November 2003

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Schmidt, Edward G.; Langan, Shawn; Lee, Kevin M.; Johnston, Dale; Newman, Peter R.; and Snedden, Stephanie A., "THE SPECTRA OF TYPE II CEPHEIDS. II. THE Hα LINE IN INTERMEDIATE-PERIOD STARS" (2003). *Edward Schmidt Publications*. 1.
http://digitalcommons.unl.edu/physicsschmidt/1

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The Astronomical Journal, 126:2495–2501, 2003 November

THE SPECTRA OF TYPE II CEPHEIDS. II. THE Hα LINE IN INTERMEDIATE-PERIOD STARS[1]

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Received 2003 July 8; accepted 2003 August 6

ABSTRACT

We present 98 Hα profiles for 21 pulsating variable stars with periods from 3 to 8 days. The strength, depth, and shape of Hα vary throughout the cycles of the stars in a way consistent with the temperature changes. Otherwise, they are quite uniform among all the stars, with a single exception. In FM Del, Hα is weaker and has a smaller central depth than in the other stars. This and the wavelength shifts of the core are attributed to incipient emission. The differential velocity of Hα relative to the metal lines is less than 25 km s^{-1} for all the stars except QY Cyg, FM Del, and EF Tau. We suggest that this indicates that only these stars are type II Cepheids despite the large distances of some of the others from the Galactic plane.

Key words: Cepheids — stars: Population II

1. INTRODUCTION

We have undertaken a survey of the behavior of Hα in type II Cepheids. This line is known to be sensitive to atmospheric dynamics in pulsating stars, and the goal is to delineate its behavior in type II Cepheids as compared with classical Cepheids. Previous studies have found some differences between the two classes of stars. Hence, Hα may provide a useful diagnostic for distinguishing between them. The definition of observable properties that provide for reliable classification is a major goal of this project.

In a previous paper (Schmidt et al. 2003, hereafter Paper I), we presented the results for stars in the period range from 1 to 3 days. In contrast to previous studies, it was found that Hα emission is common in those short-period type II Cepheids that have a significant bump on the rising branch of the light curve (Diethelm's [1990] AHB2 stars). The emission was associated with the bump. The differential velocity of the core of Hα relative to the photospheric metal lines, $\Delta \mathrm{Vel} = V_{\mathrm{H}\alpha} - V_{\mathrm{ph}}$, was found to range up to 82 km s^{-1} for the type II Cepheids, while the classical Cepheids exhibited values less than 20 km s^{-1}.

In the present paper, we continue this study by presenting spectra of stars with periods in the intermediate range from 3 to 8 days. The behavior of Hα in type I and type II Cepheids was explored by Vinkó et al. (1998), who found relatively small differential velocities ($\lesssim 25$ km s^{-1}) for eight likely type II Cepheids in this range. None of these stars exhibited either emission or line doubling. Harris & Wallerstein (1984) observed Hα during rising light in four stars in this period range and found no example of emission. Our survey of a larger number of stars will permit a more definitive result.

2. THE OBSERVATIONS

2.1. *The Sample*

The stars discussed here are listed in Table 1, where column (1) gives the names of the stars. Putative type II Cepheids were drawn from two overlapping sources: stars in the General Catalogue of Variable Stars (GCVS; Kholopov 1985, 1987) classified as "CWB" or "CWB:," and Harris's (1985a) catalog of type II Cepheids. They were selected to have appropriate periods (3 to 8 days), to be accessible from the Northern Hemisphere (north of $-20°$ declination) and to be bright enough to feasibly observe (brighter than 16th magnitude). To these stars we added some likely type I Cepheids for comparison purposes. In column (2) of Table 1, the classifications from the GCVS are listed, while column (3) identifies the stars from Harris's catalog. A "II" indicates that Harris included the star on the basis of its distance from the Galactic plane, while "II:" indicates that the star was listed as a probable type II Cepheid on other (unspecified) grounds. A blank entry in column (3), can be taken to indicate that Harris deemed the star to be a classical Cepheid and did not include it.

