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ABSTRACT

We use new high-dispersion spectroscopic and precise photometric observations to identify 12 new γ Doradus stars. Two of the 12 systems are double-lined binaries that show obvious velocity variability. Five other stars have metallic lines with composite profiles characterized by a narrow feature near the center of each broad component. Spectrograms of the Hα line indicate that all five stars are binaries rather than shell stars. The remaining five stars in our sample are probably single. All 12 stars are photometrically variable with amplitudes between 6 and 87 mmag in Johnson *B* and periods between 0.3 and 1.2 days. Four stars are monoperiodic; the rest have between two and five independent periods. The variability at all periods approximates a sinusoid. Although many of the stars lie within the δ Scuti instability strip, none exhibit the higher frequency variability seen in δ Scuti stars. We have increased the sample of known γ Doradus stars by 40% and revised the positions of a number of variables in the H-R diagram by accounting for duplicity. Our list of 42 confirmed γ Doradus variables gives some of their properties. All are dwarfs or subgiants and lie within a well-defined region of the H-R diagram that overlaps the cool edge of the δ Scuti instability strip. We compare the observed location of the γ Doradus variables with a recently published theoretical γ Doradus instability strip and find good agreement.

Key words: stars: early-type — stars: fundamental parameters — stars: oscillations — stars: variables: other

On-line material: machine-readable table

1. INTRODUCTION

This is the seventh in a series of papers (Kaye et al. 1999c, 1999b; Henry et al. 2001; Henry & Fekel 2002; Fekel & Henry 2003; Fekel, Warner, & Kaye 2003) in which we examine the spectroscopic and photometric characteristics of candidate γ Doradus stars. Early summaries of this new class of variable stars can be found in Kaye et al. (1999a) and Zerbi (2000). Kaye et al. (1999a) listed 13 members of the class, although one of those stars, HR 6277, was subsequently shown to be a δ Scuti variable (Kaye, Henry, & Rodríguez 2000). The γ Doradus stars typically have multiple photometric periods between 0.3 and 3 days and sinusoidal light curves with amplitudes of a few millimagnitudes to a few percent (e.g., Henry & Fekel 2002). Radial velocity variations of 2–4 km s^{-1} and changing spectroscopic line profiles have also been observed in some stars (e.g., Krisciunas et al. 1995; Balona et al. 1996; Hatzes 1998; Kaye et al. 1999b, 1999c; Fekel & Henry 2003). It is generally agreed that the photometric and spectroscopic variations arise from nonradial, *g*-mode pulsations of high order (*n*) and low spherical degree (*l*) (Kaye et al. 1999a). Guzik et al. (2000) proposed that the pulsations are driven by modulation of the radiative flux through the mechanism of "convective blocking" in the relatively thin convective envelopes of the γ Doradus stars.

The most recently published list of confirmed γ Doradus stars contains 30 members (Henry & Fekel 2002, their Table 5). These stars lie in a fairly tight region of the H-R diagram, on or just above the main sequence that partially overlaps the cool edge of the δ Scuti instability strip (Henry & Fekel 2002, their Fig. 15). In this paper, we examine an additional 12 γ Doradus candiates and bring the number of confirmed γ Doradus stars to 42. We also compare the observed location of these stars in the H-R diagram with the first theoretically determined γ Doradus instability strip recently published by Warner, Kaye, & Guzik (2003).

2. THE SAMPLE

Nine of the 12 γ Doradus candidates for this paper were taken from the list of prime candidates in Handler (1999), who identified them on the basis of his analysis of the *Hipparcos* photometry (ESA 1997). Two additional stars were added to our sample of candidates after they were discovered to be photometrically variable when used as comparison stars with the T4 0.75 m automatic photoelectric telescope (APT) in our program to observe brightness changes in solar-type stars (Henry 1999). A 12th candidate came from the thesis of Eyer (1998). Nine of the 12 stars were also included in the spectroscopic survey of 34 γ Doradus candidates by Fekel et al. (2003). Five of those were chosen for this present study because they exhibited composite metallic line profiles consisting of a narrow component near the center of a broad line, indicating they may be shell stars or binaries.

All 12 candidates are confirmed as γ Doradus stars in this study and are listed in Table 1 along with some of their properties determined below. Columns (4) and (5) list the *V*

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TABLE 1

Basic Properties of the New γ Doradus Stars

HD (1)	Other Names (2)	Component (3)	V[a] (mag) (4)	$B-V$[a] (mag) (5)	*Hipparcos* Variable Type[b] (6)	Ref. (7)	Spectral Class[c] (8)	Luminosity Class[c] (9)	$v \sin i$ (10)	Velocity (11)
7169	HDS 160	A, B	7.30	0.380	P	1				
		A	7.42	0.329			F1	Dwarf	100	−9.2[d]
		B	9.72	0.672			G5:	Dwarf	5:	−18.8[d]
23874	ADS 2785 AB	A, B	8.20	0.400	P	1				
		A	8.45	0.329			F1	Dwarf	95[d]	−19.8
		B	9.90	0.530			F8:	Dwarf	5:	−17.4
48271	...	...	7.49	0.315	P	1	F0	Dwarf	32:	−15.8
64729	...	...	7.57	0.321	B	2	F0	Dwarf	65	6.3
86358	HR 3936	A, B	6.48	0.362	U	1				
		A	6.87	0.300			F0[d]	Dwarf[d]	25[d]	variable[d]
		B	7.77	0.431			F5:[d]	Dwarf[d]	30:[d]	variable[d]
100215	...	A, B	7.99	0.323	U	1				
		A	8.08	0.265			A9	Dwarf	19	variable[d]
		B	10.68	0.672			G5:	Dwarf	12	variable[d]
105085	...	A, B	7.49	0.360	P	3				
		A	7.59	0.300			F0	Dwarf	60[d]	−1.6[d]
		B	10.09	0.672			G5:	Dwarf	5:	1.7[d]
113867	...	A, B	6.83	0.313	U	1				
		A	7.40	0.265			A9[d]	Dwarf[d]	120[d]	variable
		B	7.80	0.329			F1	Dwarf	10[d]	variable
152896	V645 Her	...	7.55	0.314	U	1	F1[d]	Dwarf[d]	49[d]	−0.4[d]
160295	V2381 Oph	A, B	7.71	0.413	P	1				
		A	7.87	0.354			F2[d]	Subgiant[d]	70[d]	−41.8[d]
		B	9.87	0.583			G0:	Dwarf	5:	−42.7[d]
165645	HR 6767	...	6.38	0.287	B	2	A9:	Dwarf	150:	−14.7:
171244	...	...	7.75	0.397	P	1	F2[d]	Subgiant[d]	47[d]	−13.6

[a] Single star values and combined values of binary components are from the *Hipparcos* catalog. For the individual binary components see the text.

[b] C = constant. M = possible microvariable with amplitude less than 0.03 mag. P = periodic variable. B = star could not be classified as variable or constant.

[c] From this paper unless otherwise noted.

[d] Fekel et al. (2003).

References.—(1) Handler 1999; (2) T4 APT; (3) Eyer 1998.

magnitudes and $B-V$ color indices for the single stars, for the combined light of the close binaries, and for the individual components of the binary stars. The values for the single stars and the combined binary stars are from the *Hipparcos* catalog (ESA 1997). For the individual components of the binary stars, the V magnitudes and the $B-V$ color indices as well as the spectral classifications, rotational velocities, and radial velocities were determined as described in § 3.2 below.

3. SPECTROSCOPY

3.1. *Observations*

For nine of the 12 stars in this sample, Fekel et al. (2003) previously obtained spectroscopic observations at the Kitt Peak National Observatory (KPNO) with the coudé feed telescope, coudé spectrograph, and a TI CCD detector. Using the same telescope, spectrograph, and detector combination, we acquired spectra for 10 stars in our sample between 2002 September and 2003 April. In addition, we obtained a spectrum of HD 165645 in 2000 September. Combining all of the data, we have at least one KPNO spectrum of each star.

Most of our new spectrograms are centered at 6430 Å, cover a wavelength range of about 80 Å, and have a two-pixel resolution of 0.21 Å. We also acquired a spectrogram of the Hα region for each of the five composite-spectrum stars. Those observations have a wavelength range and resolution identical to the ones of the 6430 Å region. The typical signal-to-noise ratio of our spectra is between 100 and 250.

3.2. *Analyses*

The reduction and analysis of the spectroscopic data as well as estimates of the uncertainty in the results are described in Fekel et al. (2003). They previously provided spectral classes, v sin i values, and mean radial velocities for nine stars in our sample. However, analysis of our new spectra and new conclusions about duplicity have led to improved determinations of spectral classes and v sin i values (Table 1) for some of the stars. A colon after a value indicates greater than usual uncertainty. The luminosity classes were determined from the *Hipparcos* magnitudes and parallaxes (ESA 1997) as described in Fekel et al. (2003). New individual radial velocities are listed in Table 2 along with comments about those spectra.

For single stars and single-lined binaries, the determination of basic properties is relatively straight forward. However, seven stars in our sample are double-lined binaries, making determination of the magnitudes and colors of the individual components listed in Table 1 more difficult. First a V magnitude difference is needed. The spectrum addition method described in Fekel et al. (2003) produces a

TABLE 2
Individual Radial Velocities

HD (1)	Date (HJD −2,400,000) (2)	Radial Velocity ($km s^{-1}$) (3)	Comments (4)
7169	52,707.595	−15.3	Velocity of Hα core
		−18.6	Narrow-lined component
23874	52,705.630	−19.8	Broad component
		−18.0	Narrow component
	52,706.634	−14.6	Broad component
		−17.5	Narrow compnent
	52,707.628	−15.6	Velocity of Hα core
		−18.2	Narrow compnent
48271	52,536.988	−16.5	Very asymmetric lines
	52,538.004	−16.6	Very asymmetric lines
	52,756.630	−13.4	Very asymmetric lines
	52,758.619	−16.5	
64729	52,539.018	2.7	Very asymmetric lines
	52,540.022	11.1	
	52,541.017	5.1	
86358	52,705.836	14.9	SB2, primary
		74.9	Secondary
100215	52,705.868	−49.0	SB2, primary
		36.9	Secondary
	52,706.872	−45.0	Primary
		34.7	Secondary
	52,708.889	−40.2	Primary
		24.2	Secondary
	52,755.787	−46.5	Primary
		28.2	Secondary
	52,757.773	−37.8	Primary
		16.5	Secondary
	52,759.766	−23.9	Primary
		6.3	Secondary
105085	52,707.929	−4.4	Velocity of Hα core
		3.5	Narrow component
113867	52,707.991	0.9	Velocity of Hα core
		3.4	Narrow component
	52,755.832	13.5	Broad component
		2.0	Narrow component
160295	52,708.020	−48.3	Velocity of Hα core
		−45.5	Narrow component
165645	51,805.601	−14.7:	Very broad lines
171244	52,759.976	−13.8	

continuum magnitude difference, but it is just a minimum value if the secondary has a later spectral type than the primary, as is the case for the binaries in our sample. For HD 7169 and HD 23874, a magnitude difference was taken from the *Hipparcos* (ESA 1997) results. From our spectral types of the components in the other five double-lined systems, we adopted the canonical V magnitude differences given by Gray (1992). Next, the V magnitudes of the individual components of the seven double-lined binaries were computed from the V magnitude differences and the combined V magnitudes from *Hipparcos*. Finally, as for the V magnitude differences, the $B-V$ color indices corresponding to the spectral types of the components were taken from Gray (1992). Composite $B-V$ color indices for the double-lined binaries, calculated from the V magnitudes and color indices of the individual components, were compared with the observed values from the *Hipparcos* catalog (ESA 1997). While in reasonable agreement with the *Hipparcos* values, the calculated values are generally bluer than the *Hipparcos* values by ~0.02 mag. This could be due to a small amount of reddening or slightly later spectral types. As shown in Table 1, the resulting $B-V$ values for the primary components are a few hundreths of a magnitude smaller than the values for the combined binary system. Our results on these double-lined binaries supercede those of Fekel et al. (2003).

4. PHOTOMETRY

4.1. *Observations*

The photometric observations analyzed in this paper were acquired between 2001 January and 2002 July with the T3 0.4 m APT at Fairborn Observatory. The 0.4 m APT uses a temperature-stabilized EMI 9924B photomultiplier tube to acquire data successively through Johnson B and V filters. Each program star was measured in the following sequence, termed a group observation: K, S, C, V, C, V, C, V, C, S, K, in which K is a check star, C is the comparison star, V is the program star, and S is a sky reading. Three $V-C$ and two $K-C$ differential magnitudes are formed from each

TABLE 3

Program, Comparison, and Check Stars

Program Star	Comparison	Check	$\sigma_{(V-C)}$[a] (mag)	$\sigma_{(K-C)}$[a] (mag)	Individual Observations[b]
HD 7169	HD 7444	HD 6250	0.0148	0.0057	Table 4A
HD 23874	HD 25153	HD 25102	0.0168	0.0063	Table 4B
HD 48271	HD 48073	HD 47703	0.0239	0.0058	Table 4C
HD 64729	HD 64372	HD 61295	0.0144	0.0059	Table 4D
HD 86358	HD 86090	HD 86513	0.0193	0.0054	Table 4E
HD 100215................	HD 99579	HD 101620	0.0202	0.0051	Table 4F
HD 105085................	HD 105475	HD 104452	0.0357	0.0044	Table 4G
HD 113867................	HD 111591	HD 114724	0.0296	0.0066	Table 4H
HD 152896................	HD 152306	HD 150086	0.0257	0.0054	Table 4I
HD 160295................	HD 160346	HD 158921	0.0284	0.0076	Table 4J
HD 165645................	HD 166640	HD 165567	0.0052	0.0048	Table 4K
HD 171244................	HD 171232	HD 169780	0.0148	0.0075	Table 4L

[a] In the Johnson *B* photometric band.

