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ELEVEN NEW γ DORADUS STARS

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ABSTRACT

We present new high-dispersion spectroscopic and precise photometric observations to identify 11 new γ Doradus variables. Seven of these new γ Doradus stars appear to be single, three are primaries of single-lined binaries, and one has two distant visual companions; none are double-lined or close visual binaries. Several of the stars show spectroscopic line-profile and low-amplitude radial velocity variability indicative of pulsation. All 11 stars are photometrically variable with amplitudes between 8 and 93 mmag in Johnson *B* and periods between 0.398 and 2.454 days. One star is monoperiodic; the rest have between two and five independent periods. The variability at all periods approximates a sinusoid, although three of the stars exhibit cycle-to-cycle variation in the level of maximum brightness, similar to the Blazhko effect observed in some RR Lyrae stars. We provide a new tabulation of all 54 γ Doradus stars confirmed to date and list 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. Four of the new γ Doradus variables from this paper also lie within the δ Scuti instability strip but do not exhibit the additional higher frequency variability typical of δ Scuti stars. The variability type of several of these stars given in the General Catalog of Variable Stars and in SIMBAD should now be revised.

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

Online material: machine-readable tables

1. INTRODUCTION

This work continues a series of papers in which we have examined the spectroscopic and photometric characteristics of candidate γ Doradus stars (most recently, Fekel et al. 2003; Henry & Fekel 2003, 2005; Henry et al. 2004). Early summaries of this new class of variable stars can be found in Kaye et al. (1999a) and Zerbi (2000). Kaye et al. (1999a) included a list of 13 members of the class. 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 2003). Radial velocity variations of 2–4 km s^{-1} and changing spectroscopic line profiles have also been observed in many γ Doradus stars (e.g., Krisciunas et al. 1995; Balona et al. 1996; Hatzes 1998; Kaye et al. 1999b, 1999c; Fekel & Henry 2003; Mathias et al. 2004). 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 a convective flux-blocking mechanism at the base of the relatively thin convective envelopes of γ Doradus stars. Warner et al. (2003) modeled this mechanism and computed a theoretical γ Doradus instability strip. Recently, Dupret et al. (2004) developed new models of the flux-blocking mechanism that included the influence of time-dependent convection.

The most recently published list of confirmed γ Doradus stars contains 42 members (Henry & Fekel 2003, 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 2003, Fig. 28). Henry & Fekel (2003) demonstrated that the observed location of the γ Doradus variables agrees well with the theoretical instability strip of Warner et al. (2003). Since the γ Doradus and the δ Scuti instability strips overlap, Henry et al. (2004) continued the efforts of Handler & Shobbrook (2002) to find examples of stars pulsating intrinsically with both γ Doradus and δ Scuti frequencies. They concluded that the growing number of confirmed γ Doradus variables that also lie within the δ Scuti instability strip but do not exhibit additional δ Scuti variability makes it unlikely that the two types of pulsation can coexist in the same star. Shortly thereafter, however, Henry & Fekel (2005) discovered that the Am star HD 8801, which apparently lacks a binary companion, *does* exhibit both γ Doradus and δ Scuti pulsation. The coexistence of both δ Scuti *p*-modes and γ Doradus *g*-modes is allowed in the new models of Dupret et al. (2004).

In this paper we identify an additional 11 γ Doradus variables, bringing the total number of confirmed γ Doradus stars to 54. None of the new γ Doradus variables exhibit additional δ Scuti pulsation. All fall within previously established limits for the γ Doradus instability strip.

2. THE SAMPLE

Ten of the 11 γ Doradus candidates in this paper were taken from the list of prime candidates in Handler (1999), who identified them on the basis of his analysis of *Hipparcos* photometry (Perryman et al. 1997). The 11th star, HD 213617, came from the list of further γ Doradus candidates in Handler (1999). Seven

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TABLE 1

Basic Properties of the New γ Doradus Stars

HD[a]	Other Names	V^{b} (mag)	$B-V^{b}$ (mag)	π^{b} (mas)	*Hipparcos* Variable Type[c]	Spectral Class[d]	Luminosity Class[d]	$v \sin i^{d}$ (km s^{-1})	Velocity[d] (km s^{-1})
2842	...	7.99	0.325	9.30 ± 1.00	U	F1:[e]	Dwarf[e]	90[e]	8.5[e]
17310	...	7.76	0.378	9.14 ± 1.14	U	F2	Dwarf	10	Variable
69715	BDS 4550 A	7.18	0.360	15.19 ± 0.89	U	F1:	Dwarf	150	−11.2
70645	...	8.12	0.344	7.55 ± 0.87	P	F1	Dwarf	11	Variable
80731	...	8.46	0.345	6.77 ± 1.03	P	F1	Dwarf	14	Variable
112429	IR Dra, 8 Dra, HR 4916	5.23	0.303	34.67 ± 0.53	P	F1[e]	Dwarf[e]	115[e]	8.2[e]
115466	LP Vir, 58 Vir	6.89	0.338	12.61 ± 0.76	P	F1[e]	Subgiant[e]	42	11.7
124248	MU Vir, 97 Vir	7.15	0.333	15.27 ± 0.96	P	A9[e]	Dwarf[e]	50	−1.4
175337	...	7.39	0.364	11.85 ± 0.94	U	F2[e]	Dwarf[e]	38	−1.4
195068/9	43 Cyg, HR 7828, V2121 Cyg	5.73	0.339	26.56 ± 0.48	P	F1:[e]	Dwarf[e]	45	−27.6
213617	39 Peg, HR 8586	6.43	0.350	18.90 ± 0.83	U	F1[e]	Dwarf[e]	66	−13.8

[a] All stars are from the lists of γ Doradus candidates in Handler (1999).
[b] From the *Hipparcos* catalog.
[c] (U) unresolved variable; (P) periodic variable.
[d] From this paper unless otherwise noted. A colon indicates greater uncertainty than usual.
[e] Fekel et al. 2003.

of the 11 stars were also included in the spectroscopic survey of 34 γ Doradus candidates by Fekel et al. (2003).

To create his γ Doradus candidate lists, Handler (1999) extracted all the stars from the *Hipparcos* catalog (Perryman et al. 1997) with (1) spectral types from A to G, (2) photometric periods from 0.3 to 10 days, (3) photometric amplitudes less than 0.2 mag, and (4) *Hipparcos* magnitudes brighter than 8.5 at minimum and not classified as supergiants. This resulted in a sample of more than 1000 candidates. Obvious non–γ Doradus stars were eliminated from this sample by inspection of the light curves and by preliminary period analysis. The remaining 70 stars, plus a small number of additional candidates proposed in the literature, were divided into the primary candidates (46 stars) and the further candidates (36 stars). The primary candidates consisted of those stars with the best evidence for multiperiodicity in the γ Doradus period range, which, as Handler (1999) explained, tends to eliminate the singly periodic γ Doradus variables but also eliminates nonpulsating variables such as ellipsoidal and starspot variables.

In our previous papers in this series, we have examined 15 of Handler's primary candidates and confirmed all of them as γ Doradus variables, demonstrating the success of his criteria for identifying the primary γ Doradus candidates. Therefore, we decided to observe all 33 of Handler's 46 primary candidates that are observable with our automatic photoelectric telescopes (APTs) in the northern hemisphere. For this paper we began with 12 candidates (11 from the primary list and one from the further candidates list). Only one of the 11 primary candidates (HD 173977) could *not* be confirmed as a γ Doradus star and so is not included in this paper. Fekel et al. (2003) found HD 173977 to be a short-period binary and suggested it might be an ellipsoidal variable. Before we could publish our photometric results confirming this, Chapellier et al. (2004) announced HD 173977 to be a double-lined spectroscopic binary with an orbital period of 1.801 days that also exhibits photometric variations caused by both the ellipticity effect and δ Scuti pulsations. This makes HD 173977 similar to HD 207651 (Henry et al. 2004), which appears on Handler's further candidate list. Thus, including the results in this paper, we have examined 26 of Handler's 46 primary candidates and have confirmed 25 of the 26 as γ Doradus stars, giving the Handler (1999) primary candidate list a phenomenal 97% success rate so far.

Basic data for the 11 new γ Doradus stars in this study are listed in Table 1, with some of their properties determined below. All these stars are either single, the primary of a wide visual double, or the primary of a single-lined spectroscopic binary; none are members of close visual binaries or double-lined systems. Therefore, the V magnitudes, $B-V$ color indices, parallaxes, and variability types listed in Table 1, which come from the *Hipparcos* catalog (Perryman et al. 1997), are not significantly affected by the light of a second star. The determination of spectral types, projected rotational velocities, and radial velocities listed in Table 1 are discussed in § 3 below.

3. SPECTROSCOPY

3.1. *Observations*

For seven of the 11 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 nine stars in our sample between 2002 September and 2004 September. Combining all the data, we have at least two spectra of each star.

Our new spectrograms are centered at 6430 Å, cover a wavelength range of about 80 Å, and have a 2 pixel resolution of 0.21 Å. The typical signal-to-noise ratios of our spectra are between 100 and 250.

3.2. *Analyses*

The determination of the radial velocities, $v \sin i$ values, and spectral classes, as well as estimates of their uncertainties, is described in Fekel et al. (2003). Although they previously analyzed seven stars in our sample, our additional spectra have led to slightly revised values of $v \sin i$ and mean radial velocity (Table 1) for some of the stars. A colon after a value indicates greater than usual uncertainty, generally because the spectral lines are very broad and shallow or very asymmetric. The luminosity classes were determined from the *Hipparcos* magnitudes and parallaxes (Perryman et al. 1997) as described in

TABLE 2
INDIVIDUAL RADIAL VELOCITIES

HD	Date (HJD − 2,400,000)	Radial Velocity (km s^{-1})	Comments
17310	52,542.911	−3.7	Narrow lines
	52,902.908	−1.9	
	52,903.925	1.1	
	52,904.902	−3.7	
	52,940.879	28.6	
	52,941.869	28.6	
	53,273.927	29.7	
	53,274.885	23.7	
	53,275.871	35.7	
	53,276.844	31.1	
	53,277.870	40.4	
69715	52,706.770	−10.4	Very broad lines
	52,760.673	−12.1	
70645	52,708.779	44.4	Narrow lines
	52,759.659	44.7	
	53,275.005	34.7	
80731	52,706.807	−8.7	
	52,707.783	17.2	
	52,709.814	11.6	
	52,760.758	12.4	
	53,119.702	−9.2	Asymmetric lines
	53,120.692	−18.7	
	53,123.715	11.0	
115466	52,709.934	7.9	Very asymmetric lines
	52,760.809	11.6	Asymmetric lines
	53,121.778	13.4	Asymmetric lines
	53,168.701	13.1	Asymmetric lines
124248	52,757.828	−4.2	Asymmetric lines
	52,760.825	1.4	Asymmetric lines
	53,172.693	−1.0	
175337	52,760.966	−0.8	Symmetric lines
	53,119.983	0.5	
	53,170.877	−1.3	Asymmetric lines
195068/9	53,122.003	−25.0	Very asymmetric lines
	53,275.688	−26.2	
213617	52,902.723	−15.0	
	52,903.757	−14.1	Symmetric lines
	52,940.651	−12.7	
	53,170.954	−10.2	Asymmetric lines
	53,171.962	−18.4	Asymmetric lines

Fekel et al. (2003). Our previously unpublished individual radial velocities are listed in Table 2 along with comments about those spectra.

