shown below. Interpretation of the phenomenon is considered by Shevchenko et al. (1993) and briefly summarized in the discussion section of this paper.

3.3. *Large-Amplitude Variables and Color Variations*

The range of behavior exhibited by HAEBE stars is substantial, and we take the approach here of displaying a number of examples.[2] A useful reference star for discussing common traits is LkHα 234, shown in Figure 5. It exhibits rather clearly the "quasi-Algol" behavior typical of the class. First note that the mean and median magnitude vary from season to season, typically by about 0.1 mag. In LkHα 234, as in many other stars, this variation of mean brightness appears to be cyclic, but not exactly periodic. Two cycles are clearly seen in Figure 5, and the cycle time is about 8 yr. It may be longer or shorter in other HAEBE stars, but all of them show some general "meandering" of mean brightness levels on timescales of a year or more, with amplitudes of 0.1 to more than 0.5 mag. Usually, the change from season to season is fairly slow and smooth, but occasionally more dramatic "events" occur, such as the decline seen in the last season, 1997, for LkHα 234.

A scatter about the mean brightness in any season is generated by variations that are characteristically on a timescale of days to weeks. The amount of scatter can vary substantially from year to year as Figure 5 clearly indicates. Most dramatic, and typical of HAEBE variables, is an occasional deep minimum, somewhat reminiscent of the eclipse in an Algol (semidetached binary) system, during which the star declines precipitously in brightness, often by 1 mag or more. Unlike true eclipsing systems, however, these minima occur at seemingly random intervals being completely unpredictable (with the possible exception of BO Cep, Fig. 4, *top right*). The phrase "nonperiodic Algol-type minima" has often been used in the literature to describe these stars (e.g., Grinin 1994). It is interesting that the deep minima seem to occur more frequently when the star is already at a relatively faint level in its meandering and less frequently when it is brighter. In the case of LkHα 234 this tendency gives rise to a light curve that looks like an Algol variable, but on much longer timescales and for completely different physical reasons. The general pattern of irregular variations on timescales of days superposed on longer timescale, perhaps cyclic, variations of the mean brightness level over months to years, punctuated by occasional, deep minima at irregular intervals, appears to be a description that fits most HAEBE stars. A more com-

[2] The entire data set is available for examination at ftp://sun.astro.wesleyan.edu/pub/ttauri/.

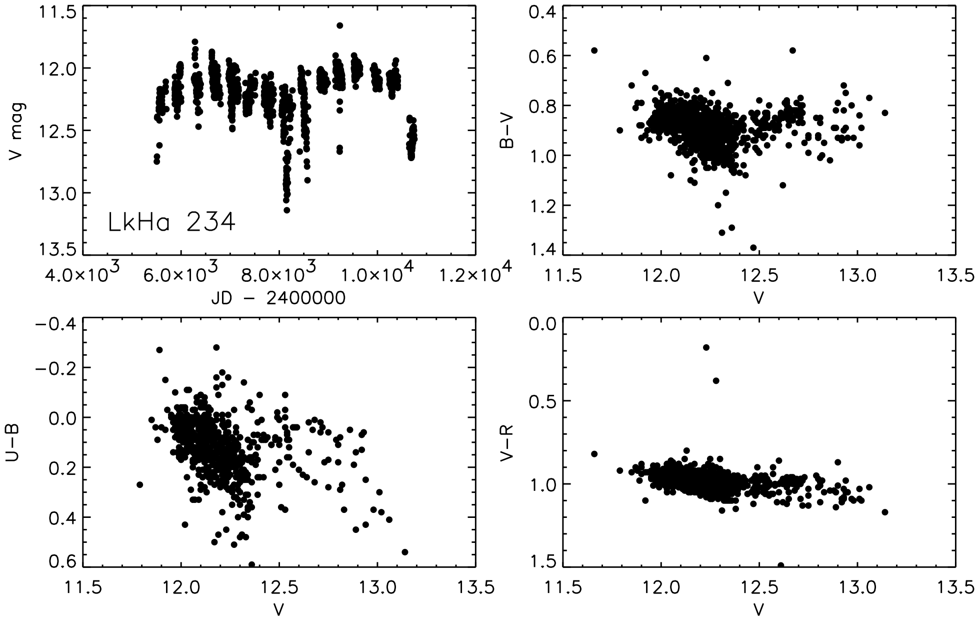

FIG. 5.—Light and color curves for LkHα 234

plete description is obtained only by displaying more examples, which we do in Figures 6–13.

Figure 6 shows the light curve of the prototype, UX Ori. In addition to the characteristics described for LkHα 234, this star shows clearly the color "turnaround" effect, first described by Zajtseva (1973), Pugach (1981), and Herbst, Holtzman, & Phelps (1982). During deep minima this star becomes increasingly bluer in $U-B$ and $B-V$ as it continues to fade. Even in $V-R$, there is evidence that the color curve turns around. An extensive photometric study of this star in the *uvby* Stromgren system is reported by Bibo & Thé (1990). As shown by Herbst et al. (1982) and Holtzman, Herbst, & Booth (1986), the Hα equivalent width also increases during minima, while the Hα flux remains roughly constant. Grinin (1994), and colleagues have shown that the polarization percentage increases dramatically during minima of this star. Their interpretation of these effects is that the photosphere is occulted by a circumstellar dust cloud and that most of the light of the system during a minimum is scattered off of circumstellar dust, resulting in the increased polarization and the bluer color. An alternative possibility is proposed in § 4 of this paper.

Four of the most active HAEBE stars are shown in Figures 7–10; all have amplitudes in excess of 3 mag. RR Tau (Fig. 7) is probably the most continually active star in the sample, with a large range of variation in virtually every