[b] The individual observations are given in Table 4.

sequence and averaged together to create group means. Group mean differential magnitudes with internal standard deviations greater than 0.01 mag were rejected to eliminate the observations taken under nonphotometric conditions. The surviving group means were corrected for differential extinction with nightly extinction coefficients, transformed to the Johnson system with yearly mean transformation coefficients, and treated as single observations thereafter. Further information on the operation of the APT and the analysis of the data can be found in Henry (1995a, 1995b).

The 12 program stars were observed up to five times each clear night at intervals of 2–3 hr throughout their observing seasons. In addition, each star was observed continuously for several hours on one night near opposition. This observing strategy allows us to discriminate easily between γ Doradus variability (with typical periods of 0.3–3.0 days) and δ Scuti variability (with typical periods of 0.02–0.25 days). Table 3 lists the comparison and check stars used for each program star as well as the standard deviation of the $V - C$ and $K - C$ observations. The $\sigma_{(K-C)}$ values demonstrate that all comparison and check stars are constant to a few millimagnitudes, which is approximately the limit of precision for this APT. The individual photometric observations of each star are given in Table 4.

4.2. *Period Search*

Our period search technique, based on the method of Vaniĉek (1971), is described in Henry et al. (2001). For each program star, we analyzed the program star minus comparison star ($V - C$) differential magnitudes over the frequency range 0.01–30.0 day^{-1}, which corresponds to the period range 0.033–100 days. The results of our analyses are given in Table 5. The frequencies and corresponding periods are given only when they could be indentified in both passbands. The peak-to-peak amplitudes reported in column (7) of the table are determined for each frequency *without* prewhitening for the other frequencies; in cases where the star is a binary, the amplitudes are the observed values for the combined light of both components. The *B* amplitudes range from 86.9 mmag down to 5.7 mmag and average about 1.3 times larger than those in *V*. The individual B/V amplitude ratios and their uncertainties are listed for each frequency in column (8). Finally, times of minimum light for each frequency are given in column (9); in each case, the times of minimum in the two passbands agree within their uncertainites, so there is no detectable phase shift in our two color photometry.

The ($K - C$) differential magnitudes were also analyzed in the same way to search for periodicities that might exist in the comparison and check stars. None were found in any of the 24 stars. Thus, all of the periodicities reported in Table 5 can be confidently assigned to the program stars.

Least-squares spectra and phase diagrams for the *B* observations of the 12 program stars are shown in § 6 below. Although the analyses were done over the frequency range of 0.01–30.0 day^{-1}, the least-squares spectra are plotted over more restricted ranges since none of the stars exhibited variability above 5 day^{-1}. In particular, no higher frequencies that could be attributed to δ Scuti-type variability were found in any of our program stars. The plots of the least-squares spectra show the results of successively fixing each detected frequency until no further frequencies could be found in both passbands. To illustrate all the amplitudes clearly, the phase diagrams are plotted for each frequency after the data sets were prewhitened to remove the other detected frequencies.

TABLE 4A

Photometric Observations Of HD 7169

Date (HJD −2,400,000)	Var *B* (mag)	Var *V* (mag)	Chk *B* (mag)	Chk *V* (mag)
52,176.7570....................	−1.017	−0.275	−1.292	−0.726
52,176.8384....................	−1.018	−0.280	−1.293	−0.723
52,176.9251....................	−1.014	−0.272	−1.300	−0.721
52,177.0094....................	−0.996	−0.274	−1.292	−0.717
52,177.6958....................	−0.986	−0.252	−1.282	−0.718

Note—Table 4 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

5. COMPOSITE-SPECTRUM STARS

Fekel et al. (2003) obtained high-resolution spectroscopic observations of 34 γ Doradus candidates. Seven of those

TABLE 5

PROGRAM STAR RESULTS FROM PHOTOMETRIC ANALYSIS

HD (1)	Photometric Band (2)	Date Range (HJD −2,450,000) (3)	N_{obs} (4)	Frequency (day^{-1}) (5)	Period (days) (6)	Peak-to-Peak Amplitude (mmag) (7)	B/V Amplitude Ratio (8)	T_{min} (HJD − 2,450,000)
7169	*B*	2176.7570–2334.5994	302	1.8229 ± 0.0003	0.5486 ± 0.0001	37.2 ± 1.6	1.36 ± 0.09	2250.028 ± 0.004
				2.7639 ± 0.0004[a]	0.3618 ± 0.0001	6.6 ± 2.9	1.43 ± 0.94	2250.229 ± 0.026
				1.9250 ± 0.0003	0.5195 ± 0.0001	16.1 ± 2.7	1.33 ± 0.35	2250.444 ± 0.014
	V	2176.7570–2334.5994	300	1.8231 ± 0.0004	0.5485 ± 0.0001	27.3 ± 1.4		2250.027 ± 0.004
				2.7624 ± 0.0004[a]	0.3620 ± 0.0001	4.6 ± 2.3		2250.213 ± 0.029
				1.9249 ± 0.0003	0.5195 ± 0.0001	12.1 ± 2.2		2250.450 ± 0.015
23874	*B*	2176.8779–2359.6075	290	2.2565 ± 0.0002	0.4432 ± 0.0001	43.8 ± 1.4	1.40 ± 0.08	2250.385 ± 0.002
	V	2176.8779–2359.6075	284	2.2566 ± 0.0003	0.4431 ± 0.0001	31.2 ± 1.5		2250.393 ± 0.003
48271	*B*	2176.9792–2392.6401	371	0.9125 ± 0.0002	1.0959 ± 0.0003	35.6 ± 2.3	1.24 ± 0.13	2300.089 ± 0.012
	V	2176.9083–2401.6255	369	0.9124 ± 0.0002	1.0960 ± 0.0003	28.6 ± 2.0		2300.078 ± 0.012
64729	*B*	2180.9366–2418.6426	375	1.3797 ± 0.0002	0.7248 ± 0.0001	28.0 ± 2.0	1.44 ± 0.15	2300.523 ± 0.008
	V	2179.9391–2418.6426	360	1.3797 ± 0.0002	0.7248 ± 0.0001	19.4 ± 1.5		2300.540 ± 0.009
86358	*B*	2188.0142–2443.6508	419	1.1210 ± 0.0002	0.8921 ± 0.0002	24.0 ± 2.7	1.38 ± 0.24	2300.349 ± 0.016
				1.2898 ± 0.0002	0.7753 ± 0.0001	30.6 ± 2.5	1.31 ± 0.17	2300.258 ± 0.010
				1.1856 ± 0.0002	0.8435 ± 0.0001	19.4 ± 2.8	1.40 ± 0.31	2300.148 ± 0.019
				1.1428 ± 0.0002	0.8750 ± 0.0001	20.5 ± 2.8	1.27 ± 0.28	2300.784 ± 0.019
	V	2188.0142–2443.6508	400	1.1211 ± 0.0002	0.8920 ± 0.0002	17.4 ± 2.2		2300.354 ± 0.018
				1.2898 ± 0.0002	0.7753 ± 0.0001	23.3 ± 2.0		2300.259 ± 0.011
				1.1859 ± 0.0003	0.8432 ± 0.0002	13.9 ± 2.3		2300.164 ± 0.022
				1.1429 ± 0.0002	0.8750 ± 0.0002	16.1 ± 2.3		2300.773 ± 0.019
100215	*B*	2209.0261–2454.6748	449	1.3221 ± 0.0002	0.7564 ± 0.0001	34.0 ± 2.0	1.27 ± 0.12	2300.290 ± 0.007
				1.4226 ± 0.0003	0.7029 ± 0.0001	16.8 ± 2.4	1.08 ± 0.27	2300.038 ± 0.017
				1.6155 ± 0.0003	0.6190 ± 0.0001	5.7 ± 2.6	0.88 ± 0.78	2300.054 ± 0.045
				1.2781 ± 0.0002	0.7824 ± 0.0001	10.3 ± 2.6	1.66 ± 0.59	2300.309 ± 0.031
	V	2209.0261–2454.6748	444	1.3221 ± 0.0002	0.7564 ± 0.0001	26.7 ± 1.7		2300.290 ± 0.008
				1.4223 ± 0.0002	0.7031 ± 0.0001	15.5 ± 2.0		2299.994 ± 0.015
				1.6149 ± 0.0003	0.6192 ± 0.0001	6.5 ± 2.1		2300.018 ± 0.032
				1.2782 ± 0.0002	0.7824 ± 0.0001	6.2 ± 2.1		2300.347 ± 0.043
105085	*B*	2217.0270–2451.6515	390	1.4536 ± 0.0002	0.6879 ± 0.0001	86.9 ± 2.9	1.29 ± 0.07	2300.519 ± 0.004
				1.6982 ± 0.0002	0.5889 ± 0.0001	18.7 ± 5.6	1.19 ± 0.58	2300.056 ± 0.028
				1.5712 ± 0.0002	0.6365 ± 0.0001	25.6 ± 5.6	1.62 ± 0.50	2300.349 ± 0.022
				1.3503 ± 0.0002	0.7406 ± 0.0001	24.3 ± 5.5	1.28 ± 0.46	2300.001 ± 0.027
				1.3364 ± 0.0002	0.7483 ± 0.0001	12.0 ± 5.8	1.06 ± 0.87	2300.349 ± 0.055
	V	2217.0270–2452.7002	386	1.4537 ± 0.0002	0.6879 ± 0.0001	67.2 ± 2.3		2300.516 ± 0.004
				1.6983 ± 0.0002	0.5888 ± 0.0001	15.7 ± 4.4		2300.050 ± 0.026
				1.5707 ± 0.0002	0.6367 ± 0.0001	15.8 ± 4.4		2300.289 ± 0.028
				1.3501 ± 0.0002	0.7407 ± 0.0001	19.0 ± 4.4		2300.001 ± 0.027
				1.3369 ± 0.0002	0.7480 ± 0.0001	11.3 ± 4.4		2300.407 ± 0.046
113867	*B*	2238.0200–2453.6704	399	0.8887 ± 0.0003	1.1252 ± 0.0003	73.2 ± 2.6	1.25 ± 0.07	2350.455 ± 0.006
				2.0084 ± 0.0002[a]	0.4979 ± 0.0001	18.3 ± 4.6	1.26 ± 0.52	2350.133 ± 0.020
				1.7785 ± 0.0002[a]	0.5623 ± 0.0001	15.3 ± 4.6	0.95 ± 0.54	2350.179 ± 0.027
				2.8965 ± 0.0003	0.3452 ± 0.0001	9.5 ± 4.7	0.68 ± 0.77	2350.057 ± 0.027
				0.8841 ± 0.0003[a]	1.1311 ± 0.0003	30.6 ± 4.4	1.11 ± 0.27	2350.422 ± 0.026
	V	2234.0270–2456.6625	398	0.8887 ± 0.0003	1.1252 ± 0.0004	58.6 ± 2.3		2350.452 ± 0.007
				2.0082 ± 0.0003[a]	0.4980 ± 0.0001	14.5 ± 3.9		2350.121 ± 0.021
				1.7786 ± 0.0003[a]	0.5622 ± 0.0001	16.1 ± 3.8		2350.184 ± 0.021
				2.8964 ± 0.0002	0.3453 ± 0.0001	13.9 ± 3.8		2350.047 ± 0.015
				0.8841 ± 0.0003[a]	1.1311 ± 0.0004	27.5 ± 3.6		2350.416 ± 0.023
152896	*B*	2277.0549–2456.7297	332	1.3384 ± 0.0002	0.7472 ± 0.0001	56.0 ± 3.7	1.35 ± 0.13	2350.463 ± 0.008
				1.2972 ± 0.0002	0.7709 ± 0.0001	35.2 ± 4.8	1.44 ± 0.28	2350.252 ± 0.016
	V	2277.0549–2456.6620	329	1.3385 ± 0.0002	0.7471 ± 0.0001	41.5 ± 2.7		2350.479 ± 0.008
				1.2971 ± 0.0003	0.7710 ± 0.0002	24.5 ± 3.5		2350.245 ± 0.017
160295	*B*	2312.0367–2456.8388	244	1.3240 ± 0.0002	0.7553 ± 0.0001	72.5 ± 2.7	1.34 ± 0.08	2400.151 ± 0.004
				1.4484 ± 0.0003	0.6904 ± 0.0001	23.6 ± 5.4	1.43 ± 0.48	2400.260 ± 0.025
				1.5365 ± 0.0003	0.6508 ± 0.0001	8.5 ± 5.6	1.42 ± 1.38	2400.394 ± 0.069
	V	2307.0535–2456.8388	248	1.3240 ± 0.0002	0.7553 ± 0.0001	54.0 ± 2.1		2400.150 ± 0.005
				1.4482 ± 0.0003	0.6905 ± 0.0001	16.5 ± 4.1		2400.259 ± 0.027
				1.5357 ± 0.0002	0.6512 ± 0.0001	6.0 ± 4.3		2400.445 ± 0.072
165645	*B*	1934.0560–2089.7799	258	2.3752 ± 0.0004	0.4210 ± 0.0001	6.9 ± 1.0	1.33 ± 0.32	2050.156 ± 0.009
	V	1934.0560–2089.7799	256	2.3754 ± 0.0004	0.4210 ± 0.0001	5.2 ± 0.9		2050.150 ± 0.012
171244	*B*	2312.0307–2462.8176	223	0.9960 ± 0.0004	1.0040 ± 0.0004	35.4 ± 1.8	1.62 ± 0.12	2400.502 ± 0.007
				1.0437 ± 0.0002	0.9581 ± 0.0002	18.7 ± 2.6	1.82 ± 0.33	2400.244 ± 0.022
	V	2313.0258–2462.8176	223	0.9956 ± 0.0003	1.0044 ± 0.0003	21.9 ± 1.6		2400.504 ± 0.010
				1.0442 ± 0.0003	0.9577 ± 0.0003	10.3 ± 2.0		2400.224 ± 0.029

NOTE.—The individual observations are given in Table 4 available in machine readable format in the electronic edition of the Astronomical Journal.