4. PHOTOMETRY

4.1. *Observations*

The photometric observations analyzed in this paper were acquired between 2002 September and 2003 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 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) and Eaton et al. (2003).

The 11 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 helped to minimize the inevitable 1 day aliases in our period analyses and allowed 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 most comparison and check stars are constant to a few millimagnitudes, which is approximately the limit of precision for this APT.

TABLE 3

Program, Comparison, and Check Stars

Program	Comparison	Check	$\sigma_{(V-C)}$[a] (mag)	$\sigma_{(K-C)}$[a] (mag)	Individual Observations[b]
HD 2842	HD 2648	HD 4526	0.0237	0.0041	Table 4A
HD 17310	HD 17037	HD 16824[c]	0.0119	0.0065	Table 4B
HD 69715	HD 71636[d]	HD 72184	0.0119	0.0044	Table 4C
HD 70645	HD 69892	HD 62066	0.0311	0.0048	Table 4D
HD 80731	HD 84558	HD 82969[e]	0.0346	0.0065	Table 4E
HD 112429	HD 115978	HD 111456	0.0230	0.0063	Table 4F
HD 115466	HD 115503	HD 114203	0.0154	0.0058	Table 4G
HD 124248	HD 124973	HD 123919	0.0255	0.0062	Table 4H
HD 175337	HD 176651	HD 171852	0.0149	0.0064	Table 4I
HD 195068/9	HD 196482	HD 195820	0.0394	0.0051	Table 4J
HD 213617	HD 212670	HD 215510	0.0204	0.0079	Table 4K

[a] In the Johnson *B* photometric band.
[b] The individual observations are given in Tables 4A–4K.
[c] The K1 III check star varies by 0.01 mag with a timescale of approximately 130 days.
[d] The F5 V comparison star is a new eclipsing binary with a period of 5.01 days. Data from two partial nights during eclipse are not included in Table 4C or in the analysis.
[e] The G5 III check star varies by 0.015 mag with a timescale of approximately 60 days.

Notes to Table 3 mention slight variability in two check stars and eclipses in one comparison star, but these problems do not affect our analyses. The individual photometric observations of each star are given in Tables 4A–4K.

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 identified 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. The *B* amplitudes range from 93 mmag down to 8 mmag and on average are 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 uncertainties, so there are no detectable phase shifts in our two-color photometry.

In the same way, the $(K-C)$ differential magnitudes were also analyzed to search for periodicities that might exist in the comparison and check stars. None were found in any of the 22 stars. Thus, all 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 11 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.

5. CRITERIA FOR CONFIRMING γ DORADUS VARIABILITY

Throughout our series of papers on γ Doradus stars, we have used the following criteria for confirming stars as γ Doradus variables: (1) late A or early F spectral class, (2) luminosity class IV or V, and (3) periodic photometric variability in the γ Doradus period range that is attributable to pulsation. Our spectroscopic observations establish the spectral types of each candidate. Our photometric observations are numerous and extensive enough (typically several hundred observations over a full observing season) to minimize the effects of 1 cycle day^{-1} aliasing and provide the correct period identifications. This is important, since the cadence of the *Hipparcos* observations, from which Handler's candidates were identified, can result in spurious photometric periods, especially for multiperiodic stars (e.g., Eyer & Grenon 2000).

Our photometric and spectroscopic observations are also used to confirm the variability mechanism(s), especially for stars with single photometric periods, which could be ellipsoidal variables in close binary systems or rapidly rotating starspot variables rather than pulsating stars. In those cases our multiple spectroscopic observations establish the absence of short-period radial velocity variations and thus eliminate the ellipticity effect. The early F spectral types of the candidates and the high level of coherence in the light curves over hundreds of cycles both argue strongly against

TABLE 4A

Photometric Observations of HD 2842

Date (HJD − 2,400,000)	Var *B* (mag)	Var *V* (mag)	Chk *B* (mag)	Chk *V* (mag)
52542.9348	1.343	1.464	−0.027	−0.549
52543.7129	1.323	1.440	−0.038	−0.550
52543.8217	1.338	1.448	−0.034	−0.543
52543.9307	1.366	1.478	−0.044	−0.546
52544.7119	1.355	1.473	−0.036	−0.543

Notes.—Table 4A, along with Tables 4B–4K for the other stars, is available in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding form and content.

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) (9)
2842	B	2542.9348–2830.9243	196	1.5368 ± 0.0002	0.65070 ± 0.00008	40.1 ± 4.0	1.36 ± 0.20	2700.254 ± 0.010
				1.7129 ± 0.0002	0.58381 ± 0.00007	34.4 ± 4.2	1.34 ± 0.25	2700.338 ± 0.012
				1.6680 ± 0.0002	0.59952 ± 0.00009	23.0 ± 4.8	1.40 ± 0.43	2700.142 ± 0.019
	V	2542.9348–2830.9243	192	1.5370 ± 0.0002	0.65062 ± 0.00008	29.5 ± 3.0		2700.239 ± 0.010
				1.7129 ± 0.0002	0.58381 ± 0.00009	25.6 ± 3.2		2700.347 ± 0.012
				1.6679 ± 0.0003	0.59956 ± 0.00011	16.4 ± 3.6		2700.146 ± 0.020
17310	B	2539.8244–2693.5938	237	0.4682 ± 0.0004	2.13584 ± 0.00182	21.1 ± 1.9	1.45 ± 0.20	2600.484 ± 0.030
				0.5472 ± 0.0004	1.82749 ± 0.00134	14.9 ± 2.0	1.25 ± 0.26	2601.183 ± 0.041
				0.4075 ± 0.0003	2.45399 ± 0.00181	12.0 ± 2.3	1.36 ± 0.40	2602.273 ± 0.068
	V	2540.8223–2693.5938	238	0.4673 ± 0.0003	2.13995 ± 0.00137	14.6 ± 1.6		2600.387 ± 0.037
				0.5488 ± 0.0004	1.82216 ± 0.00149	11.9 ± 1.5		2601.252 ± 0.040
				0.4083 ± 0.0002	2.44918 ± 0.00150	8.8 ± 1.8		2602.220 ± 0.072
69715	B	2539.9899–2787.6445	405	2.4566 ± 0.0002	0.40707 ± 0.00003	20.3 ± 1.4	1.24 ± 0.14	2700.207 ± 0.004
				2.4416 ± 0.0002	0.40957 ± 0.00003	13.9 ± 1.5	1.21 ± 0.21	2700.416 ± 0.007
	V	2539.9899–2787.6445	390	2.4565 ± 0.0002	0.40708 ± 0.00003	16.4 ± 1.1		2700.204 ± 0.004
				2.4417 ± 0.0002	0.40955 ± 0.00004	11.5 ± 1.2		2700.408 ± 0.007
70645	B	2538.9892–2782.6408	437	0.9065 ± 0.0002	1.10314 ± 0.00024	41.3 ± 3.8	1.32 ± 0.19	2700.899 ± 0.017
				1.2612 ± 0.0002	0.79290 ± 0.00013	39.9 ± 3.8	1.34 ± 0.20	2700.246 ± 0.012
				1.1640 ± 0.0002	0.85911 ± 0.00015	33.2 ± 4.0	1.36 ± 0.25	2700.724 ± 0.017
				0.8061 ± 0.0002	1.24054 ± 0.00031	31.7 ± 4.0	1.33 ± 0.26	2700.550 ± 0.025
				0.8726 ± 0.0002	1.14600 ± 0.00026	27.4 ± 4.3	1.29 ± 0.32	2700.829 ± 0.026
	V	2538.9892–2782.6408	436	0.9064 ± 0.0002	1.10327 ± 0.00024	31.4 ± 3.0		2700.901 ± 0.017
				1.2612 ± 0.0002	0.79290 ± 0.00016	29.7 ± 3.0		2700.240 ± 0.013
				1.1636 ± 0.0002	0.85940 ± 0.00015	24.4 ± 3.1		2700.732 ± 0.018
				0.8062 ± 0.0002	1.24039 ± 0.00031	23.8 ± 3.2		2700.532 ± 0.027
				0.8724 ± 0.0002	1.14626 ± 0.00026	21.3 ± 3.4		2700.830 ± 0.026
80731	B	2552.0125–2804.6458	449	0.8961 ± 0.0002	1.11595 ± 0.00019	60.8 ± 3.8	1.26 ± 0.13	2700.787 ± 0.011
				0.7823 ± 0.0002	1.27828 ± 0.00033	44.9 ± 4.2	1.31 ± 0.19	2700.831 ± 0.020
				0.6599 ± 0.0002	1.51538 ± 0.00046	19.1 ± 4.6	1.13 ± 0.45	2700.702 ± 0.060
				1.3119 ± 0.0002[a]	0.76225 ± 0.00012[a]	15.3 ± 4.7	1.15 ± 0.59	2700.627 ± 0.037
	V	2552.0125–2804.6458	451	0.8962 ± 0.0002	1.11582 ± 0.00025	48.1 ± 3.1		2700.784 ± 0.011
				0.7823 ± 0.0002	1.27828 ± 0.00025	34.4 ± 3.4		2700.816 ± 0.020
				0.6599 ± 0.0002	1.51538 ± 0.00046	16.9 ± 3.6		2700.715 ± 0.052
				1.3117 ± 0.0002[a]	0.76237 ± 0.00012[a]	13.3 ± 3.7		2700.631 ± 0.034
112429	B	2596.0349–2829.7126	460	2.3557 ± 0.0002	0.42450 ± 0.00004	46.8 ± 2.1	1.22 ± 0.09	2700.176 ± 0.003
				2.2430 ± 0.0002	0.44583 ± 0.00004	21.9 ± 2.9	1.11 ± 0.25	2700.332 ± 0.009
				2.4671 ± 0.0002	0.40533 ± 0.00003	21.8 ± 2.9	1.15 ± 0.26	2700.280 ± 0.008
				2.5107 ± 0.0003	0.39830 ± 0.00005	7.5 ± 3.0	1.27 ± 0.82	2700.174 ± 0.026
				2.0493 ± 0.0002	0.48797 ± 0.00005	17.1 ± 2.9	1.27 ± 0.35	2700.224 ± 0.014
	V	2596.0349–2830.7092	464	2.3557 ± 0.0002	0.42450 ± 0.00004	38.5 ± 1.8		2700.174 ± 0.003
				2.2431 ± 0.0002	0.44581 ± 0.00003	19.7 ± 2.4		2700.335 ± 0.008
				2.4669 ± 0.0002	0.40537 ± 0.00003	19.0 ± 2.4		2700.281 ± 0.008
				2.5108 ± 0.0002	0.39828 ± 0.00003	5.9 ± 2.5		2700.193 ± 0.028
				2.0497 ± 0.0002	0.48788 ± 0.00005	13.5 ± 2.4		2700.216 ± 0.014
115466	B	2620.0495–2829.6510	289	1.2045 ± 0.0002	0.83022 ± 0.00017	31.6 ± 1.9	1.44 ± 0.13	2700.597 ± 0.007
				1.3621 ± 0.0002	0.73416 ± 0.00013	16.4 ± 2.4	1.76 ± 0.34	2700.601 ± 0.017
				1.4387 ± 0.0002	0.69507 ± 0.00012	15.5 ± 2.5	1.36 ± 0.33	2700.137 ± 0.017
	V	2620.0495–2829.6510	285	1.2044 ± 0.0003	0.83029 ± 0.00021	22.0 ± 1.5		2700.603 ± 0.008
				1.3625 ± 0.0003	0.73394 ± 0.00016	9.3 ± 1.8		2700.616 ± 0.024
				1.4390 ± 0.0002	0.69493 ± 0.00010	11.4 ± 1.9		2700.135 ± 0.017
124248	B	2640.0420–2830.6687	276	1.3133 ± 0.0003	0.76144 ± 0.00017	52.9 ± 3.3	1.29 ± 0.13	2700.162 ± 0.007
				1.2169 ± 0.0003	0.82176 ± 0.00020	24.5 ± 4.2	1.34 ± 0.35	2700.101 ± 0.022
	V	2640.0420–2830.6687	274	1.3133 ± 0.0002	0.76144 ± 0.00014	40.9 ± 2.6		2700.156 ± 0.007
				1.2166 ± 0.0003	0.82196 ± 0.00020	18.3 ± 3.2		2700.105 ± 0.023
175337	B	2537.6061–2830.6867	232	1.2708 ± 0.0002	0.78691 ± 0.00012	34.6 ± 1.8	1.15 ± 0.10	2700.277 ± 0.006
	V	2537.6061–2830.9049	239	1.2709 ± 0.0002	0.78684 ± 0.00012	30.0 ± 1.4		2700.272 ± 0.006
195068/9	B	2537.5987–2830.9440	314	1.2507 ± 0.0002	0.79955 ± 0.00013	93.2 ± 3.6	1.32 ± 0.08	2700.502 ± 0.005
				1.2986 ± 0.0002	0.77006 ± 0.00009	31.0 ± 6.5	1.20 ± 0.40	2700.392 ± 0.023
				0.9652 ± 0.0001	1.03605 ± 0.00011	23.3 ± 6.5	1.27 ± 0.55	2701.004 ± 0.045
	V	2537.5987–2830.9440	312	1.2507 ± 0.0001	0.79955 ± 0.00006	70.4 ± 2.9		2700.499 ± 0.005
				1.2986 ± 0.0002	0.77006 ± 0.00009	25.8 ± 5.0		2700.396 ± 0.021
				0.9652 ± 0.0001	1.03605 ± 0.00011	18.3 ± 5.0		2700.999 ± 0.044