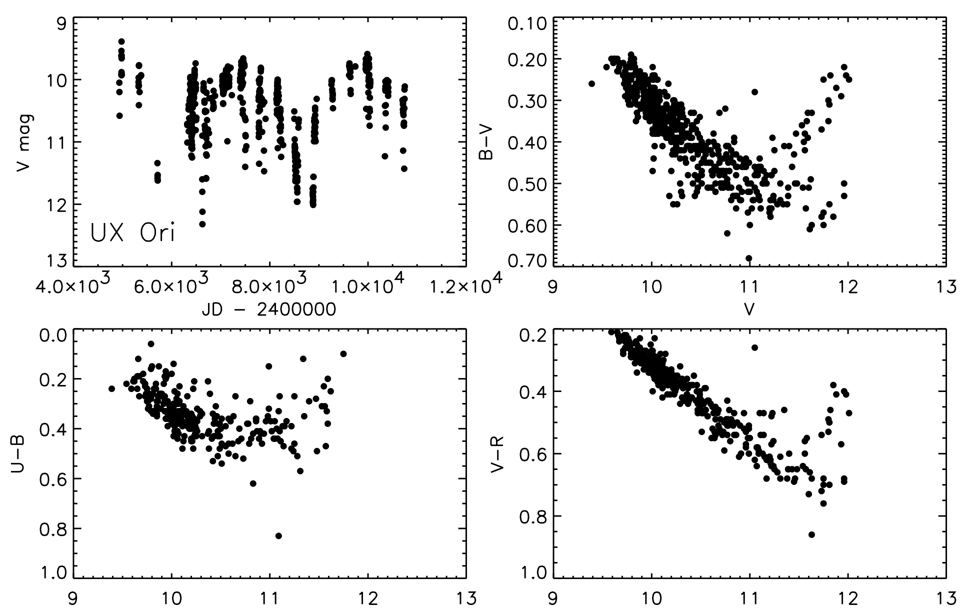

FIG. 6.—Light and color curves for UX Ori

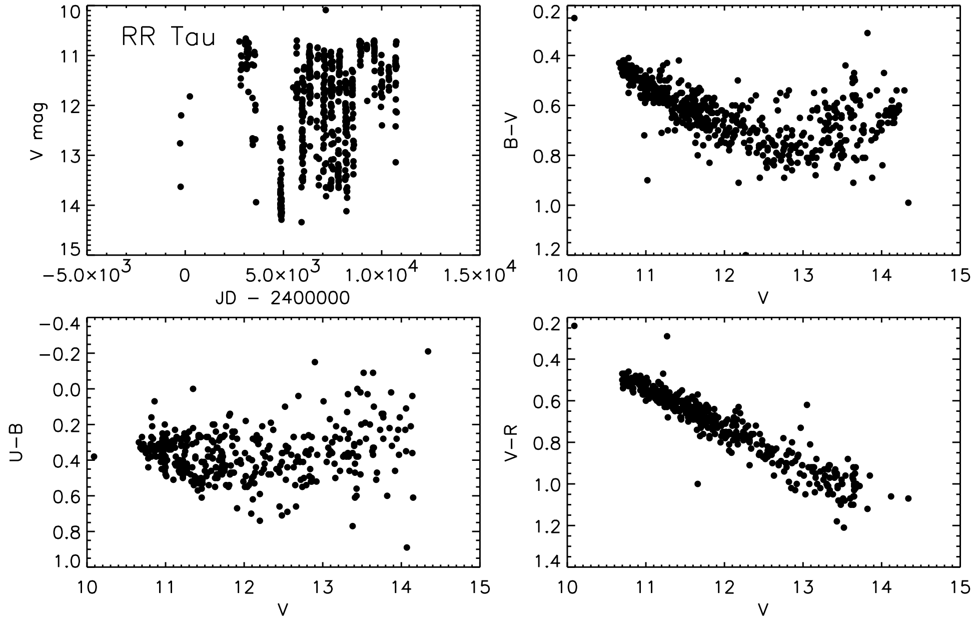

FIG. 7.—Light and color curves for RR Tau

season. Unlike the typical UXor, it seems to spend roughly similar amounts of time at all magnitude levels. Extensive photometry and polarimetry of this star have recently been published by Rostopchina et al. (1997), who interpret the data in terms of the dust occultation model. Herbig (1960) mentions that the spectrum of RR Tau resembles that of a late B star with a shell and shows no substantial change even as the star undergoes more than 2 mag of variation. BF Ori (Fig. 8) is quite typical of UXors in its light-curve form but has a very large amplitude. V1686 Cyg (Fig. 9) showed a steady decline in mean brightness for about a decade, which has now reversed itself. The most unusual light-curve form displayed by these large-amplitude variables is KK Oph, shown in Fig. 10. It went through an extended brightness peak during the early part of this decade but was fainter previously and has faded subsequently. It shows a strong color turnaround effect in all colors and was substantially bluer in $U-B$ at its faintest than at its brightest. Obviously it would be desirable to have a simultaneous photometric and spectroscopic monitoring campaign for these extremely active variables.

Four slightly atypical stars are displayed in Figures 11–14. R CrA (Fig. 11) shows a substantial range in brightness with little evidence for anything but random scatter in the color, except in $V-R$. BH Cep (Fig. 12) showed relatively little activity, discounting a few bright points, for the