Unlike the sample reported in Paper I, the identification of stars in Table I as type II is quite indefinite in most cases. This is reflected in the fact that many of the GCVS classifications are marked as uncertain. Furthermore, a comparison of column (2) and column (3) shows disagreement about a third of the time. Balog, Vinkó, & Kaszás (1997) derived Wesselink radii for a number of pulsating stars. They plotted radius versus period and showed, as expected, that there were two relationships, reflecting the two types of Cepheids. However, all five of the stars from our sample that they included, DQ And, KL Aql, TX Del, V733 Aql, and

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[1] Based in part on observations obtained with the Apache Point Observatory 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium.

[2] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

TABLE 1

The Program Stars

Star (1)	GCVS Class (2)	Harris Class (3)	[Fe/H] (4)	Period (5)	Epoch of Max.[a] (6)	Phase of Min. (7)	ΔV (8)	Source of Phot. (9)
DQ And	CWB:	II	0.0	3.20063	52,662.57	0.82	0.80	1, 2, 3, 4
GL Cyg	CEP	II	. . .	3.370693	52,535.56	0.75	0.81	1, 5, 6
FT Mon	DCEP	II	. . .	3.4218	52,615.76	0.84	1.19	1, 5, 6
EF Tau	DCEP	II:	. . .	3.4482	52,648.68	0.77	0.73	1, 4, 5, 6
BF Cas	DCEP	. . .	. . .	3.63045	52,580.67	0.83	0.88	1, 5, 6, 7
BD Cas[b]	CWB	II:	. . .	3.6509	52,639.74:	0.60:	0.39:	1, 2, 7
V572 Aql[b]	CWB	II	0.0	3.7678	52,569.70:	0.65:	0.48:	1, 2, 3
QY Cyg	CWB:	II	. . .	3.89188	52,540.71	0.81	0.92	1, 5, 6
FM Del	CWB	II	−0.9	3.9552	52,425.42	0.76	0.70	1, 6
AM Cam	CEP	II:	. . .	3.997197	52,657.07	0.76	0.64	1, 5, 6
V912 Aql	DCEP	. . .	. . .	4.4005	50,285.95[c]	0.76	0.90	1, 6
V383 Cyg	CWB:	II:	. . .	4.6123	52,569.27	0.74	0.60	1, 5, 6
CZ Cas	DCEP	. . .	. . .	5.66438	52,618.68	0.75	0.86	1, 5
V394 Cep	CWB:	. . .	. . .	5.689	52,412.42	0.76	0.82	1
KL Aql	DCEP	II:	0.6, 0.4	6.108015	52,500.65	0.72	0.74	1, 5, 8, 9, 10, 11
TX Del	CWB:	II	0.4, 0.6	6.1661	52,535.41	0.65	0.63	1, 8, 9, 10, 12, 13, 14
V733 Aql	DCEP	II	. . .	6.178748	52,569.72	0.69	0.47	1, 5, 10, 14
AP Cas	DCEP	. . .	. . .	6.8470	52,587.69	0.69	0.63	1, 5
IT Cep	CWB:	. . .	. . .	7.34744	52,472.58	0.74	0.54	1
BB Her	DCEP	II:	0.3	7.507945	52,499.59	0.71	0.65	1, 5, 9, 10
CD Cas	DCEP	. . .	. . .	7.80089	52,664.63	0.75	0.84	1

[a] Epochs are listed as Heliocentric Julian Date minus 2,400,000.

[b] Sinusoidal light curve with significant scatter. Hence, the light-curve parameters are uncertain.

[c] The most recent photometry for V912 Aql we have available is a set of 12 points taken between 1991 and 1996. Hence, the phasing of the spectra is uncertain.

References.—(1) Unpublished Behlen Observatory photometry; (2) Szabados 1977; (3) Henden 1980; (4) Schmidt, Chab, & Reiswig 1995; (5) Berdnikov 1987, 1992a, 1992b, 1992c, 1992d, 1992e, 1992f, 1993a, 1993b; (6) Henden 1996a, 1996b; (7) Schmidt & Reiswig 1993; (8) Pel 1976; (9) Harris 1980; (10) Szabados 1980; (11) Berdnikov & Turner 1995; (12) Moffett & Barnes 1984; (13) Szabados 1991; (14) Berdnikov & Voziakova 1995.