[a] Identification of true frequency somewhat ambiguous because of aliasing.

late A or early F stars had spectra that showed metallic lines having composite line profiles that consist of a narrow component near the center of a broad line. Following Mantegazza & Poretti (1996); Fekel et al. (2003) suggested that the narrow lines in the composite spectra may come from circumstellar shells, while the broad lines are formed in the photospheres of the stars. If correct, the stars would be A or F shell stars. Alternatively, the seven stars may be binaries consisting of a rapidly rotating late A- or early F-type primary and a slowly rotating F- or G-type secondary. To determine the correct explanation for each of the composite-spectrum stars, we obtained spectra of the Hα line for those stars, as well as for three A or early F shell stars plus two normal stars. Figure 1 shows the Hα region for the two normal F0 V stars, HR 2852 and HR 4288, and three shell stars, HR 1615, HR 4733 = 14 Comae, and HR 7731 = 21 Vulpeculae. Similar to the spectra presented by Slettebak (1986) for several mid-A to F shell stars, the Hα line of each shell star in Figure 1 is a pure absorption feature with a narrow absorption core from a shell. In contrast, the two normal F stars have no such sharp absorption cores.

Figure 2 shows the Hα spectra of five composite-spectrum stars identified by Fekel et al. (2003) and observed photometrically in this paper. Figure 3 presents similar spectra of two additional composite-spectrum stars, HD 108100 from Henry & Fekel (2002) and HD 202444 from Fekel et al.(2003). The Hα profiles of the seven stars are similar to each other and to the profiles of the two normal stars in Figure 1. None of the composite-spectrum stars have the sharp Hα absorption cores seen in the shell stars, arguing against the shell star interpretation.

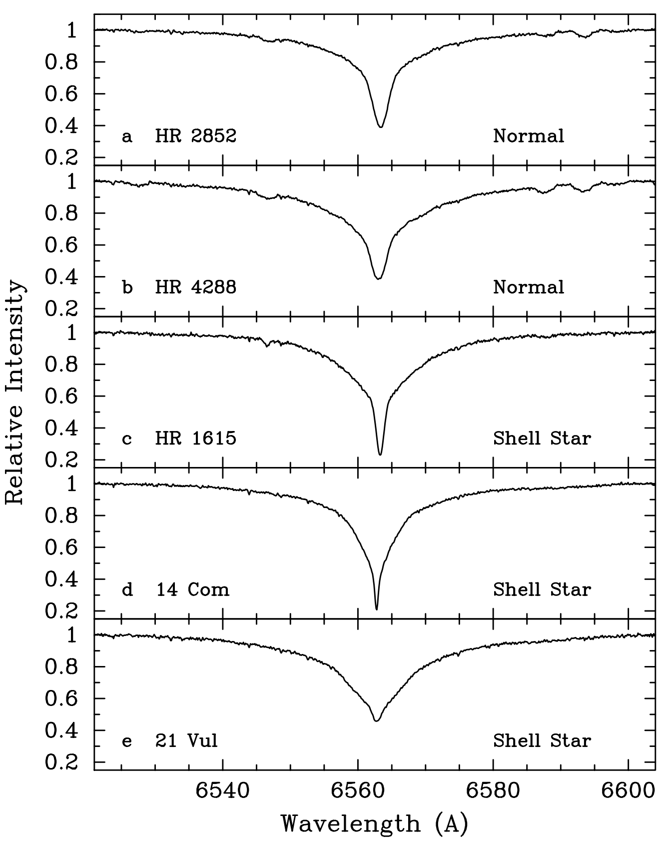

FIG. 1.— Hα region of normal early-F stars: (*a*) HR 2852 and (*b*) HR 4288. The same region for three mid-A to F shell stars: (*c*) HR 1615, (*d*) HR 4733 = 14 Com, and (*e*) HR 7731 = 21 Vul. Note the sharp Hα cores seen in the shell stars.

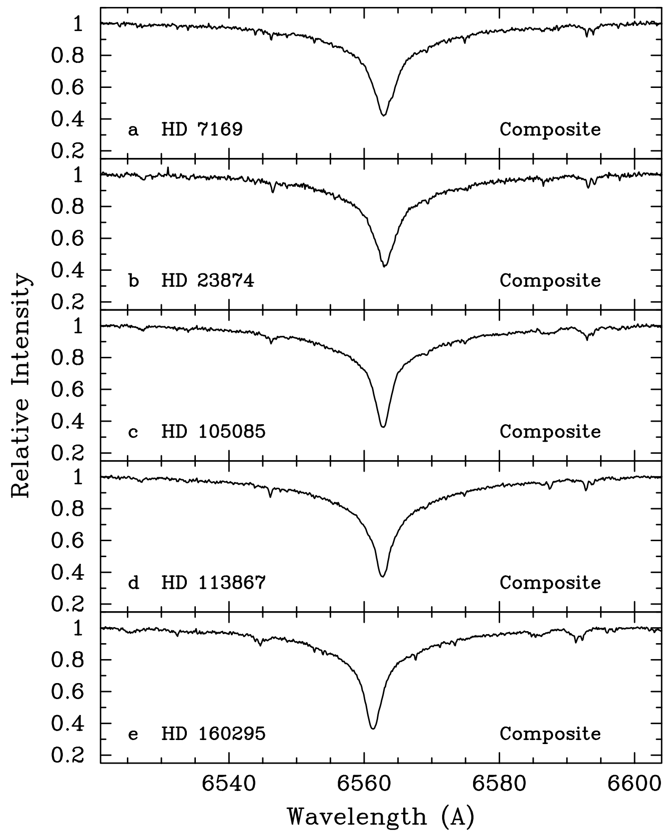

FIG. 2.—Hα region for five composite-spectrum stars: (*a*) HD 7169, (*b*) HD 23874, (*c*) HD 105085, (*d*) HD 113867, and (*e*) HD 160295. Note the lack of sharp Hα cores.

The spectrum of one of the three shell stars, 14 Com, has been extensively examined and analyzed by Dominy & Smith (1977). They found this well-known, rapidly rotating, F0 shell star to have hundreds of shell lines at blue wavelengths and discovered little evidence of rapid expansion or collapse of its shell. For 14 Com, in addition to an Hα spectrum, we obtained a spectrum in the 6430 Å region. The Fe I, Fe II, and Ca I lines that dominate this region of the spectrum appear quite broad and come from the star's photosphere. Each of the three Fe II lines also has a narrow

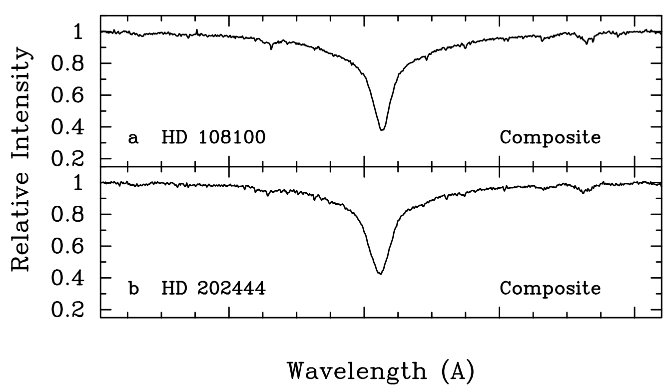

FIG. 3.—Hα region for two composite spectrum stars: (*a*) HD 108100 and (*b*) HD 202444. Note the lack of sharp Hα cores.

component, presumably from the shell, but the Fe I and Ca I lines do not have such additional components. This result is in contrast to our composite-spectrum stars for which every line of Fe I, Fe II, and Ca I at 6430 Å has both a narrow and a broad component. From this comparison and that of the Hα features, we conclude that the seven composite-spectrum stars are binaries rather than shell stars.

6. NOTES ON INDIVIDUAL STARS

6.1. *HD 7169*

Discovered to be a visual double star by *Hipparcos* (ESA 1997), Fekel et al. (2003) found HD 7169 to have a composite-spectrum. From the Hα spectra discussed above, we conclude that the composite spectrum of HD 7169 represents the two visual-binary components, which have a V magnitude difference of $\sim$2.3 mag (ESA 1997). With this information we reexamined the spectrum of HD 7169 in the 6430 Å region. We find a good representation of its spectrum with a broad-lined component of F1 spectral class and $v \sin i = 100$ km s^{-1} plus a narrow-lined component of G5: V and v sin $i = 5$: km s^{-1}. The *Hipparcos* parallax (ESA 1997) indicates that the components are dwarfs.

HD 7169 appears on the list of prime γ Doradus candidates of Handler (1999), where he finds a period of 0.549 days and possible additional periods around 1.25 days from his analysis of the *Hipparcos* photometry. The least-squares spectra of our B observations are plotted in Figure 4, and the results of our frequency analysis are given in Table 5. We find three periods of 0.5486, 0.3618, and 0.5195 days with B amplitudes of 37.2, 6.6, and 16.1 mmag, respectively. The observations are phased with these periods and the times of minimum given in Table 5 and plotted in Figure 5, which shows clear sinusoidal variations at all three periods. We find the same three periods in our V observations but note that the identification of our second period is somewhat ambiguous due to aliasing; a possible alternative period identification is 0.568 days. Thus, we confirm Handler's first period and add two additional periods of our own. We find no sign of Handler's additional periods around 1.25 days. The ratios of the photometric amplitude in B to the amplitude in V for our three periods have a weighted mean of 1.36 ± 0.09, consistent with other γ Doradus pulsators (e.g., Henry & Fekel 2002) and inconsistent with the ellipticity effect or starspots (Henry et al. 2000, their Table 8). Possible starspot variability at our observed periods in the G5 secondary is also excluded by its low rotational velocity. Therefore, the observed photometric variability in HD 7169 must arise in the F1 primary of this visual double. Given the F1 dwarf classification of the primary, the multiple periods in the γ Doradus period range, and the B/V amplitude ratio, we confirm the primary as a new γ Doradus variable.

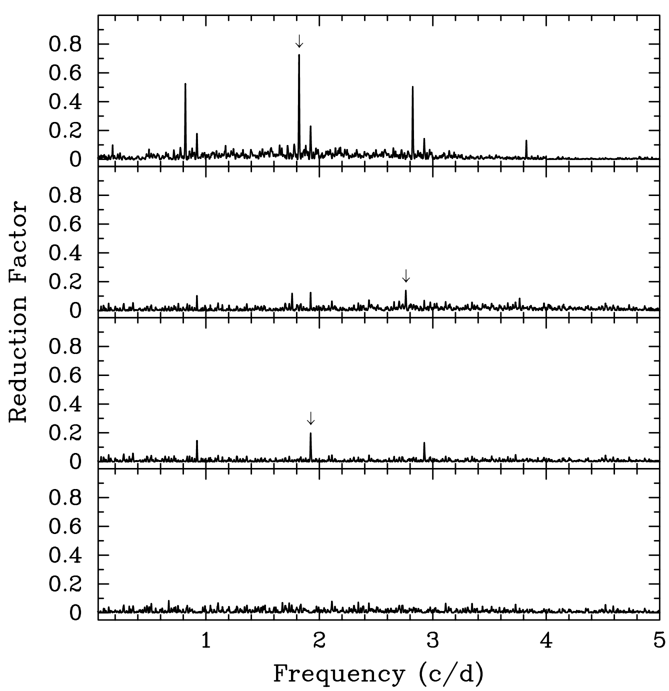

FIG. 4.—Least-squares spectra of the HD 7169 Johnson B data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies (*top to bottom*): 1.8229, 2.7639, and 1.9250 day^{-1}. All three frequencies were confirmed in the Johnson V data set.