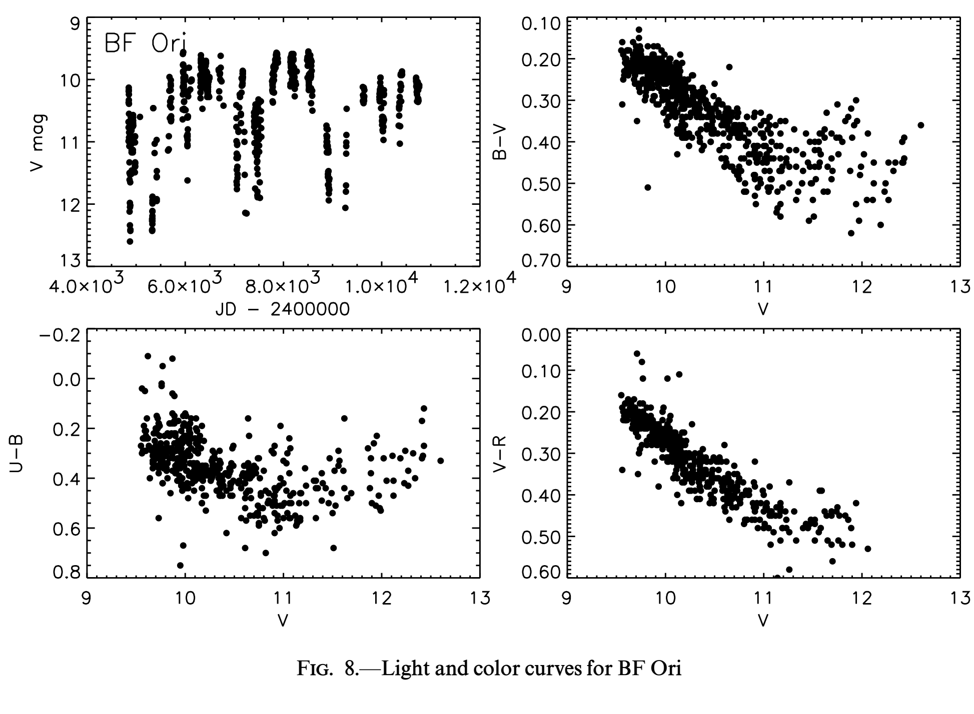

FIG. 8.—Light and color curves for BF Ori

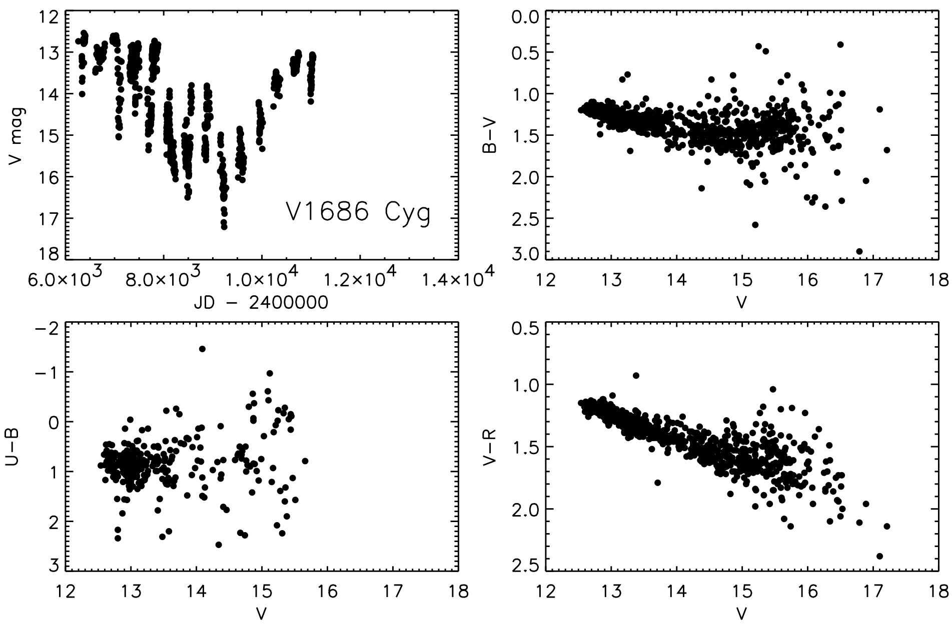

FIG. 9.—Light and color curves for V1686 Cyg

first 8 yr of monitoring, then became significantly more active in the last 3 yr. Its color behavior also does not show evidence of a turnaround. The bright points could simply be accidental errors; however, other UXors show similar "flares" in the Maidanak data and in data obtained elsewhere (e.g., RR Tau; Rostopchina et al. 1997), and the colors of these bright points lie along extensions of the lines defined by the bulk of the data (also true in RR Tau). Rostopchina et al. (1997) interpret the flares in RR Tau as moments at which the circumstellar obscuration clears dramatically; however, they could also be accretion-driven flares as discussed below. Photometry of T Ori (Fig. 13) is complicated by its location within the Orion Nebula. One may suspect that some of the bright data, and perhaps the deepest minima, are accidental errors related to the difficulties of accounting for the nebular background. On the other hand, the colors of the deepest minima are consistent with a simple extension of the brighter points, so we have chosen not to censor these data. CCD photometry is desirable for this star. Finally, in Figure 14, we display the enigmatic star V1318 Cyg, which has gradually faded below our ability to detect it. The two faintest measurements plotted represent estimates obtained from CCD images taken with the 2.3 m telescope on Mount Maidanak. Note that V1318 Cyg is a double source both in the infrared and the optical (Aspin, Sandell, & Weintraub 1994; Hillenbrand et al.

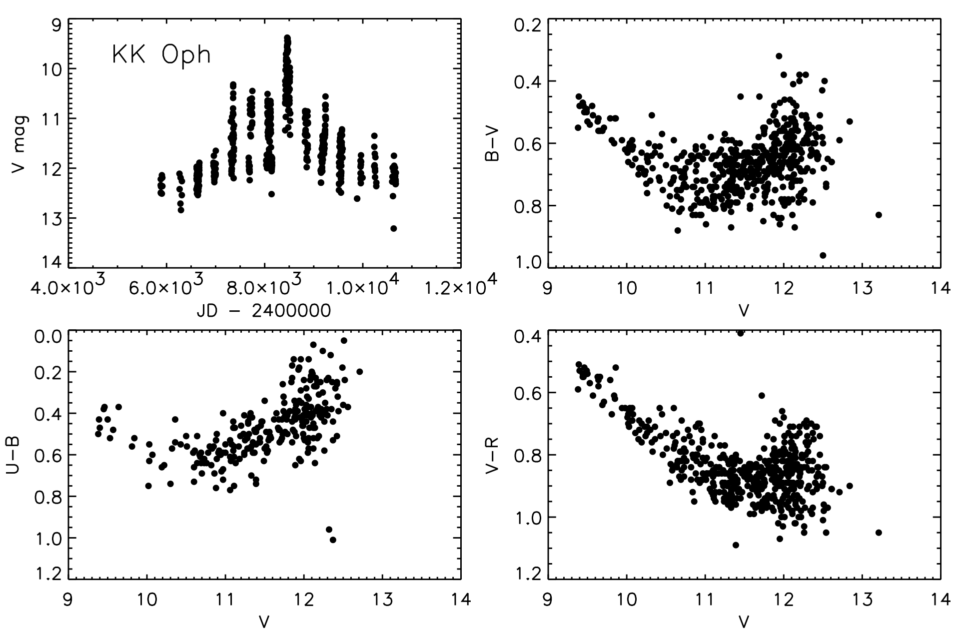

FIG. 10.—Light and color curves for KK Oph

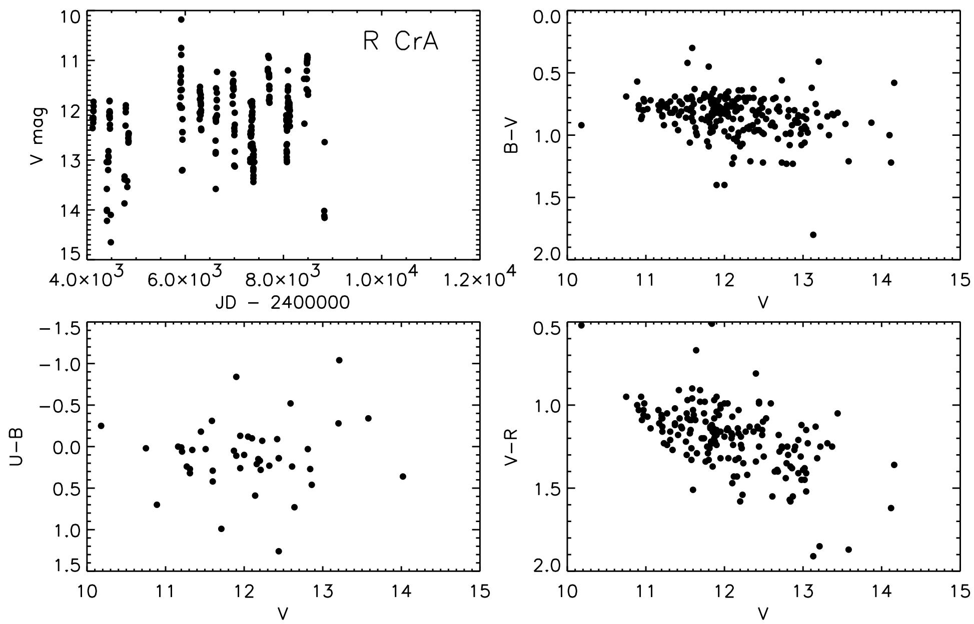

FIG. 11.—Light and color curves for R CrA

1995), so it is not clear what the combined photometry is telling us other than that the brighter source has definitely faded substantially.