BB Her, had radii appropriate to classical Cepheids. Again, this is inconsistent with the classifications in Table 1.

Column (4) of Table 1 lists metallicities from Harris (1981), Diethelm (1990), or Meakes, Wallerstein, & Opalko (1991) for six of the stars. Although there are too few metallicities available for a firm conclusion, we note that the stars with measured values are all metal-rich with the sole exception of FM Del, which is moderately metal-poor. This is in contrast to the short-period sample of Paper I, which covered a wide range of metallicity, and again suggests uncertainty regarding the status of these stars.

The uncertainty in the classification of the stars in our sample underlines the point made by various authors (e.g., Harris 1985b) that distinguishing between type I and type II Cepheids in the field is very difficult in some period ranges. Light-curve morphology is of little use in this period range, as can be appreciated through an examination of Fourier parameters (Zakrzewski, Ogłoza, & Moskalik 2000). In our discussion we will need to be mindful of these uncertainties.

The periods and epochs used to calculate phases for the spectra below are given in columns (5) and (6) of Table 1. These were determined from the photometry referenced in the last column. We have recent observations for all the stars, except V912 Aql, which will be published at a later time. Thus, the phasing of the spectra should be reliable. In columns (7) and (8) we give the phases of minimum light and the amplitudes in the V magnitude derived from the same photometry.

2.2. *The Data*

The spectra were obtained at Kitt Peak National Observatory during 2001 July and 2002 September/October and at Apache Point Observatory during 2002 June, at the same time as the observations presented in Paper I. The Kitt Peak spectra have a resolution of 2.0 Å, while those from Apache Point have a resolution of 2.6 Å. Paper I gives further details of the observations and reductions.

A log of the spectroscopic observations is given in Table 2, where the stars are identified in column (1) and the Heliocentric Julian Date of mid-exposure is given in column (2). The spectra from Apache Point Observatory can be distinguished by their having a Julian Date of 2,452,443, while the remaining dates indicate Kitt Peak spectra.

As in Paper I, we used the rms scatter in the region from 6720 to 6820 Å to obtain a lower limit for the signal-to-noise ratio (S/N) of each spectrum. We achieved a value greater than 75 per resolution element in 90% of the spectra used in this paper. There were two spectra with S/N less than 50, and these are flagged by a footnote in column (2) of Table 2.

The phases from maximum light of the observations based on the ephemerides of Table 1 are listed in column (3) of Table 2. As noted in Paper I, the phenomena of interest with regard to Hα—emission components, line doubling, and large differential velocities for Hα—are concentrated during and slightly after rising light. As before we have focused on this part of the cycle, and 57% of our spectra were taken during that interval.