TABLE 5—*Continued*

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) (9)
213617.............	*B*	2537.6179–2829.9515	225[b]	1.3232 ± 0.0002	0.75574 ± 0.00009	39.2 ± 2.9	1.23 ± 0.14	2700.218 ± 0.009
				1.3694 ± 0.0002	0.73025 ± 0.00008	24.0 ± 3.5	1.53 ± 0.32	2700.268 ± 0.017
	V	2537.6179–2829.9515	219[b]	1.3232 ± 0.0002	0.75574 ± 0.00009	31.8 ± 2.2		2700.207 ± 0.008
				1.3694 ± 0.0002	0.73025 ± 0.00011	15.7 ± 2.8		2700.269 ± 0.021

Notes.—The individual photometric observations are given in Tables 4A–4K, which are available in machine-readable format in the electronic edition of the *Astronomical Journal*.
[a] May not be an independent frequency. See § 6.5.
[b] Data from the monitoring night are not included in the analysis.

starspot variability. In addition, our observed photometric *B*/*V* amplitude ratios provide support for pulsations in these stars. Henry et al. (2000) demonstrated that ellipsoidal variables have *B*/*V* amplitude ratios close to 1.00, while starspot variables have typical *B*/*V* ratios around 1.12–1.14. The 11 stars in this paper all have significantly larger *B*/*V* amplitude ratios (typically 1.25–1.5), in agreement with theoretical models of γ Doradus stars with low spherical degree ($l = 1$, 2) nonradial pulsations (e.g., Garrido 2000).

Our Johnson *BV* photometry and limited spectroscopic observations are *not* sufficient to allow us to uniquely identify the spherical degree (l) or the azimuthal order (m) of the pulsations. Stamford & Watson (1981) demonstrated for nonradial pulsations that the wavelength dependence of the photometric amplitude and the phase shift between various photometric bands is a function of l but not m (with an additional dependence of the amplitude on the inclination of the pulsation axis to the observer). In practice, the identification of the spherical degree from photometric observations has many subtle difficulties (e.g., Garrido 2000; Sterken 2002). However, our observed *B*/*V* amplitude ratios and lack of detectable phase shifts between the two photometric bands (Table 5) are consistent with spherical degree $l = 1$ or 2 and probably inconsistent with $l = 3$ (Garrido 2000). Our spectroscopic observations, obtained primarily to determine spectral class and $v \sin i$ and to search for evidence of duplicity, are not nearly numerous enough to be used for line-profile variability and mode-identification studies. Such studies require much more extensive multisite, multitechnique observing campaigns (e.g., Handler et al. 2002; Aerts et al. 2004; Mathias et al. 2004).

6. NOTES ON INDIVIDUAL STARS

6.1. *HD 2842*

In a search for λ Bootis stars, Paunzen et al. (2001) classified HD 2842 as F0 V, similar to the F1: dwarf result of Fekel et al. (2003). Fekel et al. (2003) also reported a mean radial velocity of 8.5 km s^{-1} and $v \sin i = 90$ km s^{-1} from two spectra. Mathias et al. (2004) determined a $v \sin i$ value of 77 km s^{-1}. In their two blue-wavelength spectra, they found variations in the blue wings of its lines and, as a result, suggested that the star might be a binary. We have not obtained any additional spectroscopic observations of this star and assume that the star is single.

HD 2842 appears on the list of prime γ Doradus candidates of Handler (1999), where he finds a period of 0.562 days and possible additional periods around 0.5 days from his analysis of the *Hipparcos* photometry. The least-squares spectra of our *B* observations are plotted in Figure 1, and the results of our period analysis are given in Table 5. We find three closely spaced periods of 0.65070, 0.58381, and 0.59952 days, with peak-to-peak amplitudes in *B* of 40, 34, and 23 mmag, respectively. The observations are phased with these periods and the times of minimum given in Table 5 and plotted in Figure 2, which shows clear sinusoidal variations at all three periods. The ratios of the photometric amplitude in *B* to the amplitude in *V* for our three periods have a weighted mean of 1.36 ± 0.15, consistent with other γ Doradus pulsators (e.g., Henry & Fekel 2003) and inconsistent with the ellipticity effect or starspots (Henry et al. 2000, Table 8). Given the star's F1 dwarf classification, the multiple periods in the γ Doradus period range, and the *B*/*V* amplitude ratio, we confirm HD 2842 as a new γ Doradus variable.

6.2. *HD 17310*

Nordström et al. (2004) included HD 17310 in their solar neighborhood survey of about 14,000 F and G dwarfs but did not obtain any spectroscopic observations. From three observations Grenier et al. (1999) determined a mean radial velocity of 21.4 ± 3.6 km s^{-1} and classified the star as F2 IV–V. We determine a spectral class of F2, and its *Hipparcos* parallax (Perryman et al. 1997) indicates that the star is a dwarf. Our

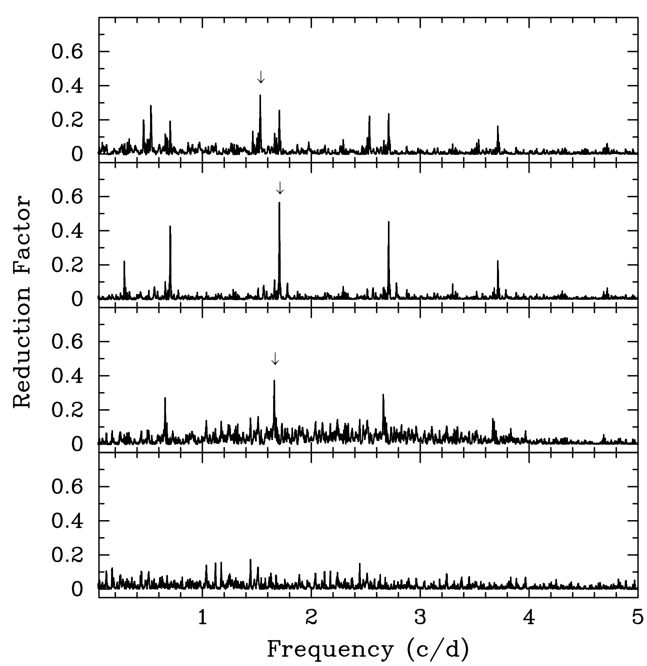

Fig. 1.—Least-squares spectra of the HD 2842 Johnson *B* data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies 1.5368, 1.7129, and 1.6680 day^{-1} (*top to bottom*). All three frequencies were confirmed in the Johnson *V* data set.

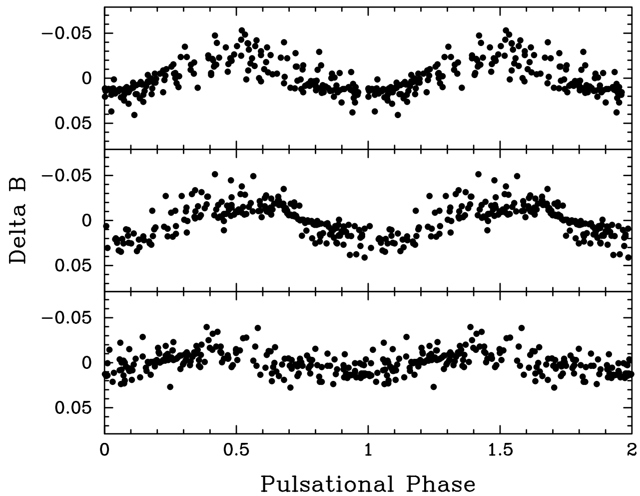

FIG. 2.—Johnson B photometric data for HD 2842, phased with the three frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies of 1.5368, 1.7129, and 1.6680 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

11 velocities (Table 2) have a range of 44 km s^{-1}, identifying HD 17310 as a spectroscopic binary. The lines of the primary, the only component visible in our spectra, are narrow but vary somewhat in width, with an average $v \sin i = 10.0 \pm 0.4$ km s^{-1}. The profile variations are presumably caused by pulsation.

We conducted a search between 0.1 and 50 days for the orbital period. The best circular-orbit fit to our 11 velocities results in a period of 0.9653 days. As a consequence of such a short period, the orbital axis of the binary and the rotational axes of the components would be aligned and the components would be synchronously rotating. The latter assumption produces a rotational velocity of 100 km s^{-1}. Combining this velocity with our $v \sin i$ value of 10 km s^{-1} results in a very low rotational inclination of 6°, which then is also the orbital inclination. Given the modest number of our velocity observations, their poor phase distribution, the very low and thus unlikely orbital inclination, plus velocity changes of several km s^{-1} from pulsation, we believe that the 0.9653 day "best" period is spurious. Instead, we prefer periods in the 20–30 day range, the best of which is 27.793 days. However, we caution that the eccentricity of such a long-period orbit may not be close to zero. Observations are continuing to determine the correct period and other orbital elements.