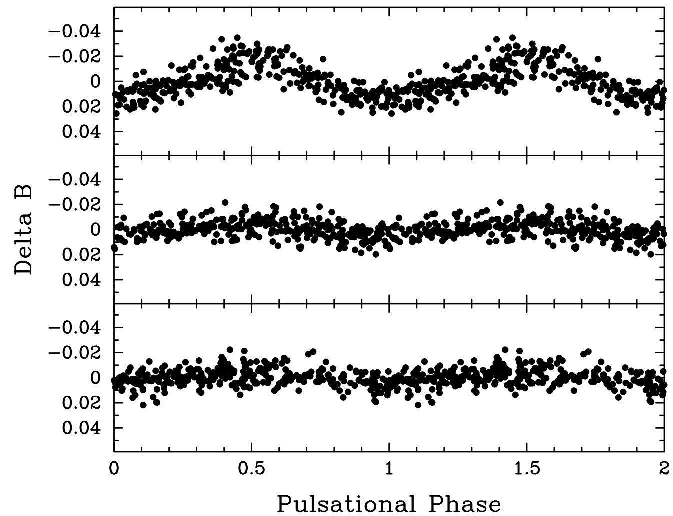

FIG. 5.—Johnson B photometric data for HD 7169, phased with the three frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 1.8229, 2.7639, and 1.9250 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

6.2. *HD 23874*

Like HD 7169, this composite-spectrum star, observed by Fekel et al. (2003), is a known visual binary. Since they made only a single observation, we obtained three additional spectra. The new velocities of the narrow and broad-lined components are listed in Table 2. Mean velocities are -19.8 ± 1.8 km s^{-1} for the broad component from three observations and -17.4 ± 0.1 km s^{-1} for the narrow component (Table 1) from four observations. Thus, neither component shows evidence of significant short-period variability.

From observations taken with the Tycho instrument of *Hipparcos*, Fabricius & Makarov (2000) found a magnitude difference of about 1.4 mag for the visual components of HD 23874, which Fekel et al. (2003) converted to $\Delta V = 1.45$ mag. Fekel et al. (2003) noted that the magnitude difference of the components in the composite spectrum was similar to that of the visual pair. The $B-V$ colors of the two visual components, however, are 0.42 for the

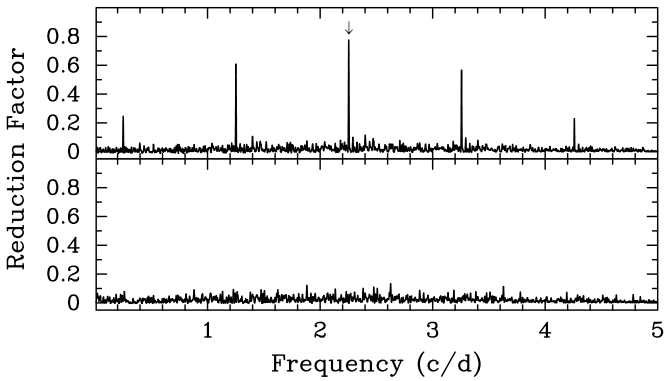

FIG. 6.—Least-squares spectra of the HD 23874 Johnson *B* data set. The arrow in the top panel indicates the single detected frequency at 2.2565 day^{-1}. The bottom panel shows the least-squares spectrum with the 2.2565 day^{-1} frequency fixed. The same frequency was confirmed in the Johnson *V* data set.

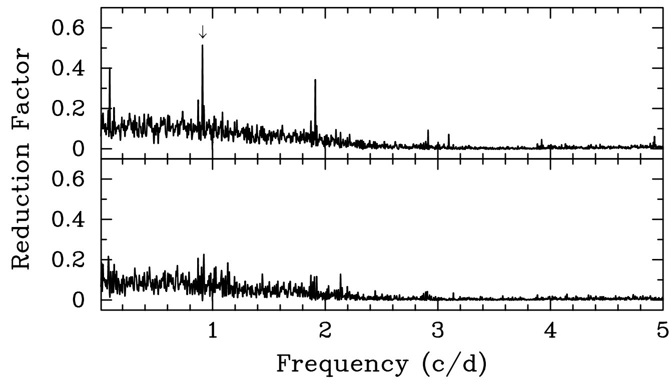

FIG. 8.—Least-squares spectra of the HD 48271 Johnson *B* data set. The arrow in the top panel indicates the single detected frequency at 0.9125 day^{-1}. The bottom panel shows the least-squares spectrum with the 0.9125 day^{-1} frequency fixed. The same frequency was confirmed in the Johnson *V* data set.

primary and 0.31 for the secondary, results that are inconsistent with the spectroscopic observations. Those colors and the large magnitude difference suggest that the primary is a giant and the secondary a dwarf, but the *Hipparcos* parallax indicates that both components are dwarfs. Even making the system a triple star does not solve the photometric problems.

Despite the color discrepancy, we presume that the narrow- and broad-lined components seen in the spectrum of HD 23874 correspond to the visual components and adopt a ΔV value of 1.45 mag. Our best combination of reference-star spectra for HD 23874 results in F1 and F8: for the broad-lined and narrow-lined components, respectively.

HD 23874 is a prime γ Doradus candidate from Handler (1999) who cited a period of 0.443 days and possible additional periods around 0.75 days. We find only a single period of 0.4432 days in our APT photometry with an amplitude of 44 mmag in *B* (Figs. 6 and 7; Table 5). The light curve phased with this period closely approximates a sinusoid with residuals of only 0.0078 mag, i.e., not much larger than the precision of the observations. Thus, we confirm Handler's first period but find no evidence for additional periods around 0.75 days. The B/V amplitude ratio is 1.40 ± 0.08, indicting the variability is due to pulsation rather than the ellipticity effect or starspots. Starspot variations at this period are also excluded in the F8 secondary by its low rotational velocity. Given the F1 dwarf spectral type of the primary star, the 0.44316 day variability, the B/V amplitude ratio, and the lack of short-period radial velocity variability, we confirm that the F1 primary in HD 23874 is a new γ Doradus variable.

6.3. *HD 48271*

Our spectroscopic observations are the first ones to be obtained for HD 48271, and three of the four red-wavelength spectra show very asymmetric lines. While it is possible that HD 48271 is an unresolved double-lined binary, we have analyzed it as a single star. The line asymmetries make determination of its properties more difficult than usual. We found a spectral class of F0, while the *Hipparcos* magnitude and parallax (ESA 1997) reveal that HD 48271 is a dwarf. We also determined a projected rotational velocity of 32: km s^{-1}. Our four radial velocities (Table 2) show no large velocity variability and result in a mean value of -15.8 ± 0.8 km s^{-1}. The asymmetric line profiles and low-level velocity variability presumably result from the nonradial pulsation of the star. We conclude that HD 48271 is single.

HD 48271 is on the list of prime γ Doradus candidates of Handler (1999) with possible photometric periods of 1.907 and 1.151 days in the *Hipparcos* data. We could positively identify only a single frequency at 0.9125 day^{-1} in our APT data (Figs. 8 and 9; Table 5), corresponding to a period of 1.0959 days, although slight additional power is suggested near this same period in our power spectra. Our 1.0959 day period is significantly different from either of Handler's periods, but we do see a possible weak second frequency around 0.86 day^{-1} (Fig. 8), corresponding closely to Handler's second period. The B/V amplitude ratio for the 1.0959 day period is 1.24 ± 0.13, so the variability is due to pulsation rather than ellipticity or starspot effects. After removing the 1.0959 day period, the rms of our photometric residuals is 0.016 mag, much higher than the typical 0.005

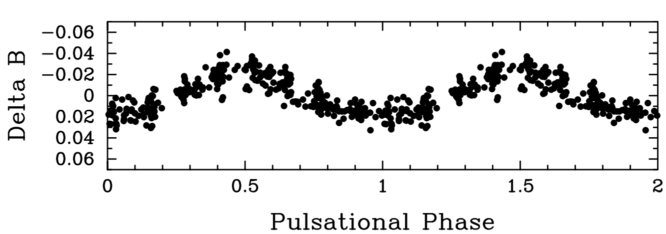

FIG. 7.—Johnson *B* photometric data for HD 23874, phased with the single frequency of 2.2565 day^{-1} and time of minimum from Table 5.

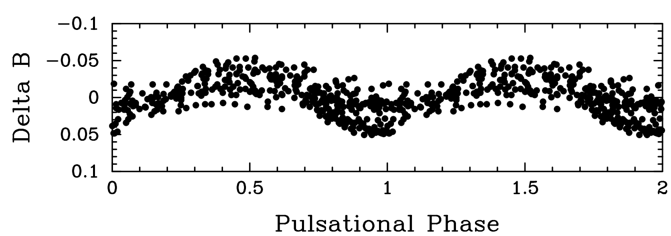

FIG. 9.—Johnson *B* photometric data for HD 48271, phased with the single frequency of 0.9125 day^{-1} and time of minimum from Table 5.

mag precision of our observations, and suggests additional variability in HD 48271. The light curve in Figure 9, phased with the 1.0959 day period, also suggests additional variability, so our single period clearly does not explain all of the photometric variation in HD 48271. Martín, Bossi, & Zerbi (2003) acquired 62 observations over four nights in 2001 January with the 90 cm telescope at Observatorio de Sierra Nevada, Spain. They also found a single period, 1.089 days, which is close to our period. More extensive photometric observations of HD 48271 are required to understand its variability fully. Nevertheless, given its spectral type, photometric period, B/V amplitude ratio, and lack of short-period radial velocity variability, we confirm that HD 48271 is a γ Doradus variable.

6.4. *HD 64729*

We obtained three spectroscopic observations of HD 64729 in the 6430 Å region, which show that its lines are asymmetric. From the spectrum with the most symmetric lines we determined a spectral class of F0, while the *Hipparcos* magnitude and parallax result in a dwarf luminosity class. Our projected rotational velocity is 65 km s^{-1}, and our mean of three radial velocities is 6.3 ± 1.4 km s^{-1}. Our results are consistent with those of Grenier et al. (1999), who classified the star as F2 IV–V and determined a radial velocity of 10.4 ± 4.5 km s^{-1} from three observations.

The photometric variability of HD 64729 was discovered with the T4 0.75 m APT when we used it as a comparison star in our program to observe brightness changes in solar-type stars (Henry 1999); there is no evidence for variability of this star in the *Hipparcos* photometry (ESA 1997). Our new T3 APT photometry presented in this paper exhibits a strong periodicity at 0.7248 days with an amplitude of 28 mmag in B and evidence for additional low-amplitude variability (Figs. 10 and 11; Table 5). The rms scatter of the observations after removing the 0.7248 day period is still high at 0.011 mag, strengthening the likelihood that additional variability is present. However, we are not able to identify uniquely any additional periods because of their low amplitude and 1 day aliases. The B/V amplitude ratio for our 0.7248 day period is 1.44 ± 0.15, so the photometric variability is due to pulsation rather than ellipticity or spots.

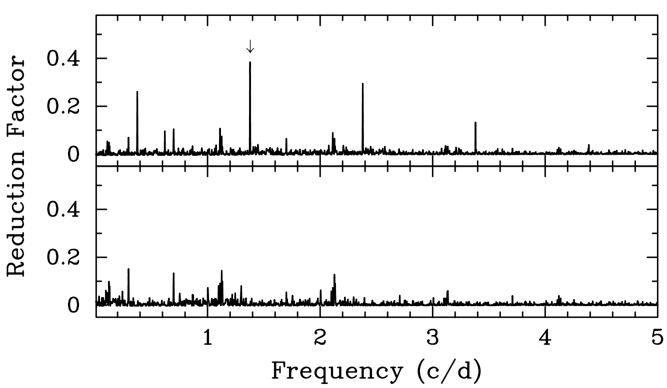

Fig. 10.—Least-squares spectra of the HD 64729 Johnson B data set. The arrow in the top panel indicates the single detected frequency at 1.3797 day^{-1}. The bottom panel shows the least-squares spectrum with the 1.3797 day^{-1} frequency fixed. The same frequency was confirmed in the Johnson V data set.

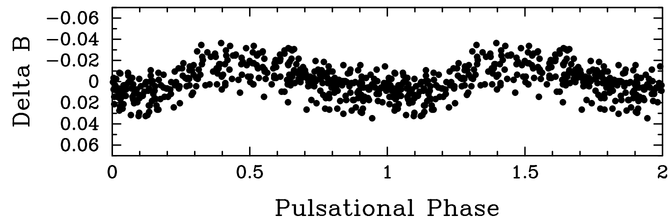

Fig. 11.—Johnson B photometric data for HD 64729, phased with the single frequency of 1.3797 day^{-1} and time of minimum from Table 5.

Therefore, we confirm HD 64729 as a new γ Doradus variable.

6.5. *HD 86358*

Fekel et al. (2003) concluded that HD 86358 is an unresolved double-lined binary with F0 and F5: dwarf components. We obtained one additional spectrum, but it, like the previous ones, shows partially blended components. The new radial velocities are listed in Table 2. We have adopted $\Delta V = 0.9$ mag.