TABLE 2
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Star (1)	Mid-Exp. HJD (2,452,000+) (2)	ϕ (3)	ΔVel (km s^{-1}) (4)	Std. Err. (km s^{-1}) (5)	Depth of Hα (6)	W_λ of Hα (Å) (7)
DQ And	105.86	0.06	−20	3	0.59	4.2
	546.72	0.80	3	2	0.61	2.9
	550.62	0.02	−18	5	0.63	4.6
	550.94	0.12	−10	2	0.60	3.9
	552.02	0.46	−10	4	0.56	2.8
	553.63	0.96	2	2	0.63	4.5
	555.97	0.69	−1	2	0.60	2.8
GL Cyg	106.76	0.79	0	4	0.57	3.1
	548.70	0.90	−1	3	0.58	3.9
	551.65	0.77	5	2	0.60	2.7
FT Mon	546.93	0.88	6	4	0.57	3.4
	551.01	0.08	−20	3	0.61	5.3
	553.89	0.92	4	3	0.60	3.4
	555.90	0.51	−4	3	0.56	3.3
EF Tau	548.87[a]	0.05	−36	5	0.60	4.6
	551.00	0.67	4	3	0.58	2.6
	551.85	0.92	8	5	0.59	3.3
	555.87	0.08	−28	4	0.59	4.1
BF Cas	104.81	0.93	−5	3	0.58	4.1
	546.96	0.71	−4	3	0.57	3.0
	547.65	0.91	5	2	0.58	2.9
	550.90	0.80	5	3	0.60	2.4
	552.01	0.11	−24	3	0.60	4.1
	554.80	0.87	2	3	0.58	2.7
	555.94	0.19	−17	3	0.59	4.1
BD Cas	101.92	0.69	−2	4	0.60	3.5
	102.81	0.93	−12	3	0.58	4.7
	104.90	0.51	−9	2	0.53	3.1
	105.82	0.76	−9	4	0.58	3.3
	106.86	0.04	−12	3	0.56	3.6
	546.94	0.58	−4	2	0.58	3.8
	551.97	0.96	−11	3	0.60	4.0
	553.88	0.48	−11	3	0.57	3.2
V572 Aql..............	104.83	0.62	−5	2	0.56	3.8
	105.82	0.88	−15	4	0.63	4.3
	550.74[a]	0.97	−9	10	0.64	3.8
	553.73	0.76	2	3	0.60	3.9
	554.74	0.03	−7	2	0.63	4.5
QY Cyg................	104.78	0.99	−24	6	0.59	5.2
	105.96	0.29	−17	3	0.54	3.7
	443.72	0.08	−28	5	0.54	4.5
	547.72	0.80	2	3	0.58	2.7
	548.67	0.05	−30	5	0.60	4.9
	551.67	0.82	2	4	0.58	2.6
	554.79	0.62	−14	3	0.58	2.8
FM Del	104.98	0.98	41	6	0.35	2.4
	546.84	0.70	−28	4	0.35	2.0
	547.69	0.91	45	4	0.39	2.7
	551.63	0.91	46	3	0.35	2.2
AM Cam..............	104.93	0.87	8	3	0.58	3.2
	548.84	0.92	4	3	0.64	3.9
	550.95	0.45	−2	3	0.60	2.8
	553.93	0.20	−14	2	0.59	3.1
	554.95	0.45	−6	3	0.58	3.0
V912 Aql..............	102.78	0.87	3	2	0.59	3.8
	106.73	0.77	−4	3	0.56	3.5
V383 Cyg	106.72	0.71	−4	3	0.54	2.6
	443.73	0.78	10	3	0.61	2.4
	546.85	0.14	−12	2	0.60	3.6
	550.60	0.95	−9	2	0.64	3.6
	554.62	0.82	2	3	0.63	3.5

TABLE 2—*Continued*

Star (1)	Mid-Exp. HJD (2,452,000+) (2)	ϕ (3)	ΔVel (km s^{-1}) (4)	Std. Err. (km s^{-1}) (5)	Depth of Hα (6)	W_λ of Hα (Å) (7)
CZ Cas	101.97	0.78	6	3	0.56	3.5
	550.65	0.99	−20	4	0.64	4.7
	552.00	0.23	−16	3	0.60	3.5
	555.82	0.90	14	2	0.59	3.2
V394 Cep	547.64	0.77	−12	3	0.52	2.6
	548.73	0.96	−13	5	0.60	4.3
	550.89	0.34	−8	4	0.56	3.1
	551.93	0.52	−5	3	0.53	2.5
	553.68	0.83	−6	3	0.56	3.3
KL Aql	547.77	0.71	23	4	0.58	3.1
	554.70	0.85	12	2	0.64	3.8
TX Del	546.81	0.85	−2	4	0.61	4.8
	551.77	0.65	−1	3	0.51	3.4
V733 Aql	104.97	0.78	11	3	0.58	3.5
	105.97	0.94	−9	3	0.61	4.2
	550.74	0.93	−2	2	0.63	4.0
	554.75	0.58	−3	2	0.58	3.5
AP Cas	106.81	0.77	−7	2	0.52	3.5
	551.75	0.75	11	3	0.58	2.5
	553.90	0.07	−11	3	0.60	3.2
	555.95	0.36	−8	3	0.57	3.0
IT Cep	104.70	0.93	−7	3	0.60	3.8
	546.91	0.12	−20	3	0.61	3.5
	551.61	0.76	−2	3	0.58	2.7
	553.65	0.03	−19	3	0.63	3.4
	553.87	0.06	−19	3	0.61	3.5
	555.93	0.34	−13	4	0.60	3.4
BB Her	106.90	0.70	1	3	0.53	2.8
	550.62	0.80	16	3	0.58	3.1
	551.63	0.93	−3	2	0.65	3.8
	554.73	0.34	−7	3	0.59	3.5
CD Cas	101.96	0.87	13	3	0.58	3.6
	546.77	0.89	12	2	0.60	3.2
	550.91	0.42	−6	4	0.60	3.2
	552.00	0.56	−8	2	0.60	3.2
	553.94	0.81	7	3	0.54	2.7
	554.75	0.91	11	3	0.65	4.2