HD 17310 is a prime γ Doradus candidate from Handler (1999), who cited a photometric period of 2.030 days along with another more uncertain period of 2.917 days. We find three independent periods of 2.136, 1.827, and 2.454 in our Johnson B APT photometry, with amplitudes of 21, 15, and 12 mmag, respectively (Figs. 3 and 4; Table 5). The light curve is sinusoidal when phased with each of these three periods. The weighted mean B/V amplitude ratio for the three periods is 1.37 ± 0.15, indicating that variability is due to pulsation and not ellipticity or starspots. Therefore, we confirm that the F2 dwarf component of this single-lined binary is a γ Doradus star.

6.3. *HD 69715*

HD 69715 is the primary of a wide visual triple star with 8.8 and 14.0 mag companions at separations of 93″ and 34″, respectively. Mathias et al. (2004) collected two spectrograms of HD 69715 over a period of 4 days. They determined $v \sin i = 145$ km s^{-1}. We find a spectral class of F1:. A dwarf luminosity class is indicated by the *Hipparcos* parallax (Perryman et al.

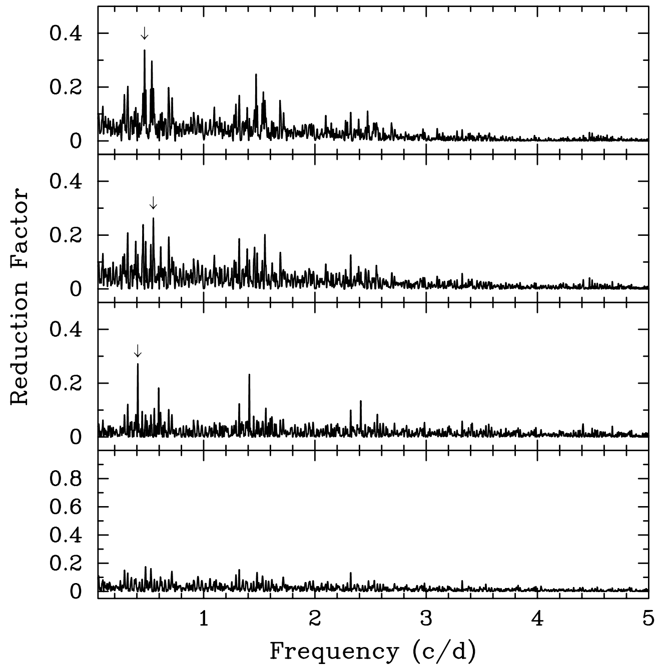

FIG. 3.—Least-squares spectra of the HD 17310 Johnson B data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies 0.4682, 0.5472, and 0.4075 day^{-1} (*top to bottom*). All three frequencies were confirmed in the Johnson V data set.

1997). The spectrum is more difficult to classify because of its broad and shallow lines, for which we measure $v \sin i = 150$ km s^{-1}. Our two radial velocities (Table 2) are likewise more uncertain. They have a mean of -11.2 km s^{-1} and show no evidence of significant variability since they differ by less than 2 km s^{-1}.

Handler (1999) lists HD 69715 as one of his prime γ Doradus candidates, with a period of 0.423 days and possible additional periods around 0.5 days. Martín et al. (2003) acquired 57 photometric observations of HD 69715 on five nights with the 90 cm telescope at Observatorio de Sierra Nevada, Spain, and reported periods of 0.579 and 0.412 days. Our more numerous APT observations cover a range of 248 days and reveal two closely spaced periods of 0.40707 and 0.40957 days, with B amplitudes

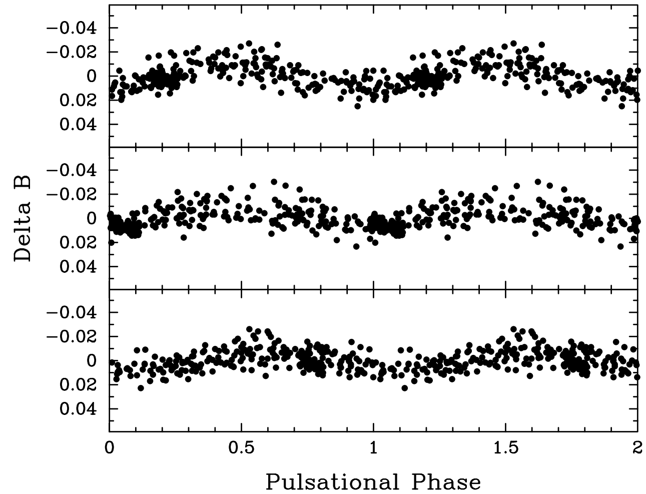

FIG. 4.—Johnson B photometric data for HD 17310, phased with the three frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies of 0.4682, 0.5472, and 0.4075 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

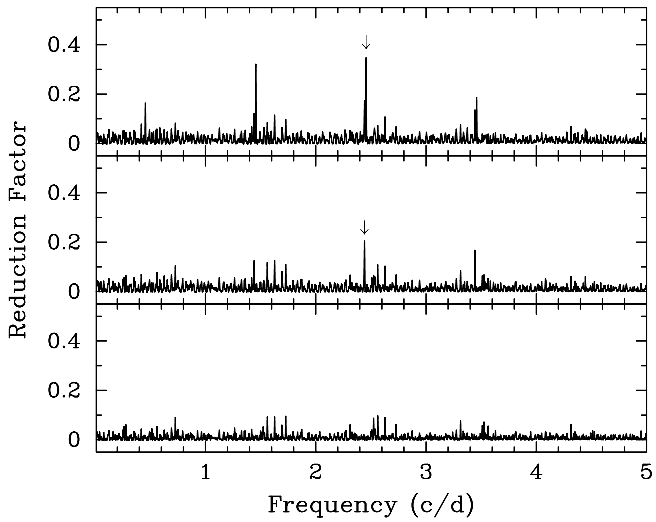

FIG. 5.—Least-squares spectra of the HD 69715 Johnson *B* data set, showing the results of progressively fixing the two detected frequencies. The arrows indicate the two frequencies at 2.4566 day^{-1} (*top*) and 2.4416 day^{-1} (*middle*). Both frequencies were confirmed in the Johnson *V* data set.

of 20 and 14 mmag, respectively (Figs. 5 and 6; Table 5). Both periods exhibit sinusoidal variations in the light curve. The weighted mean *B*/*V* amplitude ratio for the two periods is 1.23 ± 0.12, indicating that variability is due to pulsation. Therefore, we confirm HD 69715 as a γ Doradus pulsator.

6.4. *HD 70645*

Mathias et al. (2004) discovered HD 70645 to be a single-lined spectroscopic binary, and they determined an orbital period of 8.445 days with 11 velocities. We have obtained three additional velocities (Table 2). Our first two observations are separated by almost exactly six cycles, and the velocities, which are near velocity maximum, are in good agreement with the published orbit. However, our third velocity has a residual of about 10 km s^{-1}. Thus, the orbital elements require some revision. We classify HD 70645 as F1, and the *Hipparcos* parallax indicates that it is a dwarf. Like HD 17310, its lines are quite narrow and variable with an average $v \sin i = 10.7 \pm 1.1$ km s^{-1}, in agreement with the value of 11 km s^{-1} found by Mathias et al. (2004).

HD 70645 is included in the list of prime γ Doradus candidates of Handler (1999), with a period of 0.825 days and possible additional periods around 1.25 days. Martín et al. (2003)

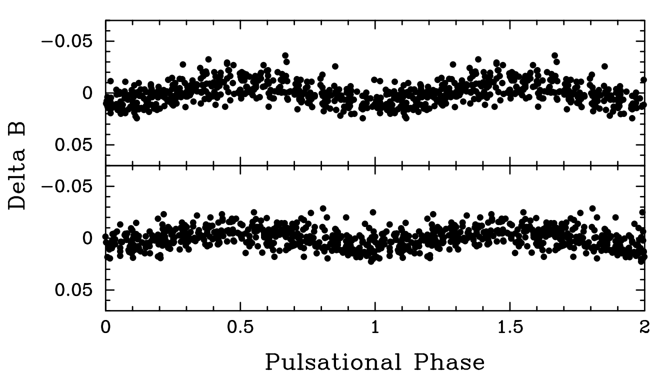

FIG. 6.—Johnson *B* photometric data for HD 69715, phased with the two frequencies and times of minimum from Table 5. The two frequencies are 2.4566 day^{-1} (*top*) and 2.4416 day^{-1} (*bottom*). For each panel, the data set has been prewhitened to remove the other known frequency.

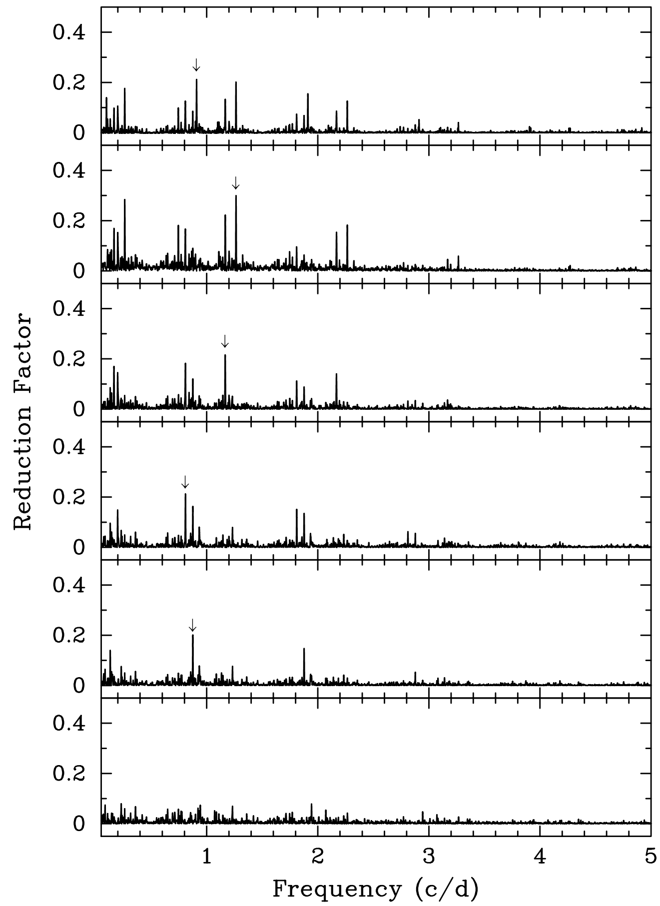

FIG. 7.—Least-squares spectra of the HD 70645 Johnson *B* data set, showing the results of progressively fixing the five detected frequencies. The arrows indicate the five frequencies 0.9065, 1.2612, 1.1640, 0.8061, and 0.8726 day^{-1} (*top to bottom*). All five frequencies were confirmed in the Johnson *V* data set.

collected 54 photometric observations on five nights at Observatorio de Sierra Nevada and reported periods of 1.148 and 0.690 days. We find five independent periods of 1.1031, 0.7929, 0.8591, 1.2405, and 1.1460 days in our APT photometry, with *B* amplitudes of 41, 40, 33, 32, and 27 mmag, respectively (Figs. 7 and 8; Table 5). All five periods give approximately sinusoidal phase curves, although there is some suggestion of cycle-to-cycle variation in the level of maximum brightness, similar to the Blazhko effect observed in some RR Lyrae variables (Szeidl 1976) and also in a few other γ Doradus stars (see, e.g., the references in Fekel & Henry 2003). The weighted mean *B*/*V* amplitude ratio for the five periods is 1.33 ± 0.10, indicating variability due to pulsation and not ellipticity or starspots. Therefore, we confirm the F1 dwarf primary component of HD 70645 as a γ Doradus variable.