In Figures 15–17 we display further examples of light curves of HAEBE stars with intermediate or small amplitudes. Our purpose is to illustrate the typical behavior seen in these stars, as well as the interesting deviations from it. The four stars shown in Figure 15 (AS 442, V517 Cyg, HK Ori, and VV Ser) are quite representative examples, displaying the traits discussed above. Some relatively small amplitude variables (V380 Ori, AB Aur, HD 200775, and V594 Cas) are shown in Figure 16. Even though the amplitudes of variation are small, the same general characteristics of irregular fluctuations of mean brightness and occasional, relatively deep minima, seen in large variables, are displayed by these stars as well. Two very unusual stars are shown in Figure 17: BD $+65°1637$ displayed a very slow decline followed by a recovery, with a timescale of years, while HD 53367 did the same sort of thing on a smaller amplitude. For comparison, we also show in Figure 17 the recent light curves of two FUors stars observed at Mount Maidanak and, in Figure 18, four examples of GTTS variables: T Tau, CO Ori, RY Tau, and SU Aur. As discussed by Herbst et al. (1994), some GTTSs behave in ways much more similar to the HAEBE stars than to CTTSs and, in our opinion, should be classified as UXors. It is also evident

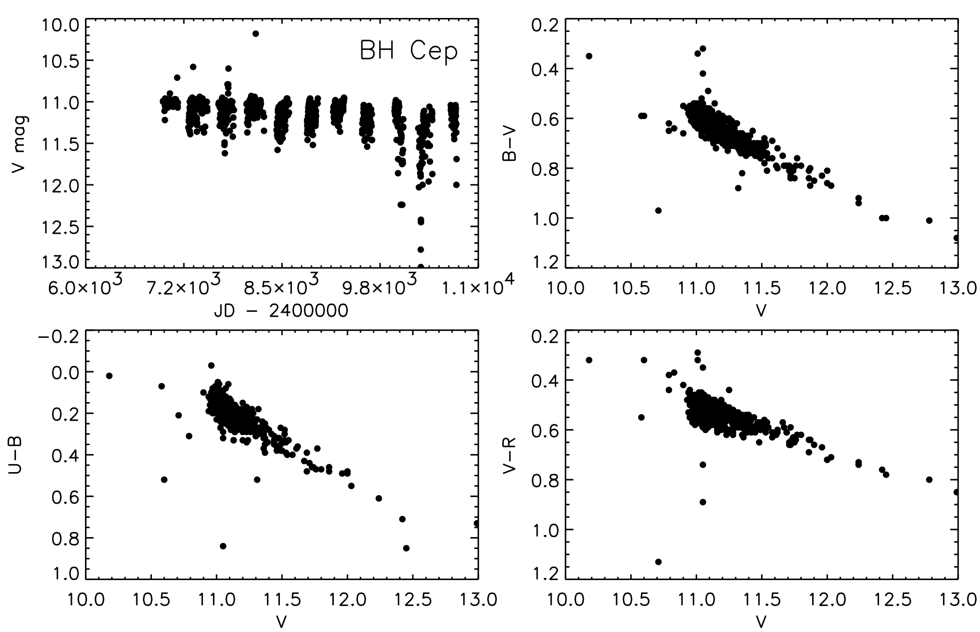

FIG. 12.—Light and color curves for BH Cep

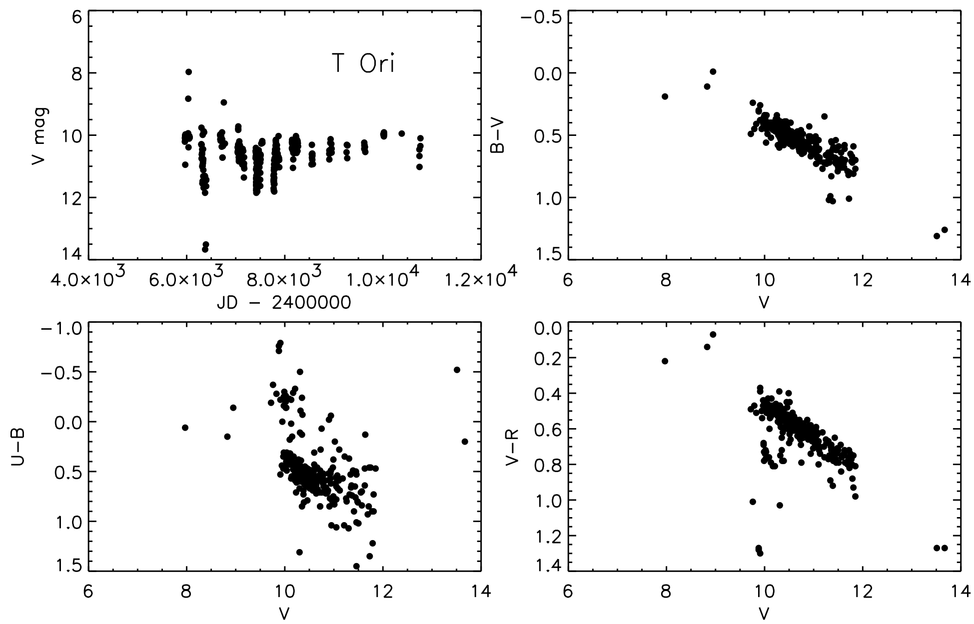

FIG. 13.—Light and color curves for T Ori

that recently the FUors have a similar appearance to UXor star variations suggesting a possible connection between them.

4. DISCUSSION

There is, as yet, no consensus on the cause or causes of the variations of HAEBE stars. Only one model—variable circumstellar obscuration—has been developed to any extent, and it has been applied to only a subset of HAEBE stars, namely those with large amplitudes. The term "UXor," in fact, has been used by Natta et al. (1997) to mean that subset of HAEBE stars whose variations are caused by the variable obscuration mechanism. A principal conclusion of their paper, however, is that there is no intrinsic difference between HAEBE stars and UXors. So, in effect, they agree with the original definition of the term by Herbst (1994), as adopted in this paper, that all HAEBE stars are UXors. Our data also suggest that we are seeing a single class of variables in which only the amplitude of variation changes substantially. The timescales, light-curve forms, color patterns, etc. do not easily separate into any subclasses that might be identified with different variation mechanisms. In this section we discuss, therefore, whether the variable obscuration model can account for all of the properties of the UXors, as a class, or whether there is reason to suspect that some other mechanism is involved. We find the obscuration model to be lacking in several respects and propose a seemingly plausible alternative,