[a] The lower limit to the S/N is less than 50.

Columns (4), (5), (6), and (7) of Table 2 contain, respectively, the differential velocities of Hα, the standard errors of the differential velocities, the Hα line depths, and the equivalent widths of Hα. The line depth is defined as $1 - r_\lambda$, where r_λ is the residual intensity at the deepest point in the line in units of the continuum flux. The uncertainties in the line depth and the equivalent width are dominated by the placement of the continuum. However, because we have used the same spectral regions to define the continuum in all of our spectra, the internal errors are smaller and are estimated to be less than 0.03 (depending on the S/N) for the line depths and less than 10% for the equivalent widths.

In Figure 1, we have plotted the region around Hα for a selection of spectra. The appearance of most of the profiles are very similar, so we have provided examples that typify them. The only exceptions are the profiles for FM Del. These are also included in Figure 1 and are discussed below.

3. DISCUSSION

In Figure 2, the depths and equivalent widths of Hα are plotted against pulsational phase. The similarities of the profiles among the stars, with the single exception of FM Del, are evident in these diagrams. In particular, the line depths range from 0.51 to 0.65, while the equivalent widths range from 2.4 to 5.3 Å. Both quantities are smallest near minimum light and largest around maximum light. This reflects the well-known increase in both strength and broadening of the Balmer lines with increasing temperature among F, G, and K stars. At a given phase, most of the scatter is accounted for by the uncertainties given above.

There are several possible explanations for the shallow, weak Hα line in FM Del. These include peculiarities in the elemental abundances, the presence of a companion, and filling by emission. This star is the most metal-poor of those stars with measured metallicities in Table 1. However, no similar weakening of Hα is apparent among stars with even lower metallicities in Paper I. Contamination of the spectrum by a companion could weaken the metal lines, resulting in the low apparent metallicity as well as the weakness of Hα. However, an inspection of the profiles in Figure 1 shows some differences in shape between FM Del and the other stars. For example, there is a bump on the blueward wing at phases 0.91 and 0.98 that is not apparent in the spectra of any other star.