6.5. *HD 80731*

Moore & Paddock (1950) observed HD 80731 at Lick Observatory as part of a general program to measure radial velocities. From two observations they determined a velocity of 4 ± 2.5 km s^{-1} and also classified the star as F0 V. Our spectral type is quite similar, F1 dwarf. Mathias et al. (2004) found HD 80731 to be a single-lined spectroscopic binary with a period of 13.57 days. At red wavelengths we also find the spectrum to be single-lined. Our seven spectrograms show a velocity range of 36 km s^{-1} (Table 2) but are *not* consistent with the orbit of Mathias et al. (2004). Mathias et al. (2004) determined a mean

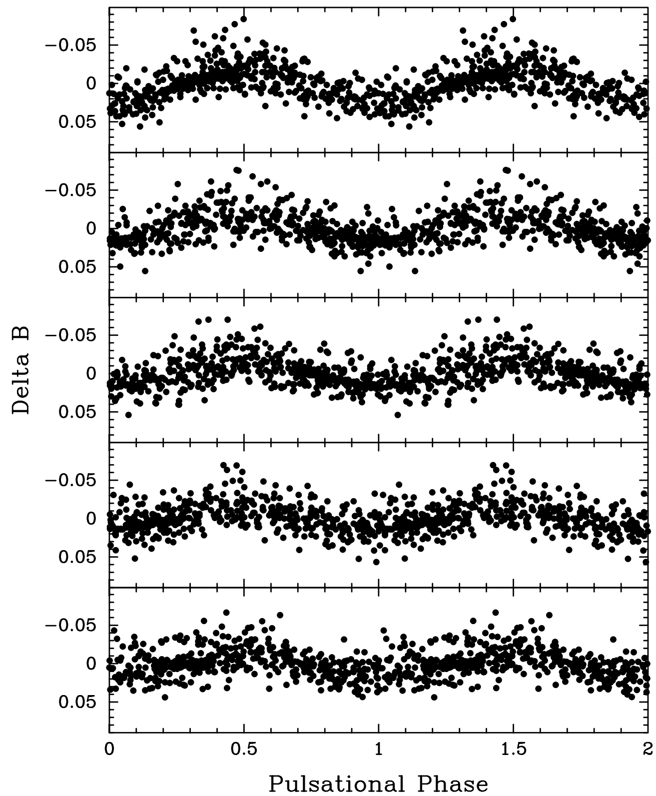

FIG. 8.—Johnson *B* photometric data for HD 70645, phased with the five frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies of 0.9065, 1.2612, 1.1640, 0.8061, and 0.8726 day^{-1}. For each panel, the data set has been prewhitened to remove the other four known frequencies.

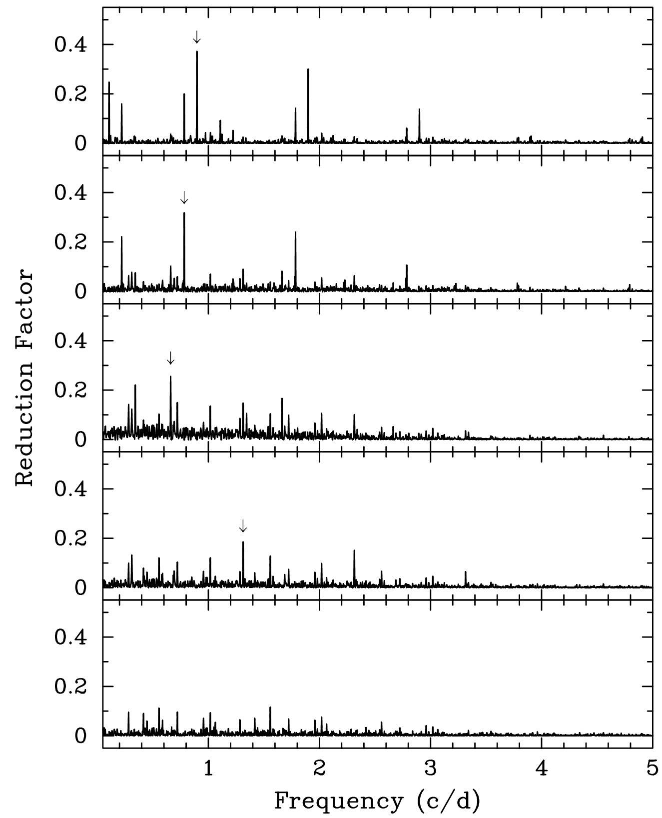

FIG. 9.—Least-squares spectra of the HD 80731 Johnson *B* data set, showing the results of progressively fixing the four detected frequencies. The arrows indicate the four frequencies 0.8961, 0.7823, 0.6599, and 1.3119 day^{-1} (*top to bottom*). All four frequencies were confirmed in the Johnson *V* data set.

$v \sin i = 13$ km s^{-1} and noted that the star has line profile variability. Our values of $v \sin i$ range from 11.3 to 18.3 km s^{-1}, and the mean value from our seven spectra is 14.5 ± 1.1 km s^{-1}.

HD 80731 is a prime γ Doradus candidate from Handler (1999), who finds a period of 1.116 days and possible additional periods around 1.4 days. Martín et al. (2003) found periods of 2.237 and 1.403 days with their 50 photometric observations in five nights from Observatorio de Sierra Nevada. In our APT data covering 252 nights, we find four periods at 1.1160, 1.2783, 1.5154, and 0.7622 days, with *B* amplitudes of 61, 45, 19, and 15 mmag, respectively (Figs. 9 and 10; Table 5). The fourth period is approximately half of the third, so it may not be an independent period. The light curve approximates a sinusoid when phased with each of the four periods. However, as with HD 70645, there is a suggestion of cycle-to-cycle variation in the level of maximum brightness. The weighted mean *B*/*V* amplitude ratio for the four periods is 1.26 ± 0.10, indicating that the photometric variability is due to pulsation. Thus, given its spectroscopic and photometric properties, we confirm that the F1 dwarf primary in HD 80731 is a γ Doradus variable.

6.6. *HD 112429 (HR 4916, IR Dra)*

HD 112429 is bright enough to be included in the Bright Star Catalogue (Hoffleit 1982). Thus, it has been observed in a wide variety of bright-star surveys. Recently, Fekel et al. (2003) classed the star as an F1 dwarf, similar to other results in the literature, and found it to have $v \sin i = 115$ km s^{-1}. The two velocities of Fekel et al. (2003) plus three others in the literature show no significant variability, indicating that HD 112429 is a single star. Mathias et al. (2004) collected 40 spectra of this star. They determined a $v \sin i$ of 101 km s^{-1} and noted that the wings

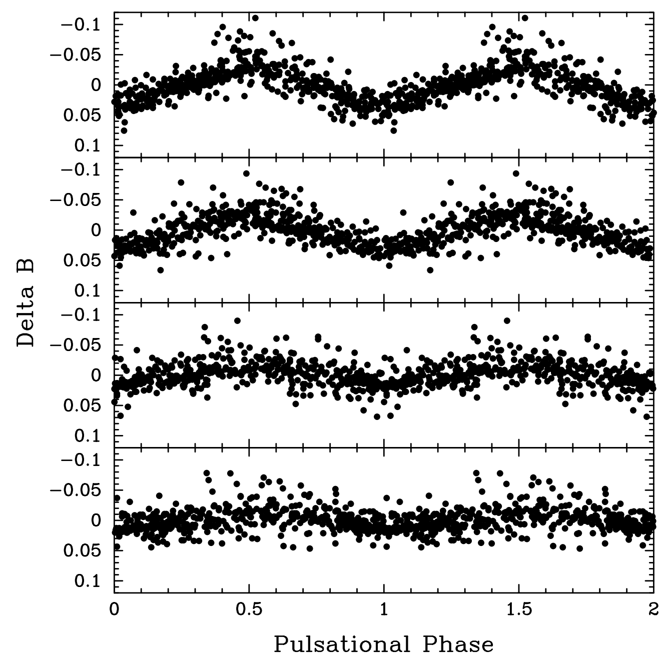

FIG. 10.—Johnson *B* photometric data for HD 80731, phased with the four frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies of 0.8961, 0.7823, 0.6599, and 1.3119 day^{-1}. For each panel, the data set has been prewhitened to remove the other three known frequencies.

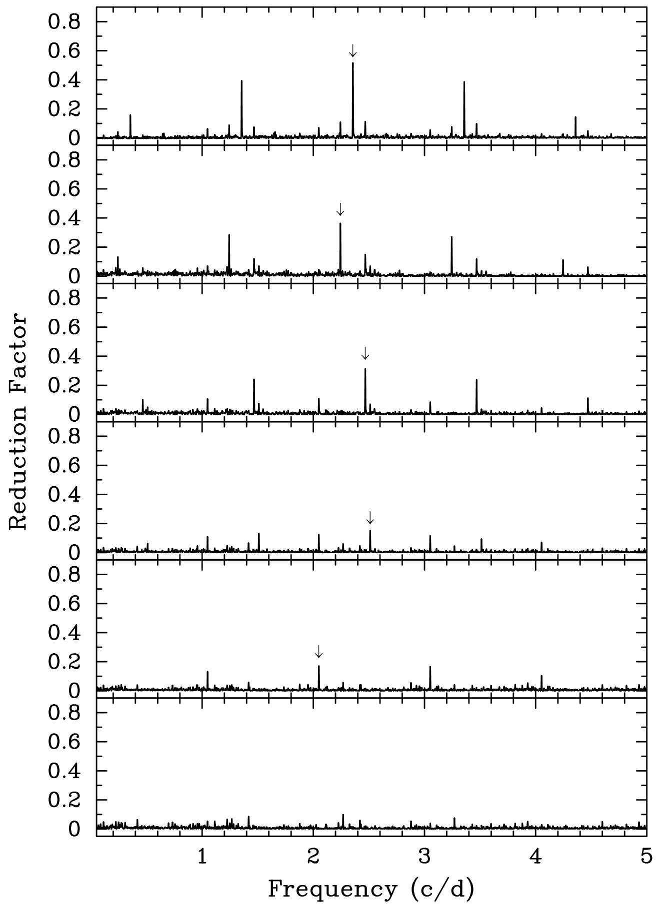

FIG. 11.—Least-squares spectra of the HD 112429 Johnson B data set, showing the results of progressively fixing the five detected frequencies. The arrows indicate the five frequencies 2.3557, 2.2430, 2.4671, 2.5107, and 2.0493 day^{-1} (*top to bottom*). All five frequencies were confirmed in the Johnson V data set.