Handler (1999) lists HD 86358 as one of his prime γ Doradus candidates with periods of 0.775 and 0.844 days. In our APT observations, we find four closely-spaced periods of 0.8921, 0.7753, 0.8435, and 0.8750 days with B amplitudes of 24, 31, 19, and 20 mmag, respectively (Figs. 12 and 13; Table 5). Thus, we confirm Handler's two periods

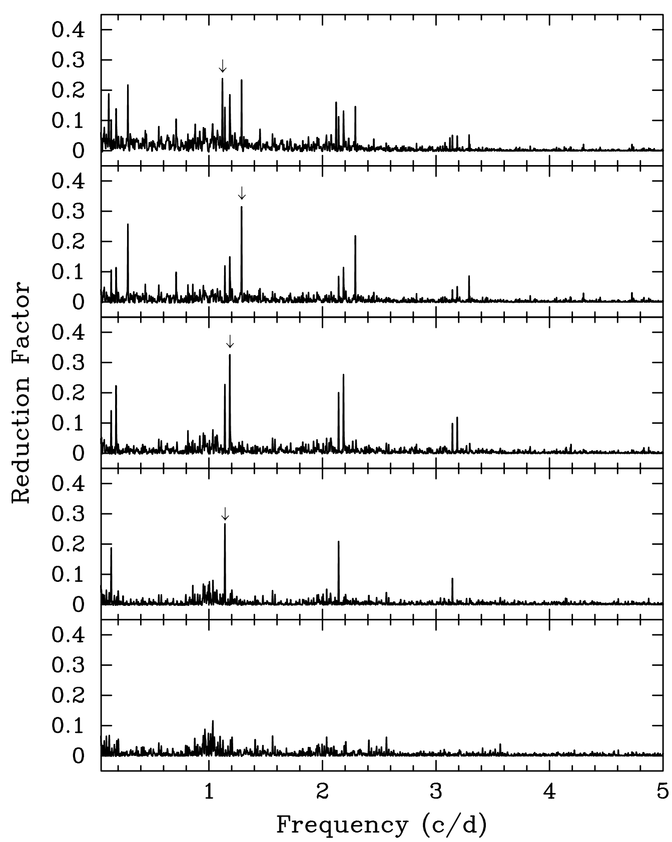

Fig. 12.—Least-squares spectra of the HD 86358 Johnson B data set, showing the results of progressively fixing the four detected frequencies. The arrows indicate the four frequencies (*top to bottom*): 1.1210, 1.2898, 1.1856, and 1.1428 day^{-1}. All four frequencies were confirmed in the Johnson V data set.

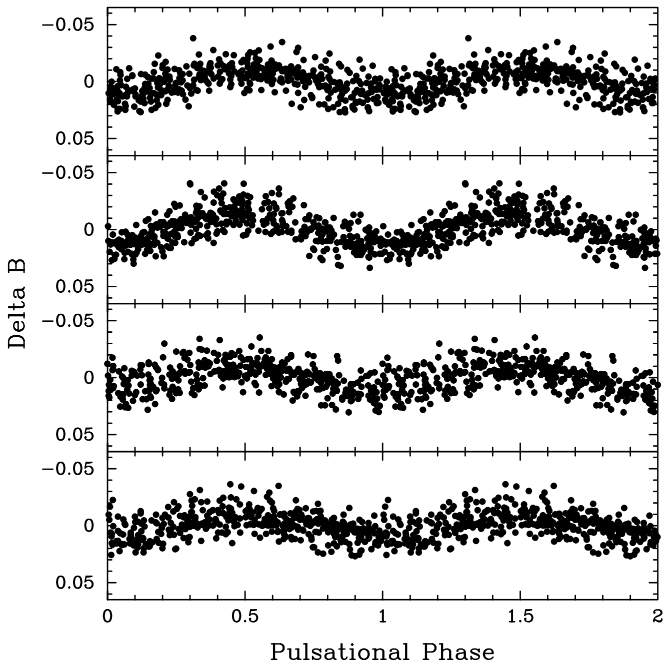

FIG. 13.—Johnson B photometric data for HD 86358, phased with the four frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 1.1210, 1.2898, 1.1856, and 1.1428 day^{-1}. For each panel, the data set has been prewhitened to remove the other three known frequencies.

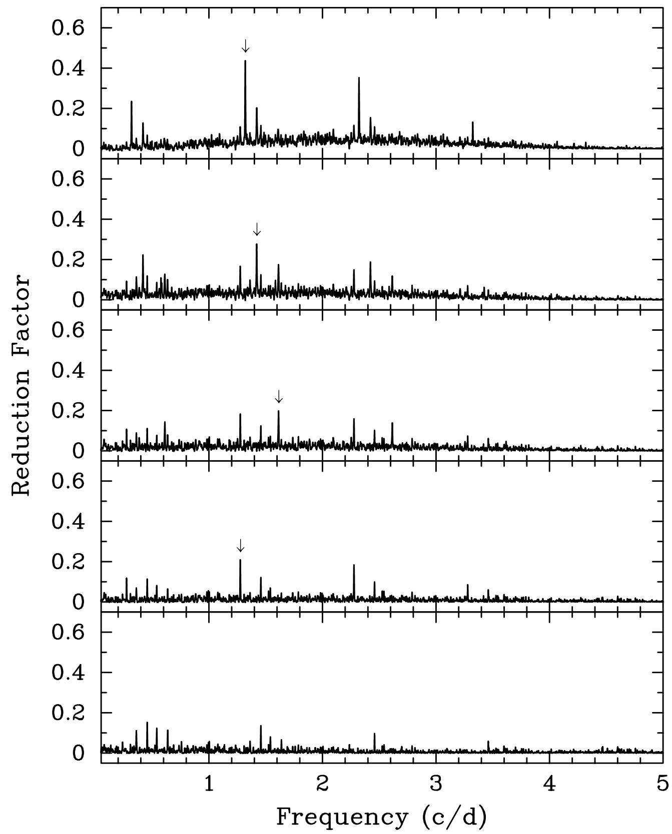

FIG. 14.—Least-squares spectra of the HD 100215 Johnson B data set, showing the results of progressively fixing the four detected frequencies. The arrows indicate the four frequencies (*top to bottom*): 1.3221, 1.4226, 1.6155, and 1.2781 day^{-1}. All four frequencies were confirmed in the Johnson V data set.

and find two more. The light curve is sinusoidal when phased with each of the four periods. The rms of the photometric residuals after removing the four periods is 0.010 mag, and the bottom panel of Figure 12 also indicates that some residual power may still be present around 1 day^{-1}. However, we cannot uniquely identify an additional period in both the B and V data. The weighted mean B/V amplitude ratio for our four periods is 1.33 ± 0.12, indicating that variability is due to pulsations and not ellipticity or starspots. Therefore, we confirm the F0 dwarf component of HD 86358 as a γ Doradus star.

6.6. *HD 100215*

From three observations Grenier et al. (1999) concluded that HD 100215 has a variable velocity. At red wavelengths Fekel et al. (2003) found it to be a double-lined spectroscopic binary. The lines of the two components have very unequal strength, leading Fekel et al. (2003) to assign spectral classes of F1 and G0:. We have obtained six additional spectra, which for the first time show resolved double lines. Our observations plus the two of Fekel et al. (2003) result in a preliminary orbital period of 12.2 days. More velocities will be necessary to confirm this period and determine orbital elements. The additional spectra enable us to obtain improved $v \sin i$ values of 19 and 12 km s^{-1} for the primary and secondary, respectively. We also redetemined the spectral classes and found the best fit to the new spectra is a combination of A9 and G5: V, which have $\Delta V = 2.6$ mag. The *Hipparcos* parallax indicates that both components are dwarfs.

This star is a prime γ Doradus candidate with periods of 0.757 and 0.434? days according to Handler (1999). Our analysis of the APT data gives results very similar to HD 86358 (above). We find four closely spaced periods of 0.7564, 0.7029, 0.6190, and 0.7824 days with B amplitudes of 34, 17, 6, and 10 mmag, respectively (Figs. 14 and 15; Table 5). Therefore, we not only confirm Handler's first period but also find three others. The light curve appears to be sinusoidal when phased with each of the four periods. The rms of the photometric residuals after removing the four periods is 0.010 mag, and the bottom panel of Figure 14 indicates possible additional variability. However, as for HD 86358, we cannot uniquely identify a fifth period in both the B and V data. The weighted mean B/V amplitude ratio for our four periods is 1.25 ± 0.11, indicating variability due to pulsations rather than ellipticity or starspots. Therefore, we confirm the A9 primary component of HD 100215 as a γ Doradus variable.

6.7. *HD 105085*

Fekel et al. (2003) found HD 105085 to have a composite spectrum but, unlike HD 7169 and HD 23874, no visual duplicity was detected by *Hipparcos* (ESA 1997). Nevertheless, based on its composite spectrum and Hα profile, we conclude that it is a binary. Four sets of radial velocities have similar means for the broad-lined component (Fekel et al. 2003), suggesting that it is not a short-period binary.

As a result of our binary conclusion, we reexamined the composite-spectrum of HD 105085. Our best spectrum-addition results produced spectral classes of F0 and G5: V for the broad-lined and narrow-lined components, respectively. We have adopted $\Delta V = 2.4$ mag for the

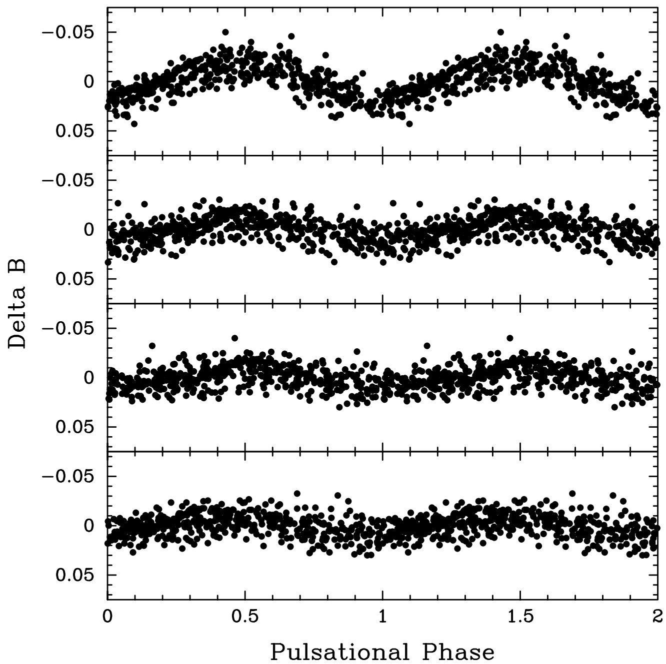

FIG. 15.—Johnson *B* photometric data for HD 100215, phased with the four frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 1.3221, 1.4226, 1.6155, and 1.2781 day^{-1}. For each panel, the data set has been prewhitened to remove the other three known frequencies.

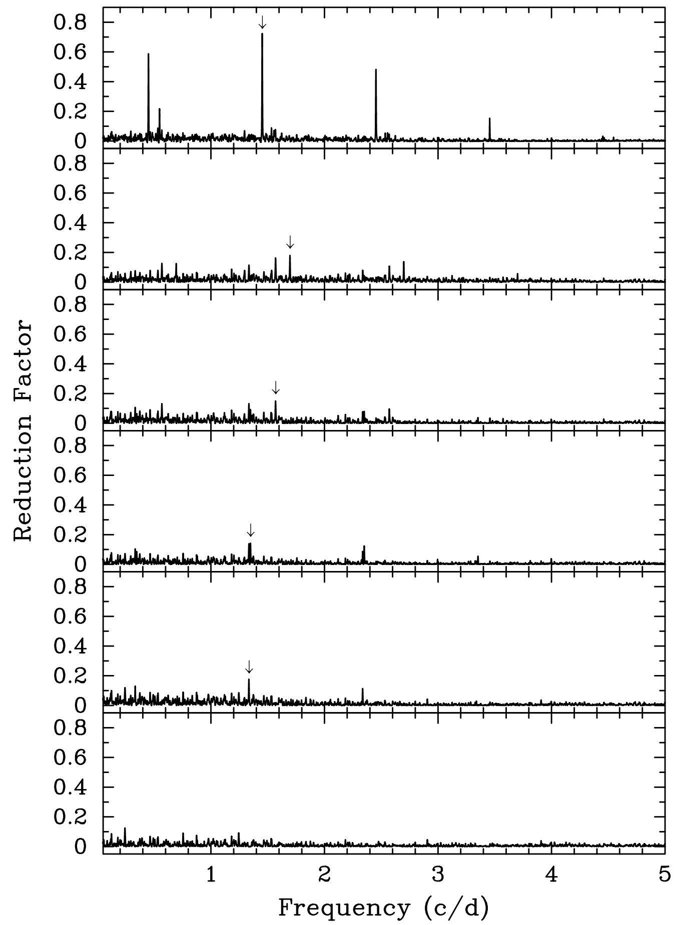

FIG. 16.—Least-squares spectra of the HD 105085 Johnson *B* data set, showing the results of progressively fixing the five detected frequencies. The arrows indicate the five frequencies (*top to bottom*): 1.4536, 1.6982, 1.5712, 1.3503, and 1.3364 day^{-1}. All five frequencies were confirmed in the Johnson *V* data set.

components. The *Hipparcos* parallax indicates that both stars are dwarfs.

Eyer (1998) listed this star as a γ Doradus candidate. We find five closely spaced periods of 0.6879, 0.5889, 0.6365, 0.7406, and 0.7483 days in our APT photometry with *B* amplitudes of 87, 19, 26, 24, and 12 mmag, respectively (Figs. 16 and 17; Table 5). All five periods give approximately sinusoidal phase curves. The rms of the photometric residuals after removing the five periods is 0.013 mag, indicating possible additional variability, but we cannot identify any further periodicity. The weighted mean B/V amplitude ratio for the five periods is 1.29 ± 0.07, indicating variability due to pulsations and not ellipticity or starspots. Therefore, we confirm the F0 primary component of HD 105085 as a γ Doradus variable.