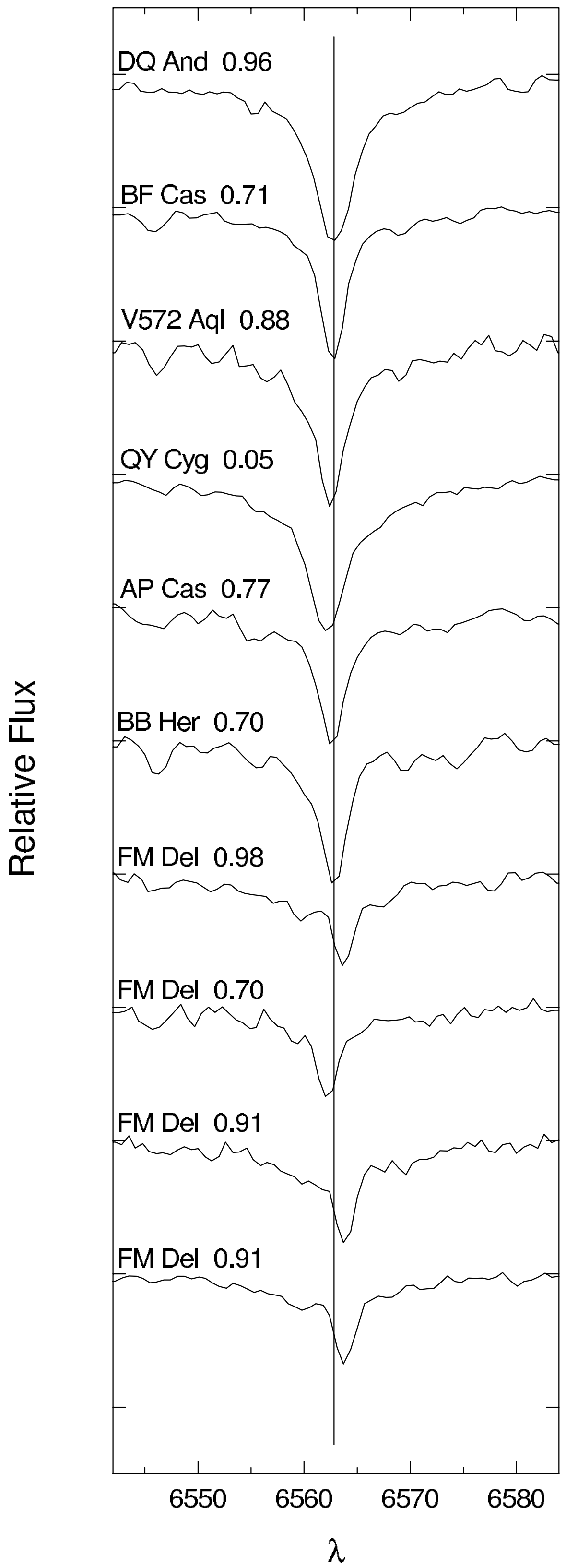

Fig. 1.—The portion of the spectra near Hα for a selection of stars from our sample. The top six are typical of a large majority of the stars, while the lower four are unusual, as discussed in the text. Each plot is normalized to a continuum level of 1 and is offset vertically from its neighbors by 0.5 for visibility. Each spectrum is identified by the name of the star and the phase. The vertical line indicates the rest wavelength of Hα, and each spectrum has been shifted to the rest frame of the photosphere as defined by the metal lines.

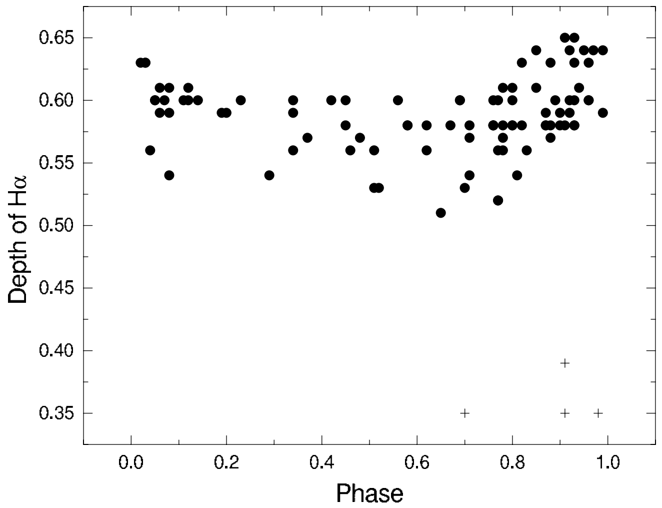

Fig. 2*a*

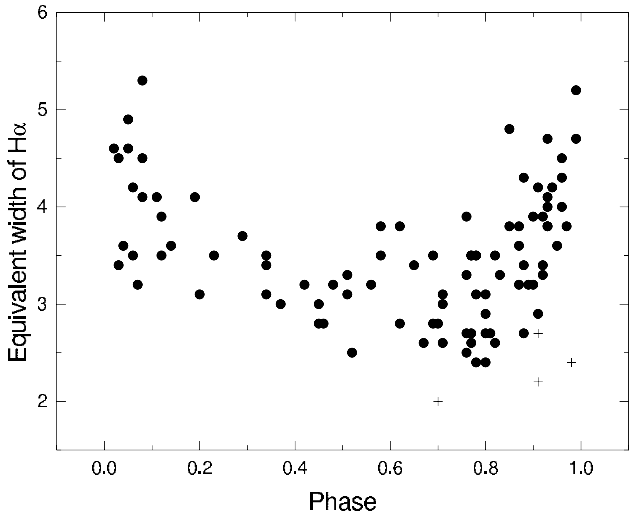

Fig. 2*b*

Fig. 2.—(*a*) Line depth of Hα plotted against the phase; (*b*) equivalent width of Hα plotted against the phase. In both plots, the plus signs represent the values for FM Del, while the data for the other stars are plotted as circles.