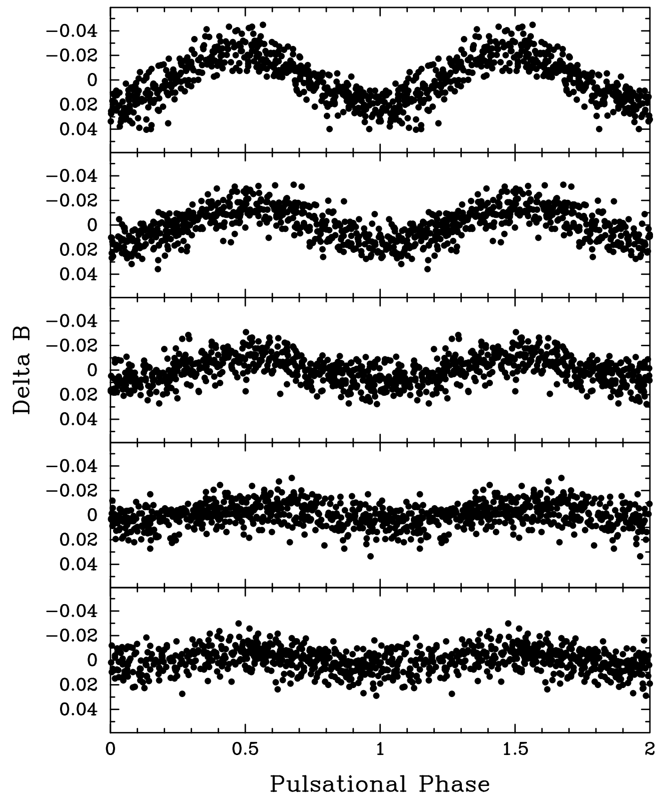

FIG. 12.—Johnson B photometric data for HD 112429, phased with the five frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies of 2.3557, 2.2430, 2.4671, 2.5107, and 2.0493 day^{-1}. For each panel, the data set has been prewhitened to remove the other four known frequencies.

of its lines had line profile variations. We have obtained no additional spectroscopic observations.

The *Hipparcos* mission team discovered HD 112429 to be variable, with a period of 0.424504 days. Aerts et al. (1998) reanalyzed that photometry and found periods of 0.4245 and 0.4458 days. They identified the star as a new candidate γ Doradus variable. As a result, Kazarovets et al. (2000) provided it with the variable star name IR Dra. It also appears as a prime γ Doradus candidate in the list of Handler (1999), who cites the periods from Aerts et al. (1998).

We find five closely spaced periods of 0.42450, 0.44583, 0.40533, 0.39830, and 0.48797 days in our APT photometry, with B amplitudes of 47, 22, 22, 8, and 17 mmag, respectively (Figs. 11 and 12; Table 5). All five periods give approximately sinusoidal phase curves. The weighted mean B/V amplitude ratio for the five periods is 1.21 ± 0.08, indicating variability due to pulsations and not ellipticity or starspots. Therefore, we confirm that HD 112429 is a γ Doradus variable.

6.7. *HD 115466 (58 Vir, LP Vir)*

Fekel et al. (2003) classified HD 115466 as an F1 subgiant and from their lone spectrum found a projected rotational velocity of 44 km s^{-1}. That value, combined with four additional observations (Table 2), results in a slightly smaller value of 42 km s^{-1}. While Christie & Wilson (1938) computed a mean radial velocity of 6 ± 1.8 km s^{-1}, Fekel et al. (2003) measured a value of 12.5 km s^{-1} from a single observation. Our four additional spectra range in velocity from 7.9 to 13.4 km s^{-1} and have an average velocity of 11.5 km s^{-1}. Thus, the mean of the five KPNO velocities is 11.7 ± 1.0 km s^{-1}. The difference between the KPNO mean velocity and that of Christie & Wilson (1938) likely results from different observatory zero points and line profile variations. HD 115466 is probably a single star, but additional observations will be necessary to confirm this conclusion.

The *Hipparcos* mission team discovered the light variability of HD 115466 and determined a period of 1.68350 days (Perryman et al. 1997). They concluded that it was an eclipsing binary. Kazarovets et al. (1999) provided the variable star designation LP Vir and classified it as an uncertain ellipsoidal variable. Handler (1999) included it in his list of prime γ Doradus candidates with periods of 0.927 and 0.703 days.

In our APT photometry, we find three independent periods of 0.8302, 0.7342, and 0.6951 days, with B amplitudes of 32, 16, and 16 mmag, respectively (Figs. 13 and 14; Table 5). The light curve closely approximates a sinusoid when phased with each of these three periods. The weighted mean B/V amplitude ratio for the three periods is 1.47 ± 0.11, indicating that the photometric variability is due to pulsation. Thus, we confirm this F1 subgiant as a γ Doradus variable, so the variability type listed in the General Catalog of Variable Stars (GCVS) and in SIMBAD should be revised.

6.8. *HD 124248 (97 Vir, MU Vir)*

Fekel et al. (2003) identified HD 124248 as an A9 dwarf and determined a projected rotational velocity of 48 km s^{-1}. Three recent observations (Table 2), combined with the one of Fekel et al. (2003), result in a slightly larger average $v \sin i$ value of 49.6 ± 0.8 km s^{-1}. The mean radial velocity of the four

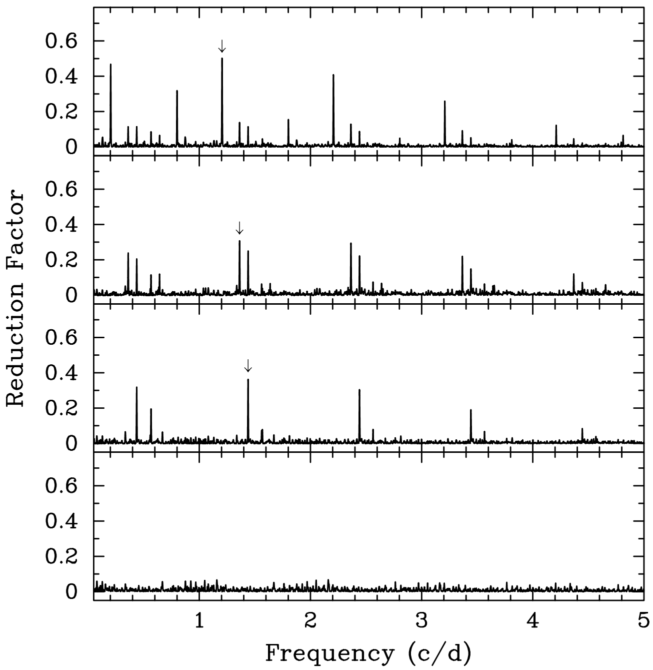

FIG. 13.—Least-squares spectra of the HD 115466 Johnson *B* data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies 1.2045, 1.3621, and 1.4387 day^{-1} (*top to bottom*). All three frequencies were confirmed in the Johnson *V* data set.

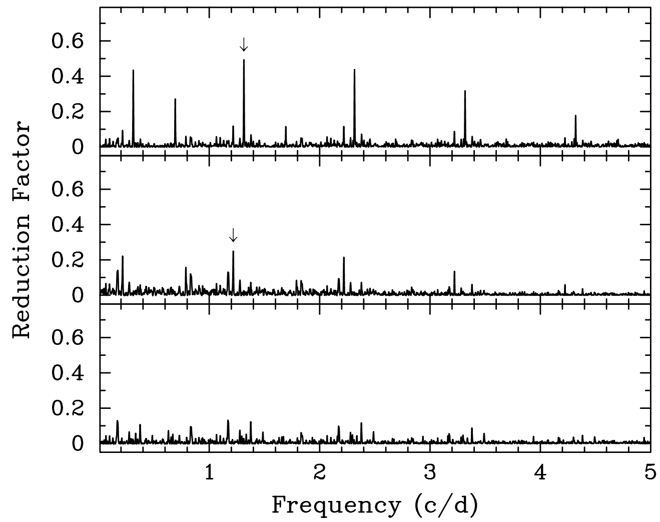

FIG. 15.—Least-squares spectra of the HD 124248 Johnson *B* data set, showing the results of progressively fixing the two detected frequencies. The arrows indicate the two frequencies at 1.3133 day^{-1} (*top*) and 1.2166 day^{-1} (*middle*). Both frequencies were confirmed in the Johnson *V* data set.

observations is -1.4 ± 1.2 km s^{-1}. This value is consistent with the mean velocity of 0.0 ± 4.0 km s^{-1} from four Mount Wilson spectra (Wilson & Joy 1950). The lines of two of the recent KPNO spectra are asymmetric, probably as a result of pulsation rather than unresolved duplicity. We currently assume that the star is single.

Hipparcos identified HD 124248 as a variable star with a period of 1.34092 days and called it an eclipsing binary (Perryman et al. 1997). Kazarovets et al. (1999) gave it the variable star name MU Vir and classified it as an uncertain eclipsing binary. It was included by Handler (1999) in his list of prime γ Doradus candidates with photometric periods of 0.671 and 0.617 days.

We find two independent periods of 0.7614 and 0.8218 days in our APT photometry, with *B* amplitudes of 53 and 24 mmag, respectively (Figs. 15 and 16; Table 5). The light curve closely approximates a sinusoid when phased with these two periods. The weighted mean *B*/*V* amplitude ratio for the two periods is 1.30 ± 0.12, indicating that the photometric variability is due to pulsation. Thus, we confirm this A9 dwarf as a γ Doradus variable. These photometric results, along with the lack of evidence for a companion in our radial velocities, indicate that the variability type listed in the GCVS and in SIMBAD should be revised.

6.9. *HD 175337*

From three spectrograms Fekel et al. (2003) concluded that HD 175337 was probably single despite significant line asymmetries. They determined the star to be an F2 dwarf with $v \sin i = 38$ km s^{-1}. Recently, from seven spectra Mathias et al. (2004) noted that line profile variability was evident and concluded that the star was unlikely to be a binary. Their $v \sin i$ value was identical to that of Fekel et al. (2003). We have obtained three additional spectrograms at KPNO (Table 2). Our six observations have a total range in velocity of 4.5 km s^{-1} and

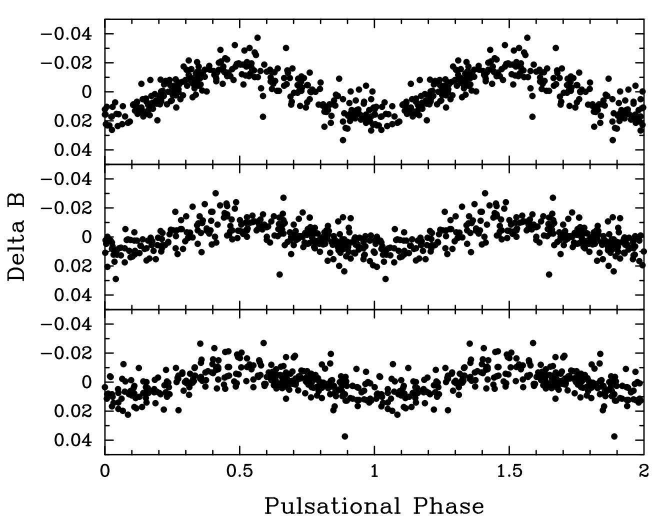

FIG. 14.—Johnson *B* photometric data for HD 115466, phased with the three frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies of 1.2045, 1.3621, and 1.4387 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

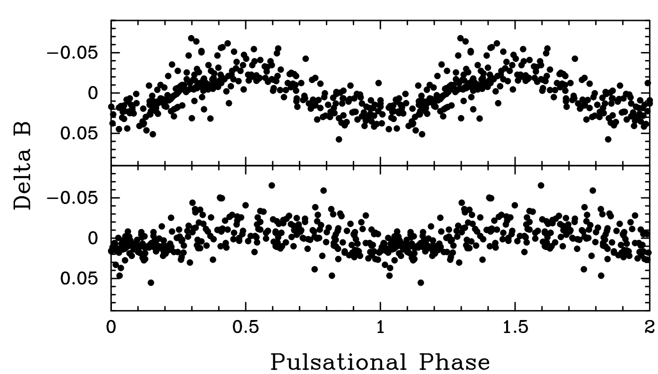

FIG. 16.—Johnson *B* photometric data for HD 124248, phased with the two frequencies and times of minimum from Table 5. The two frequencies are 1.3133 day^{-1} (*top*) and 1.2166 day^{-1} (*bottom*). For each panel, the data set has been prewhitened to remove the other known frequency.