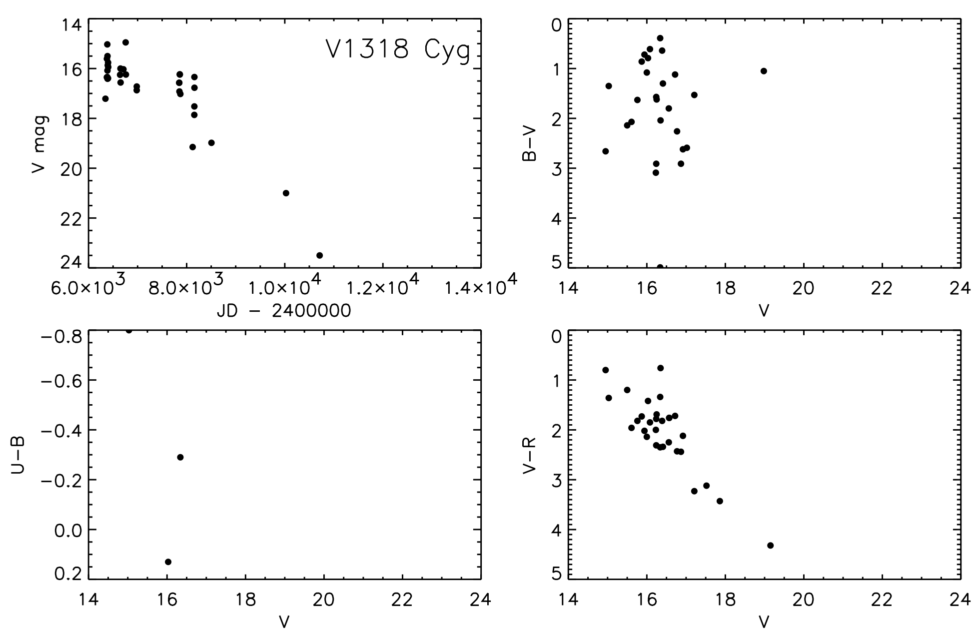

FIG. 14.—Light and color curves for V1318 Cyg

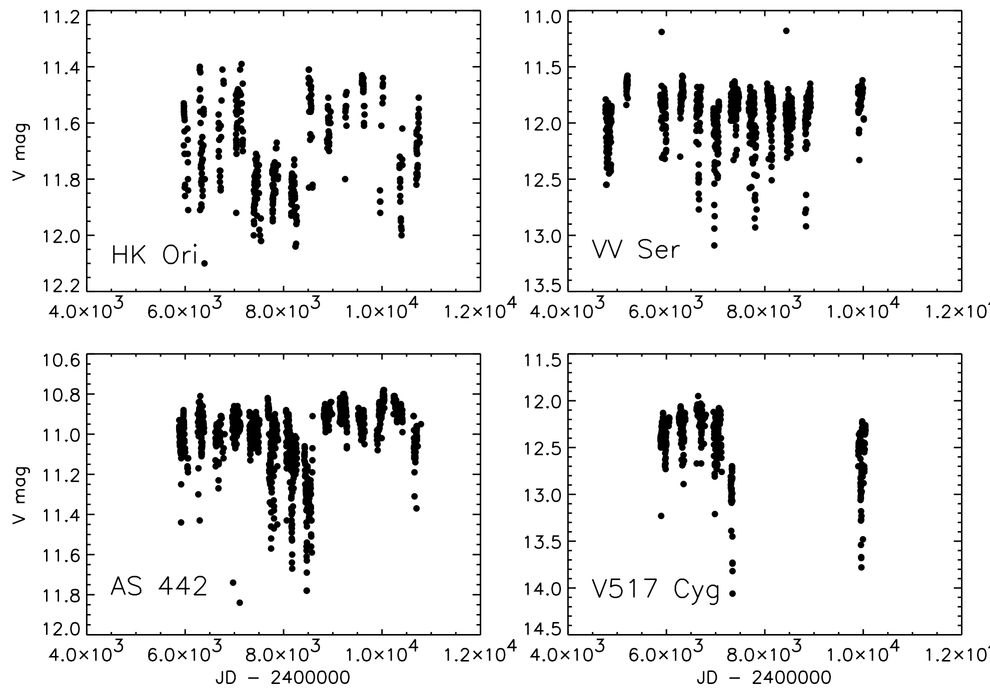

FIG. 15.—Light curves of four representative intermediate-amplitude HAEBE stars

unsteady accretion. Ultimately, of course, detailed modeling and further observations—particularly spectral data—will be required to decide whether either, both, or neither of these alternatives is viable.

4.1. *The Variable Obscuration Model*

The only well-developed model for UXors is based on the idea that orbiting circumstellar matter in the form of giant dust "clumps," sometimes called protoplanets or protocomets, regularly occults these stars resulting in the light variations (Wenzel et al. 1971). Evidence in support of this picture has been discussed by Grinin et al. (1991, 1994, 1996), Bibo & Thé (1990), Grinin (1994), Thé (1994), Herbst (1994), Herbst et al. (1994), Shevchenko et al. (1994c), Eaton & Herbst (1995), Grady et al. (1995, 1996), and Rostopchina et al. (1997). It includes the color and polarimetric behavior of the stars as they fade, mentioned above, as well as the lack of evidence for clear variations in the absorption spectra of at least some HAEBE stars or GTTSs with UXor-like behavior (e.g., Herbig 1960; Holtzman, Herbst,