Furthermore, the differential velocity of the core of Hα, evident in Figure 1 as a shift from the rest wavelength, cannot be accounted for by a companion. Finally, we note that emission could account for the weakening of Hα, the bumps in the wings of the profile, and the shift of the core. For example, the Hα profile of NW Lyr at phase 0.81 (Fig. 2*a* of Paper I) exhibits obvious emission. It is easy to imagine that the profile for FM Del at phase 0.98 differs from it only in the strength of the emission relative to the continuum. A comparison with the profile of V477 Oph at phase 0.00 (Fig. 2*d* of Paper I), which we argued was the result of incipient emission, further strengthens this impression. We conclude that the most likely explanation for the profile of Hα in FM Del is filling by an emission feature.

We are in the process of obtaining well-sampled light curves for the stars discussed here. A future publication will discuss them in detail. In the meantime, we note that an examination of published photometry shows that FM Del does not match other stars of similar period in light-curve

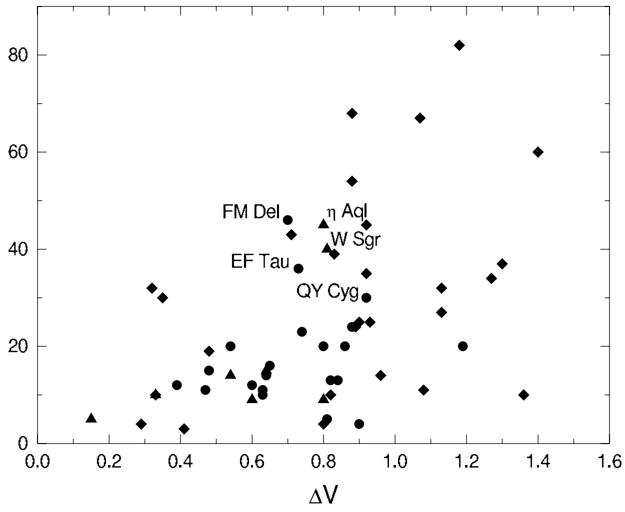

Fig. 3*a*

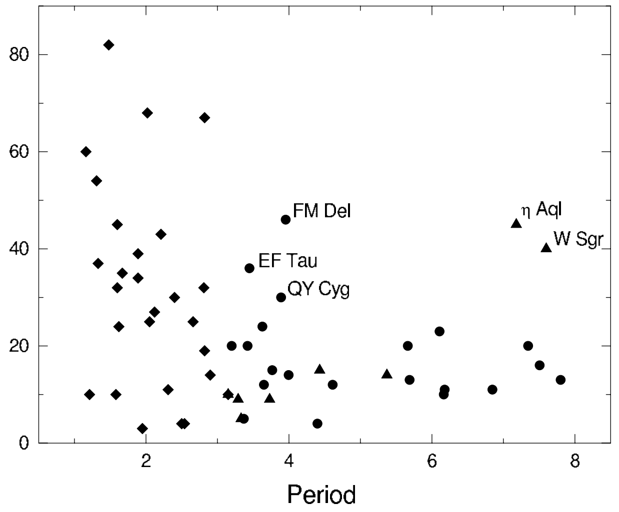

Fig. 3*b*

Fig. 3.—Absolute value of the largest observed difference for each star between the velocity of Hα and the metal lines, $|\Delta\mathrm{Vel}|_{\mathrm{max}}$, plotted against (*a*) the V amplitude and (*b*) the period. Points representing individual stars discussed in the text are labeled for convenience. Circles indicate stars listed in Table 1, and triangles denote additional stars from Vinkó et al. (1998). Diamonds represent shorter-period stars from Paper I.

morphology. For example, the photometry of Henden (1996b) suggests the presence of a hump or crest after maximum light in FM Del. This might be similar to what is seen in Diethelm's (1990) AHB3 stars.[3] This is unlike light curves for other stars of similar period shown by Henden and further strengthens the impression that this star differs from them. It also raises the question of why emission would be found in an AHB3 star when in Paper I we found that emission was largely confined to the AHB2 stars. However, a definitive discussion must await the completion of our photometric observations.