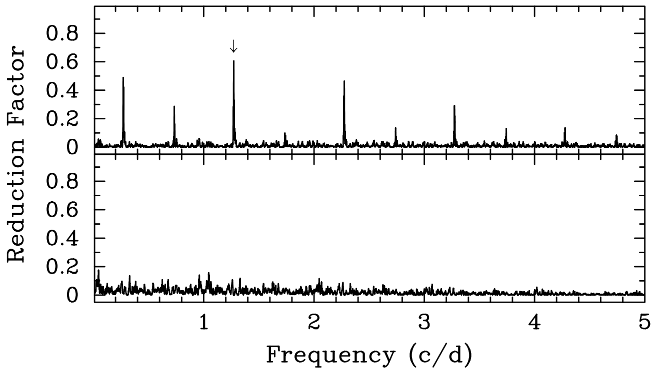

FIG. 17.—Least-squares spectra of the HD 175337 Johnson *B* data set. The arrow in the top panel indicates the single detected frequency at 1.2708 day^{-1}. The bottom panel shows the least-squares spectrum with the 1.2708 day^{-1} frequency fixed. The same frequency was confirmed in the Johnson *V* data set.

an average radial velocity of -1.4 ± 0.6 km s^{-1}. Our revised mean projected rotational velocity is still 37.6 ± 0.7 km s^{-1}. All the current spectroscopic observations indicate that HD 175337 is likely a single star with line asymmetries caused by pulsation rather than duplicity.

HD 175337 was included by Handler (1999) as a prime γ Doradus candidate, with periods of 0.787 and 1.057 days. We find only a single period of 0.7869 days in our APT photometry, with an amplitude of 35 mmag in *B* (Figs. 17 and 18; Table 5). The light curve approximates a sinusoid when phased with this period. The *B*/*V* amplitude ratio is 1.15 ± 0.10, consistent with pulsation but also with ellipsoidal variation and starspots (Henry et al. 2000, Table 8). The possibility that the photometric variability is due to the ellipticity effect in a short-period binary is excluded by the lack of large radial velocity variations. Likewise, starspot activity (implying a stellar rotation period of 0.7869 days) is unlikely because of the early spectral class of the star, its relatively low $v \sin i$ of 38 km s^{-1}, and the coherency of the light curve over hundreds of cycles. Instead, the variable line profiles suggest the presence of pulsation. Thus, we conclude the photometric variability is due to pulsation and confirm this F2 dwarf as a γ Doradus star.

6.10. *HD 195068/9 (HR 7828, 43 Cyg, V2121 Cyg)*

This star has two HD numbers and is listed as HD 195068 in the Bright Star Catalogue (Hoffleit 1982) but as HD 195069 in SIMBAD. Abt & Morrell (1995) classified HD 195068/9 as F2 V and found $v \sin i = 43$ km s^{-1}. Fekel et al. (2003) found similar results, F1: dwarf and $v \sin i = 44$ km s^{-1}, while Mathias et al. (2004) measured 46 km s^{-1}. The radial velocities of Fekel et al. (2003) and Fehrenbach et al. (1997) are in agreement, while the earlier mean velocity of Harper (1937) is 9 km s^{-1} more positive, suggesting that the star might be a binary. Fekel et al. (2003) showed that its line profiles have large asymmetries, which appear to be similar to those of HD 221866 (Henry & Fekel 2002). From an analysis of 36 spectra, covering 564 days, Mathias et al. (2004) noted that line profile variations are evident but did not comment on the duplicity of the star. We have obtained two additional spectrograms, one of which shows significant line asymmetries. The new velocities (Table 2), averaged with the two of Fekel et al. (2003), result in a mean radial velocity of -27.6 ± 1.2 km s^{-1}. Unlike HD 221866, which was recently shown to be a double-lined spectroscopic binary (Mathias et al. 2004; Kaye et al. 2004), the evidence to date indicates that HD 195068/9 is a single star.

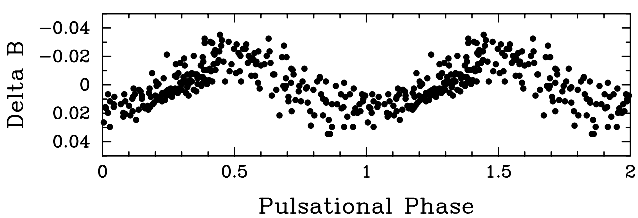

FIG. 18.—Johnson *B* photometric data for HD 175337, phased with the single frequency of 1.2708 day^{-1} and time of minimum from Table 5.

The *Hipparcos* mission team discovered HD 195068/9 to be a variable star with a period of 0.799678 days (Perryman et al. 1997). They concluded that it was an RR Lyrae variable with an asymmetric light curve. Kazarovets et al. (1999) provided it with the variable star designation V2121 Cyg. They classified it as RRAB:, an uncertain RR Lyrae variable, and noted that it had a strong Blazhko effect. Handler (1999) included the star in his list of prime γ Doradus candidates. He cited a period of 0.800 days and a more uncertain period of 3.7 days, both from the thesis of Eyer (1998).

We find three independent periods of 0.7996, 0.7701, and 1.0360 days in our APT photometry, with *B* amplitudes of 93, 31, and 23 mmag, respectively (Figs. 19 and 20; Table 5). The second panel of Figure 19 shows that Eyer's uncertain 3.7 day (0.27 day^{-1}) period is probably an alias of our second period. The light curve approximates a sinusoid when phased with each of our periods. However, as with HD 70645 and HD 80731, the Blazhko effect is apparent, as noted above by Kazarovets et al. (1999). The weighted mean *B*/*V* amplitude ratio for the three periods is 1.31 ± 0.08, indicating photometric variability due to pulsation. Therefore, we confirm HD 195068/9 as a γ Doradus variable and note that its variability type in the GCVS and in SIMBAD should be revised.

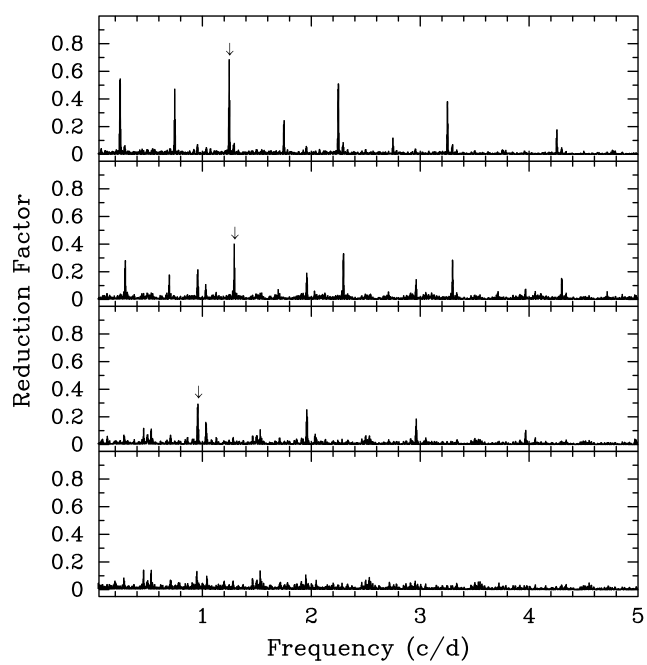

FIG. 19.—Least-squares spectra of the HD 195068/9 Johnson *B* data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies 1.2507, 1.2986, and 0.9652 day^{-1} (*top to bottom*). All three frequencies were confirmed in the Johnson *V* data set.

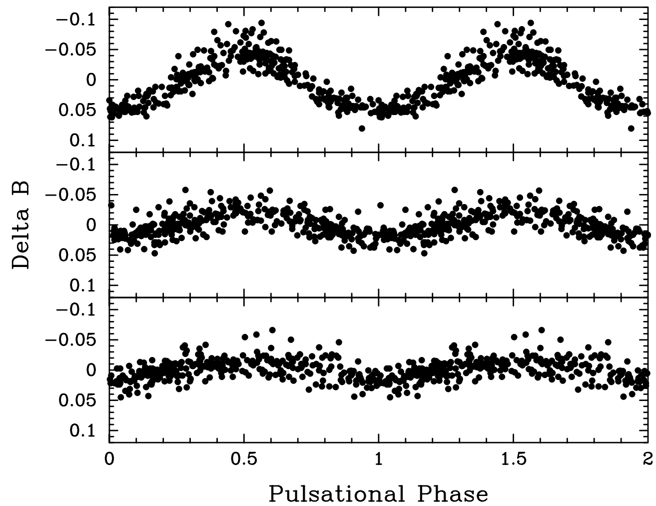

FIG. 20.—Johnson *B* photometric data for HD 195068/9, phased with the three frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies of 1.2507, 1.2986, and 0.9652 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

6.11. *HD 213617 (HR 8586, 39 Peg)*

The lone KPNO spectrogram of this F1 dwarf from Fekel et al. (2003) gives a projected rotational velocity of 70 km s^{-1} and a radial velocity of -12.1 km s^{-1}, which differs from the mean radial velocity of Shajn & Albitzky (1932) by 8 km s^{-1} and suggests that HD 213617 might be a binary. Five additional KPNO velocities (Table 2), averaged with the earlier one, result in a mean $v \sin i$ of 66.1 ± 0.9 km s^{-1} and a mean radial velocity of -13.8 ± 1.2 km s^{-1}. This reduces the radial velocity difference between the two observatories to 6.1 km s^{-1}, which is a 2 σ difference. The six KPNO velocities, obtained over a 1400 day period, show a velocity variation of 8 km s^{-1}. However, that maximum variation occurred over a 1 day interval (Table 2). Thus, we believe that HD 213617 is likely single, with the variable velocity resulting from line profile variations caused by pulsation.

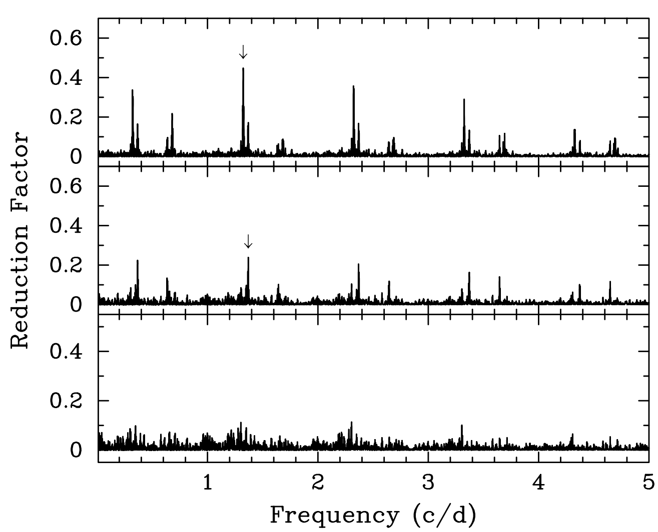

FIG. 21.—Least-squares spectra of the HD 213617 Johnson *B* data set, showing the results of progressively fixing the two detected frequencies. The arrows indicate the two frequencies at 1.3232 day^{-1} (*top*) and 1.3694 day^{-1} (*middle*). Both frequencies were confirmed in the Johnson *V* data set.