6.8. *HD 113867*

Fekel et al. (2003) identified HD 113867 as a composite-spectrum star having broad and narrow lines with similar equivalent widths. Thus, unlike the other composite-spectrum stars discovered by Fekel et al. (2003), the narrow-lined component appears to dominate the spectrum (Fig. 6 of Fekel et al. 2003). As a result, Fekel et al. (2003) suggested that it may be a binary rather than a shell star, a conclusion supported by our Hα observation. Although *Hipparcos* observations (ESA 1997) produced no evidence of visual duplicity, orbital motion appears evident in the slowly changing radial velocity of the components. In 2000 July the narrow component had a mean velocity of 8.8 km s^{-1}, while its velocity was 3.8 in 2002 February, 3.4 km s^{-1} in 2003 March, and 2.0 km s^{-1} in 2003 April. The radial velocity of the broad component is very difficult to measure. Nevertheless, its velocity appears to be increasing with time, from a mean of 4.7 km s^{-1} in 2000 July to 13.5 km s^{-1} in 2003 April, indicating that the broad and narrow components are part of the same binary system. From Fekel et al. (2003) we adopt a magnitude difference of 0.4 in the Johnson *V* band with the broad component corresponding to the A9 primary and the narrow component corresponding to the F1 secondary. The *Hipparcos* parallax results in a dwarf luminosity class for each star.

Handler (1999) included HD 113867 in his list of prime γ Doradus candidates and found periods of 1.073 and 0.762 days. We find five periods between 0.35 and 1.13 days in our APT photometry (Figs. 18 and 19; Table 5); our period with the largest amplitude, 1.1252 days, is closest to Handler's first period, but none of our other periods matches his second period. We note in Table 5 that some of our period identifications in Figure 18 are uncertain because of aliasing. However, all five of the periods we identified give approximately sinusoidal phase curves in Figure 19. The rms of the photometric residuals after removing the five periods is 0.010 mag, indicating possible additional variability, but we find no additional periods. Further intensive photometric monitoring is needed to identify all of the periods with complete confidence. The weighted mean B/V amplitude ratio for the five periods is 1.23 ± 0.07, implying variability due to pulsations and not ellipticity or starspots. Therefore, we confirm that HD 113867 is a γ Doradus star.

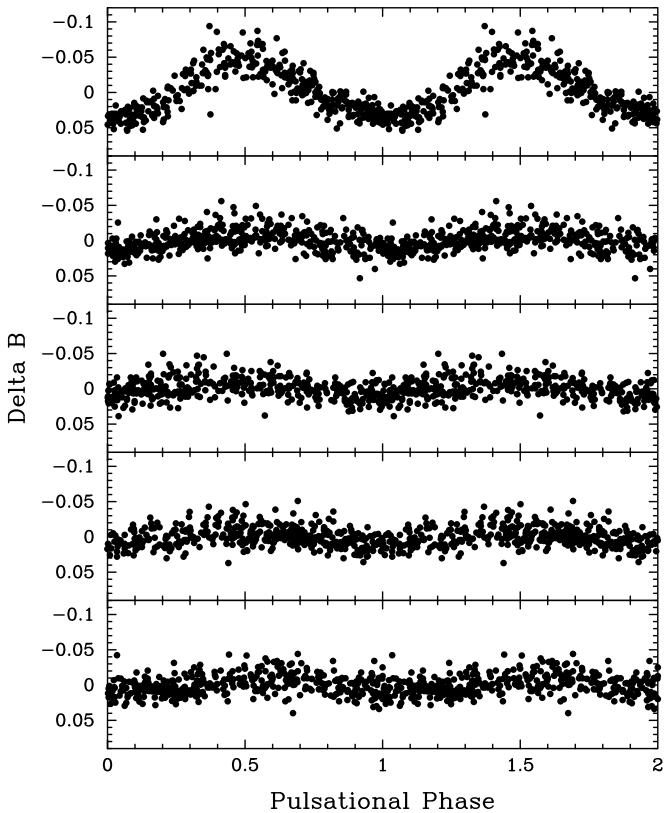

FIG. 17.—Johnson *B* photometric data for HD 105085, phased with the five frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 1.4536, 1.6982, 1.5712, 1.3503, and 1.3364 day^{-1}. For each panel, the data set has been prewhitened to remove the other four known frequencies.

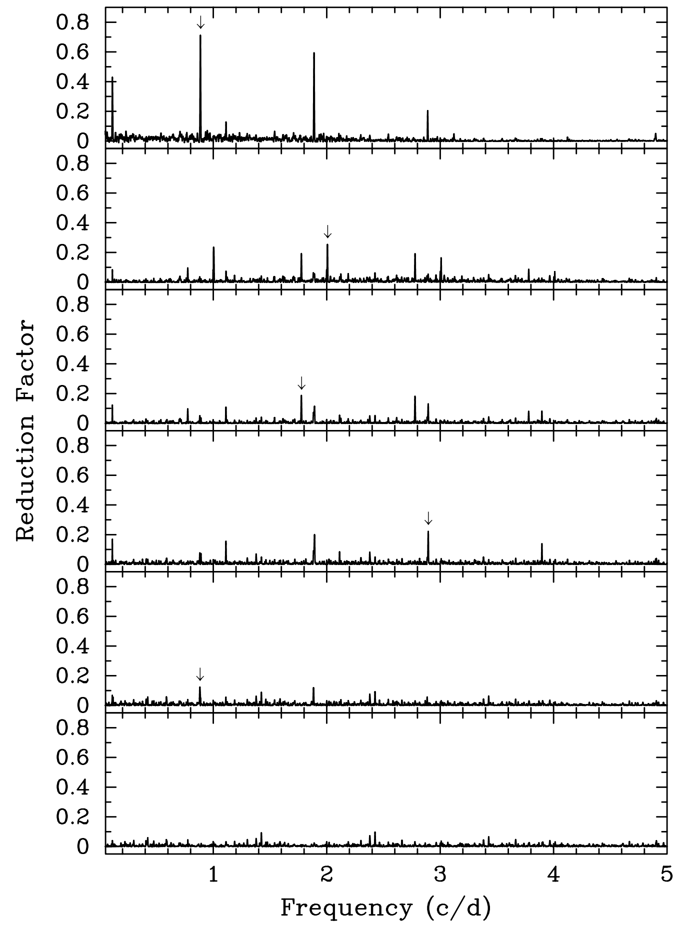

FIG. 18.—Least-squares spectra of the HD 113867 Johnson *B* data set, showing the results of progressively fixing the five detected frequencies. The arrows indicate the five frequencies (*top to bottom*): 0.8887, 2.0084, 1.7785, 2.8965, and 0.8841 day^{-1}. All five frequencies were confirmed in the Johnson *V* data set.

However, given the similarity in brightness and spectral class of the A9 and F1 components, we cannot say which component is responsible for the photometric variability. In fact, since HD 113867 has multiple photometric periods, both components could be γ Doradus stars.

6.9. *HD 152896*

Despite its asymmetric lines Fekel et al. (2003) concluded that HD 152896 is likely not a binary. We have obtained no additional spectroscopic observations of this star, and its properties from Fekel et al. (2003) are given in Table 1.

HD 152896 is a prime γ Doradus candidate from Handler (1999) with periods of 0.746 and 0.844 days. We find periods of 0.7472 and 0.7709 days with *B* amplitudes of 56 and 35 mmag in our APT photometry (Figs. 20 and 21; Table 5), so we confirm Handler's first period and find a slightly different second one. The light curve closely approximates a sinusoid when phased with each of our two periods. The rms of the residuals with the two periods removed is 0.016 mag, strongly suggesting further variability. Figure 20 does indicate additional power at low frequencies, but we are not able to identify any additional periods with certainty. The weighted mean B/V amplitude ratio for the two periods is 1.37 ± 0.12, indicting that the photometric variability is due to pulsation. Thus, given the spectroscopic and photometric properties of HD 152896, we confirm that this F1 variable is a γ Doradus star.

6.10. *HD 160295*

Fekel et al. (2003) reported that HD 160295 has a composite spectrum, but the *Hipparcos* observations (ESA 1997) provide no evidence that HD 160295 is a close visual binary. Despite this result, our Hα observations lead us to conclude that HD 160295 is a double star. The limited number of radial velocities obtained so far show no evidence for significant velocity variability of either the broad-lined or narrow-lined component. The best fit to our spectra leads to a spectral class of F2 for the broad-lined component and G0: V for the narrow-lined component. The *Hipparcos* parallax (ESA 1997) indicates that the primary is a subgiant, while the secondary is a dwarf. We adopt $\Delta V = 2.0$ mag.

According to Handler (1999), HD 160295 is a prime γ Doradus candidate with a period of 0.755 days and possible additional periods around 0.7 days. We find three closely-spaced periods of 0.7553, 0.6904, and 0.6508 days with *B* amplitudes of 72, 24, and 8 mmag, respectively (Figs. 22 and 23; Table 5). Therefore, we confirm and extend Handler's results. The light curve appears to be sinusoidal when phased with each of the first two periods but distinctly asymmetric when phased with the third period. The rms of the photometric residuals after removing the three periods is 0.010 mag, but we cannot identify additional periods. The

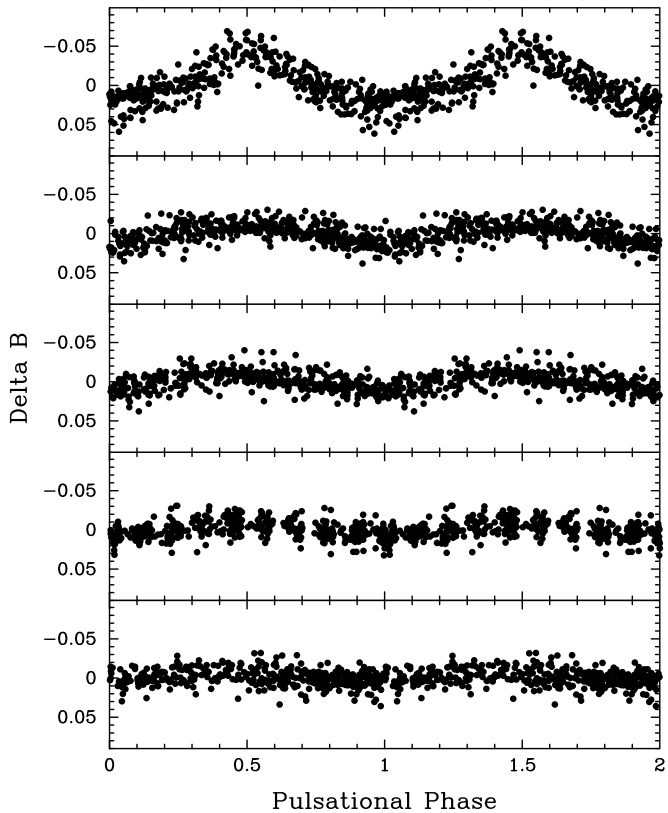

FIG. 19.—Johnson *B* photometric data for HD 113867, phased with the five frequencies and times of minimum from Table 5. (*Top to bottom*): Frequencies are 0.8887, 2.0084, 1.7785, 2.8965, and 0.8841 day^{-1}. For each panel, the data set has been prewhitened to remove the other four known frequencies.

weighted mean B/V amplitude ratio for the three periods is 1.34 ± 0.08, indicating the variability is due to pulsation and not ellipticity or starspots. Therefore, we confirm the F2 primary component of HD 160295 as a γ Doradus variable.

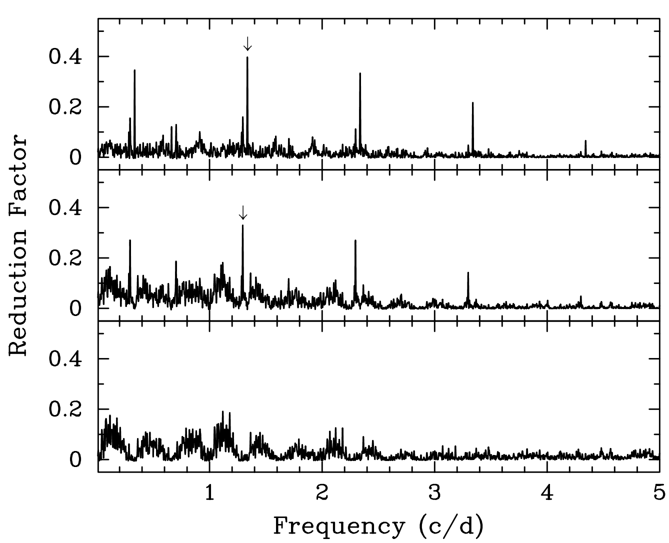

FIG. 20.—Least-squares spectra of the HD 152896 Johnson *B* data set, showing the results of progressively fixing the two detected frequencies. The arrows indicate the two frequencies at 1.3384 day^{-1} (*top*) and 1.2972 day^{-1} (*middle*). Both frequencies were confirmed in the Johnson *V* data set.

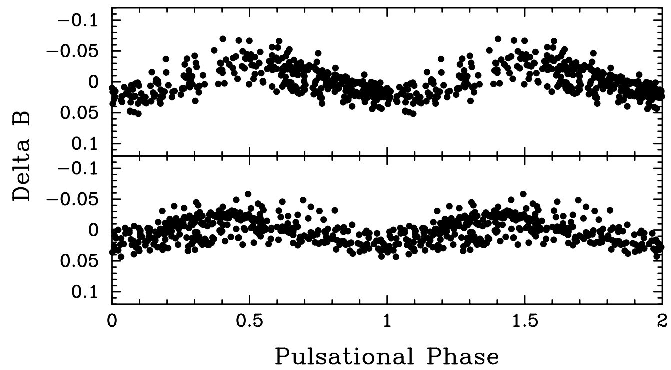

FIG. 21.—Johnson *B* photometric data for HD 152896, phased with the two frequencies and times of minimum from Table 5. The two frequencies are 1.3384 day^{-1} (*top*) and 1.2972 day^{-1} (*bottom*). For each panel, the data set has been prewhitened to remove the other known frequency.