Following Paper I, the maximum for each star of the absolute value of the differential velocity of Hα relative to the metal lines ($|\Delta\mathrm{Vel}|_{\mathrm{max}}$) is plotted against amplitude in the V magnitude (ΔV) and against the period in Figure 3. For TX Del we have used the value from Vinkó et al. (1998), since it is larger than ours. We have added eight additional stars from that same source, η Aql, RT Aur, δ Cep, V1334 Cyg, W Sgr, SZ Tau, T Vul, and HD 32456, and have also plotted the stars from Paper I. It can be seen that the majority of intermediate-period stars have relatively small differential velocities, less than about 25 km s^{-1}. The exceptions are η Aql, QY Cyg, FM Del, W Sgr, and EF Tau. Vinkó et al. showed that for stars in their sample, there was a positive correlation between $|\Delta\mathrm{Vel}|_{\mathrm{max}}$ and the pulsational amplitude. However, looking at Figure 3*a* it is evident that the amplitude does not explain the larger differential velocities of these five stars. On the other hand, in Figure 3*b* it is clear that the large differential velocities occur at the extremes of the period range. In the case of η Aql and W Sgr, this is just the increase in $|\Delta\mathrm{Vel}|_{\mathrm{max}}$ among classical Cepheids with periods longer than 8 days (see Fig. 19 of Vinkó et al. 1998). We will not be concerned further with these stars here.

The other stars in our sample that stand out in Figure 3, FM Del, EF Tau, and QY Cyg, are at the short end of the present period range. Since their differential velocities are similar to the shorter-period type II Cepheids discussed in Paper I, it is natural to associate them with that group of stars. This hypothesis is supported by the low metallicity of FM Del and the fact that both QY Cyg and FM Del are far enough from the Galactic plane to be considered bona fide type II Cepheids (Harris 1985a). A final discussion must include consideration of the forthcoming photometry. We will also present metallicities determined from our spectra, which will bear on this question. For now, we suggest that the short-period type II Cepheids should be considered to have periods ranging up to about 4 days.

The homogeneity of the remainder of our sample presents a puzzle. This uniformity includes not just the Hα profiles, but also the fact that all those with measured values of [Fe/H] are close to solar metallicity. In addition, as noted above, the measured radii for five of them, DQ And, TX Del, V733 Aql, KL Aql, and BB Her, clearly place them among the type I Cepheids despite their large distances from the Galactic plane (Balog et al. 1997). It is also noteworthy that these were the only field stars in Balog et al.'s sample in this period range; they found no field stars between 3 and 8 days with type II radii. On the other hand, six of the stars (those classed as "II" in col. [3] of Table 1) would be more than 600 pc from the Galactic plane if they were classical Cepheids. This issue will also be revisited when we present our photometry, but we can note now that photometry has not been found to differentiate between type I and type II Cepheids in this period range (see, e.g., Zakrzewski et al. 2000). Given these various factors, it seems likely that all the stars in Table 1 are, in fact, classical Cepheids except EF Tau, QY Cyg, and FM Del. The question that must then be addressed is why so many are so far outside of the young, thin disk.

We are grateful to the staffs of Kitt Peak National Observatory and Apache Point Observatory for their help in obtaining the data used here. We made extensive use of the McMaster Cepheid Photometry and Radial Velocity Data Archive in both the selection of stars for the program and in locating photometric data for use in this paper. We are appreciative of the efforts on the part of Douglas Welch in providing this resource. This work is supported in part by NSF grant AST 00-97353.

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[3] Diethelm classified this star as "RRa?." The significance of this class is not clear, and it is uncertain why he did not consider it an AHB3 star.

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