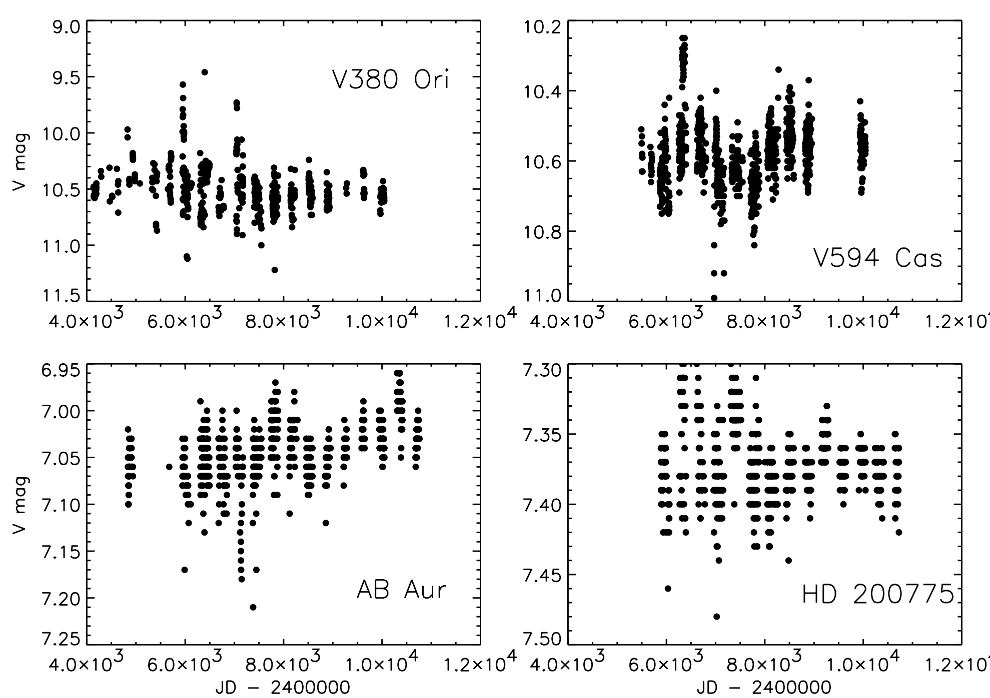

FIG. 16.—Light curves of four representative low-amplitude HAEBE stars

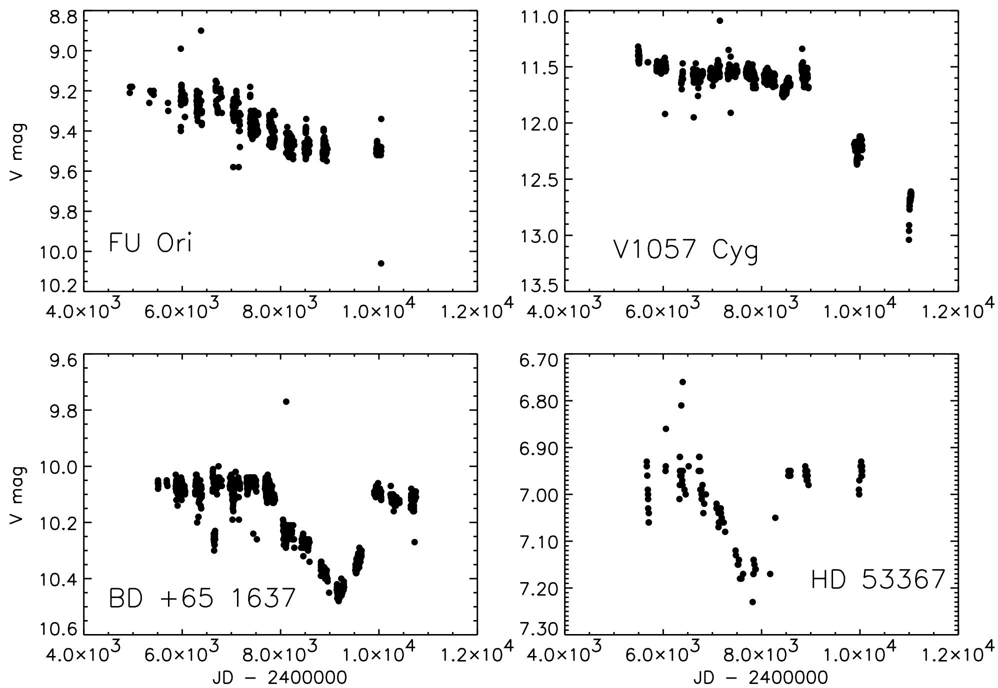

FIG. 17.—Light curves of two unusual HAEBE stars (BD +65°1637 and HD 53367) and two FUors

& Booth 1986; Gahm et al. 1993). Can this model, developed in an essentially ad hoc fashion to account for the behavior of a few stars (those seen "edge-on," through their disks, according to the model's proponents), be extended to the entire set of HAEBE stars?

This question has been addressed in a recent paper by Natta et al. (1997). They searched unsuccessfully for correlations between the degree of variability of a HAEBE star and disk properties, such as its mass and age. They concluded that (if the variable obscuration model is correct) the range of amplitudes must reflect the inclination of the system. However, there is no evidence to support this view, and some that argues against it, as discussed below. Naturally, it would be quite exciting if the photometry is revealing protocomets, planetesimals, or protoplanets around these stars. Of course, the color variations indicate that selective extinction is involved in most cases, so the occulting bodies should perhaps be thought of as clumps of dust grains, not as larger solids such as asteroids (cf. Rostopchina et al. 1997; Fig. 10).

Grady et al. (1999) have summarized the spectroscopic evidence for infalling "planetesimals" in HAEBE stars, but

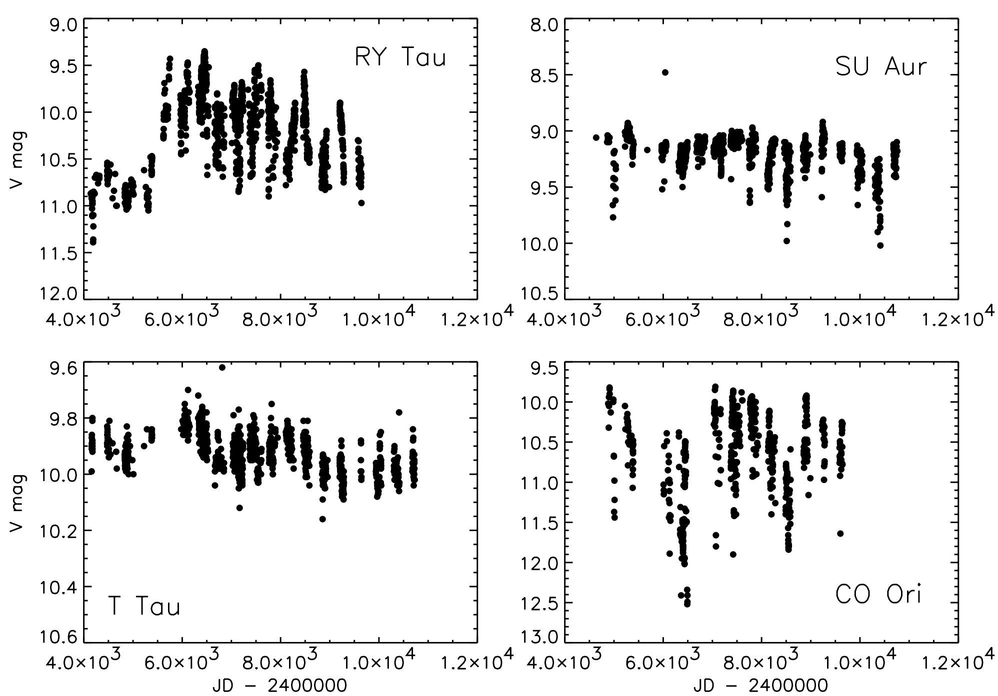

FIG. 18.—Light curves of four GTTSs that we would classify as UXors

it should be noted that the timescales for these events are of order 20–60 hr, which is much shorter than the variability timescales, so these objects are presumably not directly related to those that cause the photometric variations. Since essentially all HAEBE stars are variables at some level, the occulting bodies also cannot be thought of as confined to a plane, although according to Natta et al. (1997) they must be somewhat concentrated to a plane if system inclination is to be the determining factor in variability range. The lack of strict periodicity on any timescale is also a bit puzzling, suggesting either that the orbital timescales are longer than several years or that the objects' structures evolve on timescales shorter than an orbital period. Perhaps the existence of quasi periodicity on timescales of years, as exhibited, for example, by BF Ori, suggests that we are detecting the orbital timescale of some evolving giant protocomets in these cases. Coupled with this is the fact that one sometimes finds intermediate-timescale (10–100 day) quasi periodicity in some stars. One possible explanation for this behavior is that the giant protocomets disintegrate during perihelion passage to form a chain of fragments similar to what happened with comet Shoemaker-Levy during its recent close approach to Jupiter. Details of this model are discussed by Shevchenko et al. (1993, 1994c).

4.2. *Problems with the Obscuration Model*

While the obscuration model may have some merits as an explanation for a few large-amplitude HAEBE stars, we also see difficulties in adopting it as a general model of the UXor phenomenon, some of which has been alluded to above. Natta et al. (1997) argue that a single mechanism operates, and we do not disagree, but their conclusion is that differences in behavior can be principally attributed to the inclination angle at which the system is viewed. If the circumstellar matter is concentrated to a disk, as it must be to explain the polarization observations, then it is not immediately obvious why there should be any variability at all when viewing outside of the relatively small set of directions that correspond to "along the disk plane." Rostopchina et al. (1996), for example, quote 13°–14° as the opening angle for the disk around RR Tau. If this were typical, then most HAEBE stars would not be seen through any portion of their disks and should not be variable according to the hypothesis. To account for the ubiquitous variability of HAEBE stars one must invoke a much more spherical distribution of occulting matter, in addition to the disk, not in place of it.

While several authors (e.g., Hartmann et al. 1993; Miroshnichenko et al. 1997) have argued that a spherical or quasi-spherical dust distribution does exist around HAEBE stars, one would have to further invoke opacity variations along the line of sight to the star in just the right ways to account for the observed amplitudes, timescales, and color variations of the stars. The similarity between the CTTSs and HAEBE stars range distributions would need to be regarded as coincidental, since the variability mechanisms would be completely different. Rather than appearing as a natural consequence of the principal distinguishing characteristic (an accretion disk) of the class, as in CTTSs, the irregular variability in HAEBE stars would be ad hoc. There would be no connection between it and the irregular variations seen in other astrophysical phenomena where an accretion disk is involved, such as CTTSs, FUors, dwarf novae, and even quasars.