6.11. *HD 165645*

We obtained a single red-wavelength spectrum of HD 165645. Its lines are quite broad, leading to greater than normal uncertainties in the properties derived from its spectrum. We determined a spectral class of A9:. From the *Hipparcos* magnitude and parallax we conclude that the star is a dwarf. These results are consistent with several previous classifications ranging from A8 III to F0 V (Abt 1981; Grenier et al. 1999). Our $v \sin i$ value of 150: km s^{-1} is consistent with values of 149 km s^{-1} from Abt & Morrell (1995), as revised by Royer et al. (2002), and 175 km s^{-1} from Danziger & Faber (1972).

Plaskett et al. (1920) called the star a spectroscopic binary from four velocities that produced an average velocity of -20.3 km s^{-1}. However, they characterized its spectrum as

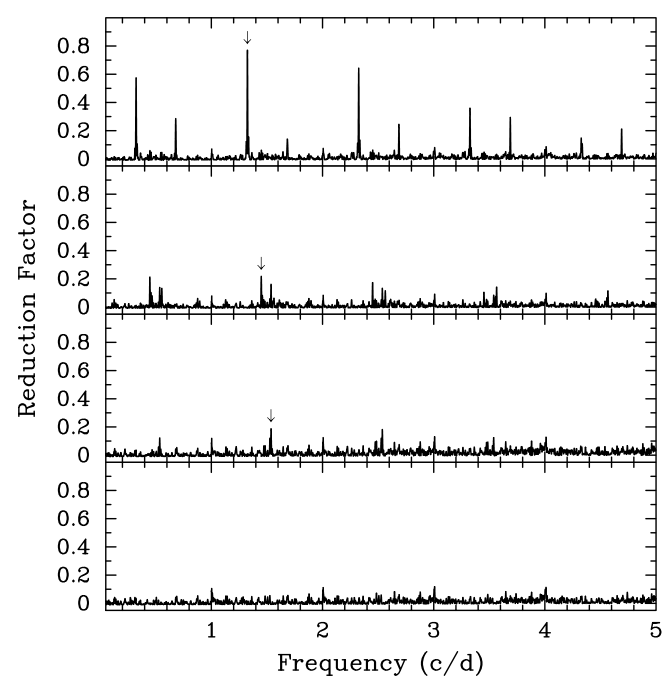

FIG. 22.—Least-squares spectra of the HD 160295 Johnson *B* data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies (*top to bottom*): 1.3240, 1.4484, and 1.5365 day^{-1}. All three frequencies were confirmed in the Johnson *V* data set.

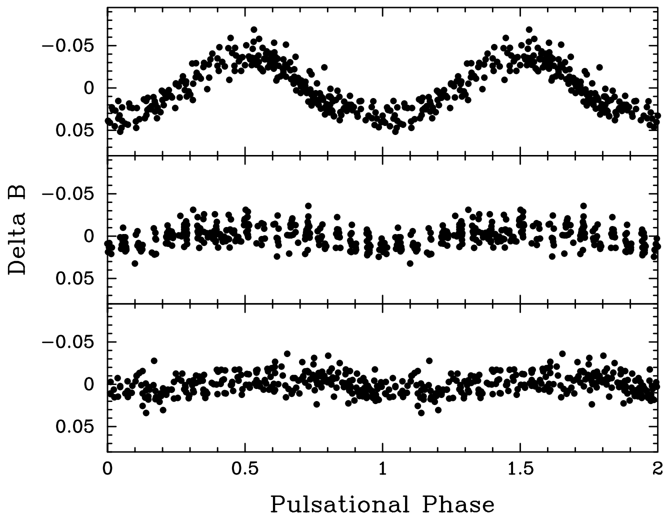

FIG. 23.—The Johnson *B* photometric data for HD 160295, phased with the three frequencies and times of minimum from Table 5. (*Top to bottom*): Frequencies are 1.3240, 1.4484, and 1.5365 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

having " many rather ill-defined lines " that were difficult to measure. Deleting their most discrepant radial velocity, which came from a plate of poorer quality than the other three measurements, results in a mean of -13.0 km s^{-1}. We obtained a radial velocity of -14.7 km s^{-1} from measurement of the three best lines in the 6430 Å region. From four observations Grenier et al. (1999) found a mean velocity of -10.7 ± 3.7 km s^{-1}. Thus, we consider the star to have a constant velocity.

We discovered the photometric variability of HD 165645 when we observed it as a comparison star with the T4 0.75 m APT in our solar-type star program (Henry 1999); it was not detected as a variable star in the *Hipparcos* photometry (ESA 1997). Our preliminary analysis of earlier observations obtained with the T3 APT were described in Kaye et al. (1998) where a single period of 0.4213 days and a *B* amplitude of 6.2 mmag were reported. Our new observations presented in this paper give essentially the same results (Figs. 24 and 25; Table 5). The rms scatter of the observations after removing the 0.4210 day period is only

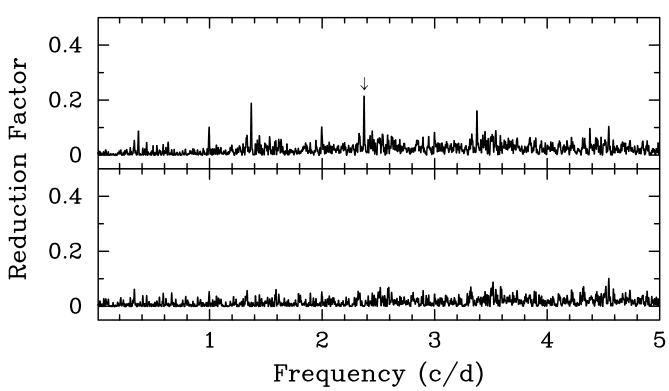

FIG. 24.—Least-squares spectra of the HD 165645 Johnson *B* data set. The arrow in the top panel indicates the single detected frequency at 2.3752 day^{-1}. The bottom panel shows the least-squares spectrum with the 2.3752 day^{-1} frequency fixed. The same frequency was confirmed in the Johnson *V* data set.

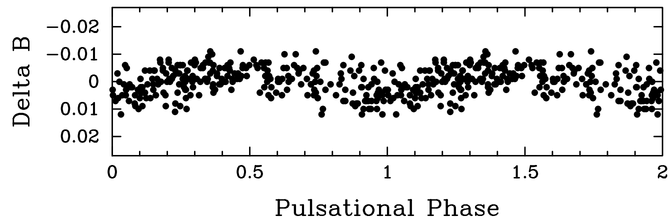

FIG. 25.—Johnson *B* photometric data for HD 165645, phased with the single frequency of 2.3752 day^{-1} and time of minimum from Table 5.

0.005 mag, and we see no evidence for additional periodicity. The B/V amplitude ratio for our single period is 1.33 ± 0.32; the small *B* and *V* amplitudes and their large relative uncertainties allow the amplitude ratio to be as small as 1.0. However, the ellipticity effect as an explanation of the photometric variability is precluded by the absence of short-period radial velocity variations. Starspots are also precluded by the star's early spectral type and the high degree of coherence in the light curve over 370 cycles. Therefore, we confirm HD 165645 as a γ Doradus variable.

6.12. *HD 171244*

Fekel et al. (2003) discussed the spectroscopic observations of this star. Based on a comparison of its mean radial velocity obtained at three different observatories, Fekel et al. (2003) suggested that the star's velocity is possibly variable. A single additional velocity, obtained in 2003 April, is in excellent agreement with two velocities from 2000 July (Fekel et al. 2003), resulting in a mean velocity of -13.6 ± 0.2 km s^{-1}. While duplicity remains a possibility, we assume that HD 171244 is single. Other basic parameters of this star are taken from Fekel et al. (2003).

HD 171244 is a prime γ Doradus candidate from Handler (1999) with periods of 1.004 and 0.817 days from the *Hipparcos* photometry. We find periods of 1.0040 and 0.9581 days with *B* amplitudes of 35 and 19 mmag in *B* from the APT photometry (Figs. 26 and 27; Table 5). Thus, we

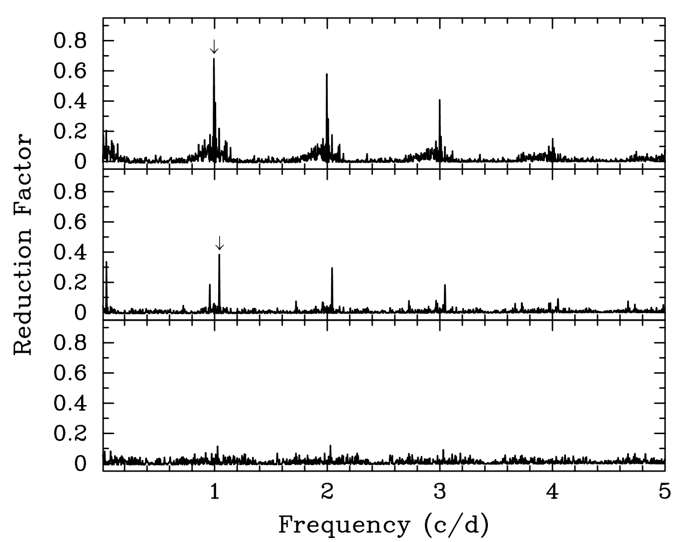

FIG. 26.—Least-squares spectra of the HD 171244 Johnson *B* data set, showing the results of progressively fixing the two detected frequencies. The arrows indicate the two frequencies at 0.9960 day^{-1} (*top*) and 1.0437 day^{-1} (*middle*). Both frequencies were confirmed in the Johnson *V* data set.

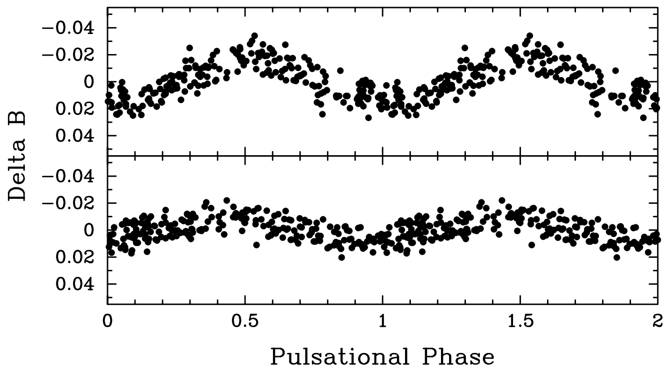

FIG. 27.—Johnson B photometric data for HD 171244, phased with the two frequencies and times of minimum from Table 5. The two frequencies are 0.9960 day^{-1} (*top*) and 1.0437 day^{-1} (*bottom*). For each panel, the data set has been prewhitened to remove the other known frequency.

confirm Handler's first period but find a second that is different from his. The light curve closely approximates a sinusoid when phased with each of our two periods. The rms of the residuals with the two periods removed is 0.006 mag, and we find little evidence for additional periodicity. The weighted mean B/V amplitude ratio for the two periods is 1.64 ± 0.11, quite high compared with the other stars in our sample but still indicative of pulsation rather than spots or ellipticity. This further suggests the possibility of a secondary companion to HD 171244, which would preferentially dilute the primary's light variation in V and increase the B/V amplitude ratio. Nonetheless, given the star's spectroscopic and photometric properties, we confirm that this F2 subgiant is a γ Doradus star.

7. DISCUSSION

In Table 6, we list all of the γ Doradus stars that have been confirmed to date, including the 12 stars in this paper. The table contains entries for 42 stars, of which 20 are known spectroscopic binaries or visual double stars. In most of the cases involving duplicity, it is clear that the primary component is the γ Doradus variable, so we have added an "A" to the HD number in column (1) to designate the primary component. However, for three double-lined binaries, HD 86371, HD 113867, and HD 221866, the two components are similar in spectral type so that it is *not* clear which star is the variable (see the next paragraph). Since all three of these binaries have multiple photometric periods, it is possible that *both* components are γ Doradus stars. In those three cases, we have listed both the primary and secondary componets in Table 6 with designations of "A:" and "B:", respectively, where the colon indicates that the identification of the γ Doradus component(s) is uncertain.