Another objection comes from the correlation shown in Figure 4 between spectral type and amplitude of variability. Why should earlier type stars be less variable than the B8 and later type HAEBE stars? One can imagine that radiation pressure removes dust from the immediate environment of the more luminous stars, but their infrared excesses and millimeter continuum fluxes indicate that in some cases there is substantially more circumstellar matter surrounding them than surrounding the A-type HAEBE stars. Yet, these early-type, large–IR excess stars (such as MWC 1080 and V645 Cyg) have only modest variability ranges. How do the circumstellar disks or envelope material of these stars know that they should obscure them less erratically than they obscure stars of later type? It may be possible to concoct plausible answers to this question, but it represents another example of the "tweaking" that the variable obscuration model must undergo if it is to be successfully applied to the entire class of UXors.

As a further example, we mention the flares that are occasionally seen in HAEBE stars. Rostopchina et al. (1997) attribute these to special "clearings" of the circumstellar dust, allowing us to see the actual photosphere of the star directly for a brief period. But the $U-B$ color of the system becomes extremely blue during these instants, just like a T Tauri star undergoing an accretion flare. An explanation of the flares in terms of "violent non-stationary processes in the neighborhood of the star" is required, to quote Rostopchina et al. (1997). The obscuration model by itself therefore fails to account for all of the observations of even RR Tau, perhaps its most compelling example. Similar "flares" are seen on a number of HAEBE stars in our photometry, including T Ori, LkHα 234, and BH Cep.

While absence of evidence is never grounds for dismissing a model, it is nonetheless telling that when positive evidence in favor of the obscuration model is sought, even by its proponents, it is not found. As mentioned above, Natta et al. (1997) could find no evidence that variability range correlated with any property of the stellar systems that they could measure that would connect the variability to the obscuration model. We have also looked for a correlation between the near-infrared excesses measured for a large set of HAEBE stars by Corcoran & Ray (1998) and their variability. As Figure 19*a* shows, these quantities are not correlated in the sense expected if it were matter close to the star that was causing the obscuration. In fact, there is a weak trend in the opposite sense, that large-amplitude variables have smaller IR excesses. This can be understood as a contrast effect in the unsteady accretion model, as we demonstrate below, but is one more mark against the variable obscuration model.

Natta et al. (1997) argued that a factor that they could not measure, system inclination, was the dominant one in explaining variability ranges. That can be tested by looking for a relationship between $v \sin i$ and variability range. Early-type stars are expected to spin at close to their critical velocities, which are around 200–300 km s^{-1} for HAEBE stars. If it is assumed that the disk and star have nearly aligned angular momentum vectors, then large-amplitude variables should have large values of $v \sin i$. Böhm & Catala (1996) have recently carefully measured $v \sin i$ values for a fair number of HAEBE stars, and L. Hillenbrand (1999, private communication) has done likewise. Figure 19*b* shows the relationship between $v \sin i$ and the range of variability. It is evident that these quantities are not corre-

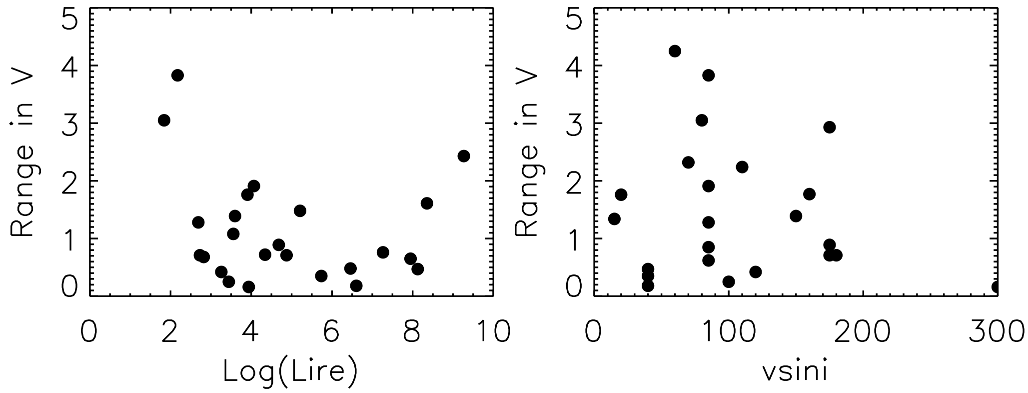

FIG. 19.—Range in V is plotted against the near-IR excess luminosity ($L_{\rm ire}$) from Corcoran & Ray (1998) in the left panel. Range in V is plotted against v sin i measurements from L. Hillenbrand (1999, private communication) in the right panel.

lated. Once again, no evidence in support of the variable obscuration model can be found.

4.3. *An Alternate Explanation for UXors: Variable Accretion Luminosity*

The absence of supporting evidence and the ad hoc nature of the variable obscuration model have encouraged us to consider what seems to be the "natural" explanation of UXors, unsteady accretion. This is generally regarded as the source of the irregular variations of CTTSs, FUors, and close binary disk systems. If HAEBE stars are PMS stars in their accretion phase, then one can expect a contribution to their luminosity from accretion in the amount

$$L_{\rm acc} = \frac{G\dot{M}M_*}{R_*} .$$

If we take, as an example, a HAEBE star with $L_* = 35\ L_\odot$, $T = 8000$ K, $R = 3\ R_\odot$, and $M = 3\ M_\odot$, then the accretion luminosity will equal the stellar luminosity for a mass accretion rate of $\sim 10^{-6}\ M_\odot\ {\rm yr}^{-1}$. This is certainly a possible value for an actual accretion rate based on infrared excesses and on mass-loss rates inferred from winds (Hillenbrand et al. 1992; Corcoran & Ray 1998). As the stellar effective temperature increases, it rapidly becomes more difficult to match the stellar luminosity with plausible accretion rates. This provides a simple, natural explanation for the fact that large-amplitude variables are confined to spectral types of B8–A0 or later. Certainly for the A- and F-type HAEBE stars there is a good chance that an important, if not dominant, source of their luminosity is, in fact, accretion. If this is true, then it is plausible to account for their optical variability by the same mechanism that operates in CTTSs, i.e., unsteady accretion.

An additional plausibility argument for the importance of accretion luminosity comes from a comparison of optical outflows in HAEBE stars with those in low-mass PMS stars. According to Edwards, Ray, & Mundt (1993) and Mundt & Ray (1994), a single relationship applies to the mass-loss rate in PMS stars of different luminosity, namely, $\dot{M}_{\rm loss} \propto L_{\rm bol}^{0.6\pm0.1}$. If we assume that $L_{\rm acc} \propto \dot{M}_{\rm loss}$ (e.g., Corcoran & Ray 1998) and that the degree of optical variability depends on the ratio of $L_{\rm acc}$ to $L_{\rm star}$, then we can compare the expected variability in HAEBE stars to what is observed in CTTSs. For the example HAEBE star in the previous paragraph, $L_{\rm acc}/L_{\rm star}$ is nearly identical to a K-type CTTS with a mass of 0.5 $M_\odot$ and radius of 2 $R_\odot$. If, as is believed, variable accretion luminosity accounts for the irregular variability of the CTTS, then it ought to also be important in HAEBE stars unless their inner accretion flows are, for some reason, much more steady.