For the single stars, the wide visual doubles, and the single-lined binaries in Table 6, the V magnitudes and $B-V$ colors listed in columns (4) and (5) are taken from the *Hipparcos* catalog (ESA 1997). For all visual double stars and the double-lined spectroscopic binaries, the V magnitudes and $B-V$ colors refer to the individual components designated in column (1). For the seven binary systems in this paper, the magnitudes and colors of the individual components were determined as described in § 3.2 and listed in

TABLE 6
DERIVED PROPERTIES OF γ DORADUS STARS

HD (1)	Other Names (2)	Duplicity (3)	V (mag) (4)	$B-V$ (mag) (5)	M_V (mag) (6)	L ($L_\odot$) (7)	R ($R_\odot$) (8)	Period (days) (9)	Ref. (10)
277	...	Single	8.37	0.379	3.31	3.7	1.4	0.9005	1
7169A	HDS 160	VB, SB2	7.42	0.329	2.98	5.0	1.5	0.5486	2
12901	...	Single	6.74	0.311	2.35	8.9	1.9	0.82270	3
18995	...	Single	6.72	0.342	2.32	9.1	2.1	1.0833	4
19684A	...	SB1	6.96	0.301	1.86	13.8	2.4	0.34722	4
23874A	ADS 2785 A	VB, SB2	8.45	0.329	2.67	6.6	1.7	0.4432	2
27290	γ Dor, HR 1338	Single	4.26	0.312	2.72	6.3	1.6	0.7570	5
32537A	V398 Aur, 9 Aur, HR 1637, ADS 3675 A	VB	4.98	0.343	2.89	5.4	1.6	1.2582	6
48271	...	Single	7.49	0.315	2.62	6.9	1.7	1.0959	2
48501A	HR 2481, ADS 5377 A	VB	6.26	0.321	2.81	5.8	1.6	0.7750[a]	3
49015A	...	VB	7.04	0.375	2.83	5.7	1.7	0.52718	4
55892	QW Pup, HR 2740	Single	4.49	0.324	2.86	5.5	1.6	0.9584	7
62454A	DO Lyn	SB2	7.43	0.329	2.67	6.6	1.7	0.62447	8
64729	...	Single	7.57	0.321	2.55	7.4	1.8	0.7248	2
65526	V769 Mon	Single	6.98	0.297	3.03	4.7	1.4	0.644	9
68192	KO UMa	Single	7.15	0.363	2.29	9.4	2.1	0.7691	8
86358A	HR 3936	SB2	6.87	0.300	2.75	6.1	1.6	0.7753	2
86371A:	...	SB2	7.37	0.314	2.91	5.3	1.5	2.459	9
86371B:	...	SB2	7.37	0.314	2.91	5.3	1.5	2.459	9
99329	80 Leo, HR 4410	Single	6.35	0.345	2.41	8.4	2.0	0.45286	4
100215A	...	SB2	8.08	0.265	2.91	5.3	1.4	0.7564	2
105085A	...	SB2	7.59	0.300	2.82	5.7	1.5	0.6879	2
105458	...	Single	7.77	0.299	2.84	5.6	1.5	0.7571	1
108100A	DD CVn	SB2	7.27	0.329	2.68	6.5	1.7	0.7541	4, 10
113867A:	...	SB2	7.40	0.265	2.53	7.5	1.7	1.1252	2
113867B:	...	SB2	7.80	0.329	2.93	5.2	1.5	1.1252	2

TABLE 6—*Continued*

HD (1)	Other Names (2)	Duplicity (3)	V (mag) (4)	$B-V$ (mag) (5)	M_V (mag) (6)	L ($L_\odot$) (7)	R ($R_\odot$) (8)	Period (days) (9)	Ref. (10)
139095	CF UMa, HR 4550	Single	7.91	0.366	2.62	7.0	1.9	0.634	9
152896	V645 Her	Single	7.55	0.314	2.85	5.6	1.5	0.7472	2
155154	HR 6379	Single	6.17	0.306	2.91	5.3	1.5	0.34510	1
160295A	V2381 Oph	SB2	7.87	0.354	2.38	8.6	2.0	0.7553	2
160314A	...	VB	7.74	0.405	2.54	7.5	2.0	0.82763	1
164615	V2118 Oph	Single	7.03	0.354	2.82	5.8	1.7	0.8117	11, 12
165645A	HR 6767, ADS 11054 A	VB	6.38	0.287	2.59	7.1	1.7	0.4210	2
166233A	73 Oph, HR 6795, ADS 11111 A	VB	6.03	0.320	2.49	7.8	1.8	0.61439	13
167858A	V2502 Oph, HR 6844	SB1	6.62	0.312	2.64	6.8	1.7	1.307	9, 13
171244	...	Single	7.75	0.397	2.06	11.7	2.5	1.0040	2
181998	...	Single	7.67	0.328	2.81	5.8	1.6	1.334	9
206043	NZ Peg, HR 8276	Single	5.77	0.314	2.81	5.8	1.6	0.41113	1
207223	V372 Peg, HR 8330	Single	6.18	0.350	2.67	6.6	1.8	2.59381	14
209295A	...	SB1	7.33	0.261	1.90	13.4	2.2	0.88547	15
218396	V342 Peg, HR 8799	Single	5.97	0.259	2.96	5.0	1.4	0.5053	16
221866A:	...	SB2	7.92	0.228	2.55	7.3	1.6	1.1416	4
221866B:	...	SB2	8.62	0.380	3.25	3.9	1.4	1.1416	4
224638	BT Psc	Single	7.49	0.342	2.98	4.9	1.5	1.2323	17
224945	BU Psc	Single	6.93	0.292	3.07	4.5	1.4	1.4943	17

NOTES.—A colon indicates that either component A and/or B could be the γ Doradus star; VB = visual binary or double star; SB = spectroscopic binary.

[a] Also has a period of 10.959 days with a slightly larger amplitude.

REFERENCES.—(1) Henry et al. 2001; (2) this paper; (3) Eyer & Aerts 2000; (4) Henry & Fekel 2002; (5) Balona, Krisciunas, & Cousins 1994; (6) Zerbi et al. 1997a; (7) Poretti et al. 1997; (8) Kaye et al. 1999b; (9) Handler & Shobbrook 2002; (10) Breger et al. 1997; (11) Zerbi et al. 1997b; (12) Hatzes 1998; (13) Fekel & Henry 2003; (14) Kaye et al. 1999c; (15) Handler et al. 2002; (16) Zerbi et al. 1999; (17) Mantegazza et al. 1994.

Table 1. The magnitudes and colors for the components of HD 62454 (Kaye et al. 1999b), HD 221866 (Fekel et al. 2003), and HD 108100 (Henry & Fekel 2002) were also determined in a similar manner, starting with the spectral types of the components. For HD 108100 we reexamined our spectra from (Henry & Fekel 2002) in light of our new determination in this paper that the star is a spectroscopic binary and not a shell star (Fig. 3) and classified the individual components as F1 subgiant and G0: dwarf. For HD 86371 we obtained a spectrum of the star at KPNO that showed its two components have essentially identical line strengths, indicating $\Delta V = 0$, and so we have increased the V magnitude of each component by 0.75 and adopted for both components the $B-V$ from the *Hipparcos* catalog (ESA 1997). Finally, for HD 166233A the V and $B-V$ values are from Fekel & Henry (2003). The stellar properties of the individual components listed in columns (6)–(8) of Table 6 have all been determined based on the individual V magnitudes and $B-V$ colors by the method outlined in Henry et al. (2001). Most of these stars have multiple photometric periods, so the period given in column (9) is the one with the largest photometric amplitude. The final column gives the literature reference establishing each star as a γ Doradus variable.

In his Table 1, Handler (1999) listed 46 prime γ Doradus candidates based on his analysis of the *Hipparcos* photometry. We have now confirmed 19 of those candidates as γ Doradus stars, and these are listed in our Table 6. In addition, we are currently observing another 11 of Handler's prime candidates and our preliminary analysis indicates that all are probably γ Doradus stars as well. Thus, at least two-thirds of Handler's prime candidates are true γ Doradus stars. Indeed, every one of the 30 candidates that we have observed to date appears to be a γ Doradus variable. Therefore, Handler's criteria for designating γ Doradus candidates from the *Hipparcos* photometry has been very successful, and the rest of his prime candidates deserve additional follow-up observations.

We plot all of the γ Doradus stars from Table 6 in the H-R diagram of Figure 28 using the $B-V$ color indices and absolute magnitudes in columns (5) and (6). The solid lines represent the dwarf and giant sequences from Tables B1 and B2 of Gray (1992) and the subgiant sequence of Allen (1976). The dotted lines indicate the boundaries of the δ Scuti instability strip, converted from those of Breger (2000) with the $b-y$ to $B-V$ calibration in Table B1 of Gray (1992). These same boundaries were shown by Fekel et al. (2003) to contain 97% of a sample of 146 δ Scuti stars, taken from the catalog of Rodríguez, López-González, & López de Coca (2000), that had *Hipparcos* parallaxes with uncertainites $\leq$10%. The γ Doradus stars in Table 6 with V magnitudes and $B-V$ colors that were explicitly measured or determined are plotted as filled circles. Twelve SB2 components are plotted as open circles because their V magnitude differences and/or $B-V$ colors could only be estimated from their spectral types, so their positions in the H-R diagram have greater uncertainties. One γ Doradus pulsator, HD 209295, is plotted with a cross since its low-frequency pulsations are thought to be excited by the presence of a degenerate companion (Handler et al. 2002). The dashed lines mark the observed boundaries of the γ Doardus instability strip, determined by Fekel et al. (2003) from the 30 confirmed γ Doradus stars in Henry & Fekel (2002). These boundaries show that the majority of confirmed γ Doradus stars are dwarfs, with a few subgiants, and their location straddles the cool boundary of the δ Scuti instability strip.

Although we have increased the sample of known γ Doradus stars by 40% and revised the positions of a

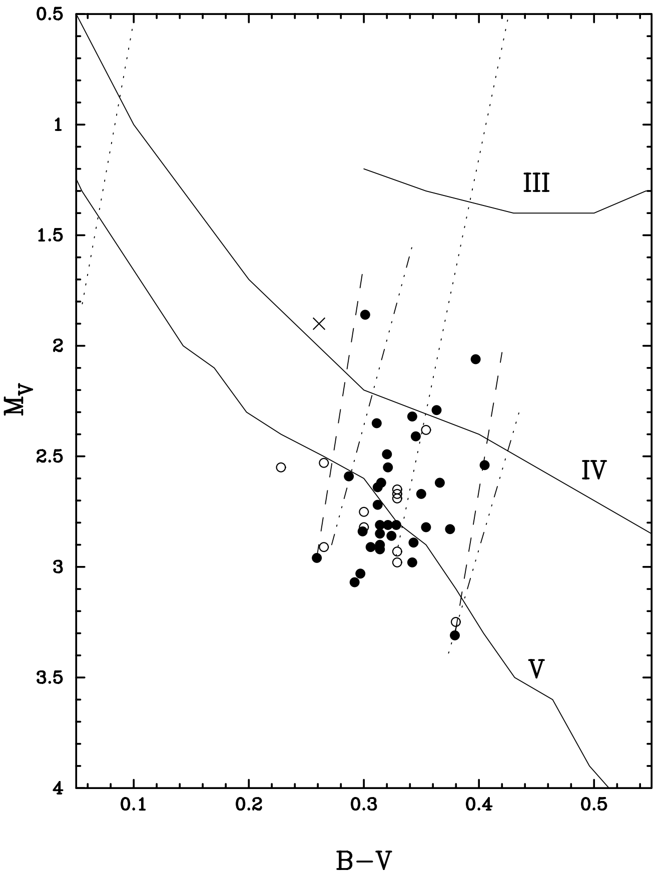

FIG. 28.—Location of all the 42 confirmed γ Doradus stars (Table 6) in the H-R diagram, including the 12 stars discussed in this paper. Both components of three of the SB2 binaries are plotted for a total of 45 individual stars. Stars with well-determined locations in the diagram are plotted as filled circles, while those with somewhat greater uncertainty (most of the SB2 binary components) are plotted with open circles. One star, HD 209295, is plotted with a cross since its pulsation may be tidally excited. The dotted lines indicate the boundaries of the δ Scuti instability strip, converted from those of Breger (2000). The dashed lines show the observed domain of the γ Doradus pulsators, adopted from Fekel et al. (2003) and unchanged in this paper. The triple-dot–dashed lines show the theoretical boundaries of the γ Doradus instability strip, converted from those of Warner et al. (2003).

number of the variables in the H-R diagram by accounting for duplicity, Figure 28 shows that the enlarged sample of γ Doradus variables (Table 6) remains in good accord with the boundaries of the γ Doradus region determined by Fekel et al. (2003). There are three possible exceptions. The primary of HD 113867 is positioned just 0.01 mag blueward of the blue γ Doradus boundary. Given the greater uncertainty in its position, this discrepancy is not significant. HD 209025, represented by the cross in Figure 28, is positioned well outside the blue boundary but, as noted above, its γ Doradus pulsations are probably tidally excited. The third exception is the primary of HD 221866, which lies well outside the blue boundary. However, the secondary of this binary is positioned on the red boundary, so it is possible that the secondary of HD 221866 rather than the primary is the γ Doradus star. Additional evidence for this comes from the fact that the primary is an Am star (Fekel et al. 2003), and the models of Turcotte (2002) indicate that pulsating Am stars should be significantly evolved. However, the primary of HD 221866 is positioned on the main sequence.

Warner et al. (2003) have recently determined the first theoretical instability strip for the γ Doradus variables, based on the "convective blocking" mechanism of Guzik et al. (2000). This proposed mechanism requires that the convective timescale be comparable to or longer than the pulsation period and predicts both the red and blue edges of the instability strip. We have plotted the extreme edges of their calculated instability strip with triple-dot–dashed lines in Figure 28, where we have adopted their absolute magnitude limits and converted their effective temperature limits to observed $B-V$ with the calibration of Flower (1996). There is very good agreement between the observed distribution of γ Doradus stars and the theoretical instability strip; only a few of the hottest pulsators lie outside the calculated boundaries. However, we note that the conversion from effective temperature to $B-V$ is uncertain by 0.02 mag or so. This, combined with a similar uncertainty in the $B-V$ values of the individual stars, makes it difficult to determine whether stars near the edges of the theoretical instability strip are just inside or just outside its boundaries.

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