We can test the accretion hypothesis crudely in the following way. Corcoran & Ray (1998) have recently observed wind diagnostics and near-infrared emission for a number of HAEBE stars. They calculate infrared excess luminosity ($L_{\rm ire}$) between 0.7 and 10 μm, which is presumed to measure inner disk accretion rates, and show that it is well correlated with wind signatures such as the [O I] λ6300 and Hα emission lines. If accretion luminosity is important in HAEBE stars then we would expect to see a correlation between $L_{\rm star}$ and $L_{\rm ire}$, and, indeed, Corcoran & Ray (1998) have shown precisely such a correlation. Furthermore, if unsteady accretion is responsible for the light variations, we might expect some degree of correlation between $L_{\rm ire}/L_{\rm star}$ and the range of variability. In Figure 20 we show that, indeed, such a correlation does exist. Once again it is apparent, as it was from Figure 3, that the luminosity of the star plays a role in the degree of optical variation. This is naturally accounted for (as a contrast effect) by the accretion hypothesis but is a puzzle for the variable obscuration mechanism.

We conclude with a few comments on other aspects of the variable obscuration model. Its principal successes are in

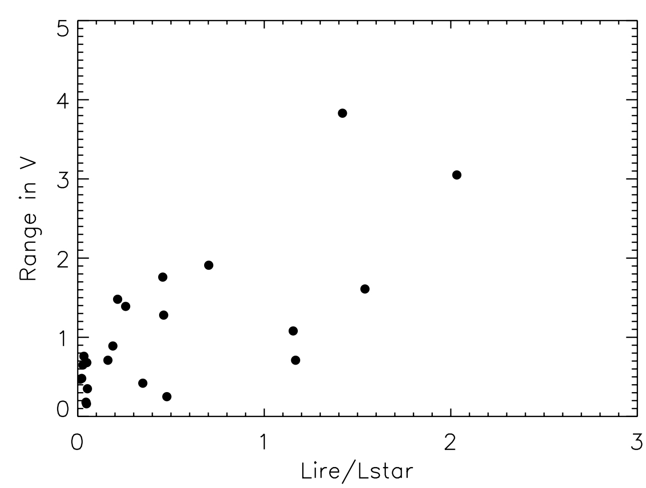

FIG. 20.—Range in V is plotted against the ratio of the near-IR excess luminosity ($L_{\rm ire}$) to the stellar luminosity ($L_{\rm star}$) from Corcoran & Ray (1998). Two stars with $L_{\rm ire} \gg L_{\rm star}$ lie beyond the boundaries of the figure, to the right. Both have substantial photometric variability.

explaining the color behavior and polarimetry of large-amplitude UXors and the apparent lack of substantial spectral changes as the stars vary by 2 mag or more. Can these phenomena be accounted for by a variable accretion model? It does not seem impossible to us, although only detailed modeling will tell. In particular, it may be noted that the spectra of HAEBE stars are often dominated by shell lines, not photospheric lines, so the lack of spectral variations may reflect the fact that the accretion-driven luminosity variations are occurring within a shell and the absorption spectrum is fairly insensitive to the continuum flux that it overlays. In fact, there is one consistent spectral variation that does correlate with brightness, namely, the equivalent width of Hα. Photometric studies by Herbst et al. (1982) have shown that in some UXors the flux in the Hα line remains constant, while the equivalent width in emission increases as the star fades, reflecting the drop in the continuum. This may be a general characteristic of the class and has a natural explanation in the accretion model, since the source of the continuum is inside the shell or wind region where the Hα arises. In the variable obscuration model one must envisage a conveniently oriented "natural coronagraph," as Rostopchina et al. (1997) refer to it, with the proper size and location to block the starlight without substantially blocking the Hα emission. This is, of course, possible but easier to accept in a few special cases than as a general explanation for an entire class of variables.

In the dust obscuration model (see Fig. 10 of Rostopchina et al. 1997 for a schematic picture), the "bluing" and increased polarization near light minima come from "zodiacal light," i.e., light scattered off a dust disk. In an accretion luminosity model, one can imagine that the polarization arises by electron scattering in an optically thin, geometrically flattened shell that produces the Hα emission and possibly some absorption lines. Classical Be stars, for example, show polarization from flattened, electron scattering disks (e.g., Waters & Marlborough 1992). Their maximum polarization is about 1.5%, which is somewhat smaller than the most extreme cases for the HAEBE stars, but presumably the disks of the latter are more substantial. In principle, one should be able to distinguish between electron scattering polarization and dust polarization by the wavelength dependence, but optical depth effects may complicate the analysis.

The "bluing" would, in the accretion model, be caused by either an increasing contribution to the total luminosity from a hot, optically thin component—the same component in which the Hα emission arises—or by an optically thick, inner disk or stellar photosphere that becomes more prominent as the accretion luminosity declines. A particularly attractive possibility is that the thermal instability mechanism responsible for outbursts in close binary system disks and possibly FUors (e.g., Pringle 1981; Frank, King, & Raine 1992; Bell et al. 1995; Hartmann 1998) might be operating in UXors. The temperature range for this mechanism is 5000–10,000 K (i.e., the ionization temperature of H I at relevant densities), which is the temperature range of UXors. The timescale for the instability is probably short enough to account for the deep minima and subsequent recoveries of typical UXors. The amplitude of variation also seems to be of the right order to make this mechanism plausible. The bluing would arise naturally as the portion of the disk responsible for the light of the UXors near maximum made a rapid transition to lower temperature and optical depth leaving the hotter inner disk, boundary layer, or photosphere to dominate the spectrum.

5. CONCLUSION

To summarize, we propose a schematic, three-component model for the light variations of UXors, consisting of the following:

1. The stellar photosphere, which dominates in the higher luminosity, higher temperature, lower variability range stars (e.g., all those with spectral types earlier than about B8), but is often masked by the other components in the later type, more active stars.
2. An inner disk region from which the accretion luminosity is radiated. This zone must also be the source of the optical spectrum for highly variable objects such as BF Ori and RR Tau, in the same way that the optical spectrum of FUors is accounted for in the models of Hartmann & Kenyon (1985). As shown by Hartmann et al. (1993), the inner disks of HAEBE stars with high mass accretion rates are expected to be optically thick at visible wavelengths and could, therefore, be mistaken for photospheres. The inner disk is the seat of the variations in our proposal, with temperature and density fluctuations driven by unsteady accretion producing the optical variability. The same thermal instability mechanism that is thought to produce outbursts in dwarf novae and FUors could, conceivably, cause deep minima in UXors.
3. An optically thin, geometrically flattened hot shell, which overlays region 2 and might also include a jet or disk wind. This is the source of the shell absorption and emission lines and probably some of the blue excess emission that causes the color turnarounds. Electron scattering in this flattened shell is proposed as the source of the polarization.

It is beyond the scope of this paper to develop this proposal further. We simply note that, in our opinion, it has the potential to account for all aspects of UXor variability in a manner that links the phenomenon to the CTTSs, FUors, and other disk accretion systems. Coordinated spectroscopy and photometry of particularly active stars such as RR Tau and BF Ori should be useful in testing the proposal empirically, while considerable theoretical development is needed to test it rigorously.

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