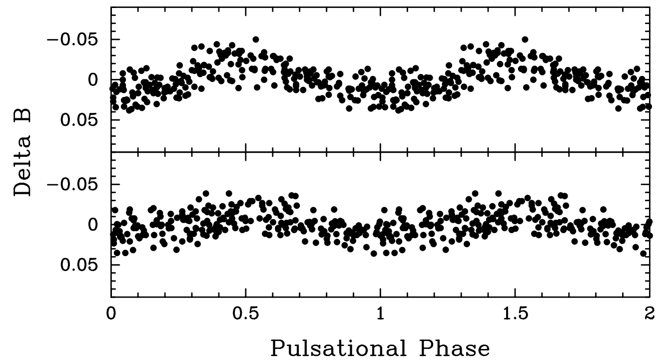

FIG. 22.—Johnson *B* photometric data for HD 213617, phased with the two frequencies and times of minimum from Table 5. The two frequencies are 1.3232 day^{-1} (*top*) and 1.3694 day^{-1} (*bottom*). For each panel, the data set has been prewhitened to remove the other known frequency.

HD 213617 is the only star in our sample that came from the list of further candidates in Handler (1999). He gave a photometric period of 0.569 days but noted that it was a weak signal. We find two closely spaced periods of 0.7557 and 0.7302 days in our APT photometry, with *B* amplitudes of 39 and 24 mmag, respectively (Figs. 21 and 22; Table 5). The single night of monitoring data was not included in our analysis since it seemed to complicate the analysis rather than simplify it. The light curve closely approximates a sinusoid when phased with our two periods. The weighted mean *B*/*V* amplitude ratio for the two periods is 1.28 ± 0.13, indicating that the photometric variability is due to pulsation. Thus, we confirm this F1 dwarf as a γ Doradus variable.

7. DISCUSSION

In Table 6 we list all 54 γ Doradus stars that have been confirmed to date, including the 11 stars in this paper. The list includes 29 single stars, six single-lined spectroscopic binaries, 11 double-lined binaries, and 10 visual double or multiple systems. Both HD 7169 and HD 23874 are very close visual doubles (Perryman et al. 1997) *and* double-lined binaries (Fekel et al. 2003), and so were counted in both categories. In most of the cases involving duplicity, it is clear that the primary component is the γ Doradus variable; in those cases, we have appended an "A" to the HD number in column (1) to designate the primary component. HD 221866, however, is a double-lined system for which Kaye et al. (2004) have shown that the *secondary* is probably the γ Doradus star; we have appended a "B" to its HD number in Table 6. The two components of the double-lined binaries HD 86371 and HD 113867 are similar in spectral type, so it is not clear which star is the γ Doradus variable; indeed, both components could be pulsating. In those two cases we have listed both the primary and secondary components in Table 6 with designations of "A:" and "B:", indicating uncertainty in identifying the γ Doradus component. Therefore, Table 6 actually contains 56 entries.

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 directly from the *Hipparcos* catalog (Perryman et al. 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); Henry & Fekel (2003) provide details on the determination of those values. The stellar properties listed in columns (6)–(8) have all been determined from the *V* magnitudes,

TABLE 6

Derived Properties of γ Doradus Stars

HD[a] (1)	Other Names (2)	Duplicity[b] (3)	V (mag) (4)	$(B-V)$ (mag) (5)	M_V (mag) (6)	L ($L_\odot$) (7)	R ($R_\odot$) (8)	Period (days) (9)	References (10)
277	...	Single	8.37	0.379	3.31	3.7	1.4	0.9005	1
2842	...	Single	7.99	0.325	2.83	5.7	1.6	0.65070	2
7169A	HDS 160	VB, SB2	7.42	0.329	2.98	5.0	1.5	0.5486	3
8801	HR 418, ADS 1151 A	VB	6.42	0.311	2.68	6.5	1.7	0.40331	4
12901	...	Single	6.74	0.311	2.35	8.9	1.9	0.82270	5
17310A	...	SB1	7.76	0.378	2.56	7.3	1.9	2.13584	2
18995	...	Single	6.72	0.342	2.32	9.1	2.1	1.0833	6
19684A	...	SB1	6.96	0.301	1.86	13.8	2.4	0.34722	6
23874A	ADS 2785 A	VB, SB2	8.45	0.329	2.67	6.6	1.7	0.4432	3
27290	γ Dor, HR 1338	Single	4.26	0.312	2.72	6.3	1.6	0.7570	7
32537A	V398 Aur, 9 Aur, HR 1637, ADS 3675 A	VB	4.98	0.343	2.89	5.4	1.6	1.2582	8
48271	...	Single	7.49	0.315	2.62	6.9	1.7	1.0959	3
48501A	HR 2481, ADS 5377 A	VB	6.26	0.321	2.81	5.8	1.6	0.7750[c]	5
49015A	...	VB	7.04	0.375	2.83	5.7	1.7	0.52718	6
55892	QW Pup, HR 2740	Single	4.49	0.324	2.86	5.5	1.6	0.9584	9
62454A	DO Lyn	SB2	7.43	0.329	2.67	6.6	1.7	0.62447	10
64729	...	Single	7.57	0.321	2.55	7.4	1.8	0.7248	3
65526	V769 Mon	Single	6.98	0.297	3.03	4.7	1.4	0.644	11
68192	KO UMa	Single	7.15	0.363	2.29	9.4	2.1	0.7691	10
69715A	BDS 4550 A	VB	7.18	0.360	3.09	4.5	1.5	0.40707	2
70645A	...	SB1	8.12	0.344	2.51	7.7	1.9	1.10314	12, 2
80731A	...	SB1	8.46	0.345	2.61	7.0	1.8	1.11595	12, 2
86358A	HR 3936	SB2	6.87	0.300	2.75	6.1	1.6	0.7753	3
86371A:	...	SB2	7.37	0.314	2.91	5.3	1.5	2.459	11
86371B:	...	SB2	7.37	0.314	2.91	5.3	1.5	2.459	11
99329	80 Leo, HR 4410	Single	6.35	0.345	2.41	8.4	2.0	0.45286	6
100215A	...	SB2	8.08	0.265	2.91	5.3	1.4	0.7564	3
105085A	...	SB2	7.59	0.300	2.82	5.7	1.5	0.6879	3
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	13, 6
112429	IR Dra, 8 Dra, HR 4916	Single	5.23	0.303	2.93	5.2	1.5	0.42450	2
113867A:	...	SB2	7.40	0.265	2.53	7.5	1.7	1.1252	3
113867B:	...	SB2	7.80	0.329	2.93	5.2	1.5	1.1252	3
115466	LP Vir, 58 Vir	Single	6.89	0.338	2.39	8.5	2.0	0.83022	2
124248	MU Vir, 97 Vir	Single	7.15	0.333	3.07	4.6	1.4	0.76144	2
139095	CF UMa, HR 4550	Single	7.91	0.366	2.62	7.0	1.9	0.634	11
152896	V645 Her	Single	7.55	0.314	2.85	5.6	1.5	0.7472	3
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	3
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	14, 15
165645A	HR 6767, ADS 11054 A	VB	6.38	0.287	2.59	7.1	1.7	0.4210	3
166233A	73 Oph, HR 6795, ADS 11111 A	VB	6.03	0.320	2.49	7.8	1.8	0.61439	16
167858A	V2502 Oph, HR 6844	SB1	6.62	0.312	2.64	6.8	1.7	1.307	11, 16
171244	...	Single	7.75	0.397	2.06	11.7	2.5	1.0040	3
175337	...	Single	7.39	0.364	2.76	6.1	1.7	0.78691	12, 2
181998	...	Single	7.67	0.328	2.81	5.8	1.6	1.334	11
195068/9	V2121 Cyg, 43 Cyg, HR 7828	Single	5.73	0.339	2.85	5.6	1.6	0.79955	12, 2
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	17
209295A	...	SB1	7.33	0.261	1.90	13.4	2.2	0.88547	18
213617	39 Peg, HR 8586	Single	6.43	0.350	2.81	5.8	1.7	0.75574	2
218396	V342 Peg, HR 8799	Single	5.97	0.259	2.96	5.0	1.4	0.5053	19
221866B	...	SB2	8.62	0.380	3.25	3.9	1.4	1.1416	6, 20
224638	BT Psc	Single	7.49	0.342	2.98	4.9	1.5	1.2323	21
224945	BU Psc	Single	6.93	0.292	3.07	4.5	1.4	1.4943	21

[a] Colon indicates that component A and/or B could be the γ Doradus star.

[b] (VB) Visual binary or double star; (SB) spectroscopic binary.

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

References.—(1) Henry et al. 2001; (2) this paper; (3) Henry & Fekel 2003; (4) Henry & Fekel 2005; (5) Eyer & Aerts 2000; (6) Henry & Fekel 2002; (7) Balona et al. 1994; (8) Zerbi et al. 1997a; (9) Poretti et al. 1997; (10) Kaye et al. 1999c; (11) Handler & Shobbrook 2002; (12) Mathias et al. 2004; (13) Breger et al. 1997; (14) Zerbi et al. 1997b; (15) Hatzes 1998; (16) Fekel & Henry 2003; (17) Kaye et al. 1999b; (18) Handler et al. 2002; (19) Zerbi et al. 1999; (20) Kaye et al. 2004; (21) Mantegazza et al. 1994.

$B-V$ colors, and parallaxes by the method outlined in Henry et al. (2001). Most of these stars have multiple photometric periods; the period given in column (9) is the one with the largest amplitude. Column (10) gives the literature reference(s) establishing each star as a γ Doradus variable.

Handler (1999) listed 46 prime γ Doradus candidates, based on analysis of *Hipparcos* photometry. We have now confirmed 25 of those candidates as γ Doradus stars in our series of papers. In many cases, however, the periods determined from our APT observations differ significantly from those in Handler (1999) and also from those cited in Martín et al. (2003) for HD 69715, HD 70645, and HD 80731. The γ Doradus variables typically have multiple periods around 1 day, which makes it difficult to identify the correct periods from the *Hipparcos* photometry because of its unusual sampling pattern and modest ($\sim$100) number of observations. Thus, the *Hipparcos* candidates require additional photometry to confirm their γ Doradus nature, as recommended by Zerbi (2000). Even greater difficulty is encountered in single-site, ground-based data sets covering only a few days and containing only a few dozen observations, such as those in Martín et al. (2003). The larger APT data sets, which typically cover an entire observing season and contain hundreds of observations with multiple observations per night, allow better characterization of the multiperiodic variability of the γ Doradus variables. Although our single-site data are still subject to 1 day aliasing, our observing strategy maximizes the chances of identifying the periods correctly. For the 11 stars in this paper, we find periods ranging from 0.398 to 2.454 days, entirely within the period range of previously known γ Doradus variables.

Using the $B-V$ color indices and absolute magnitudes in columns (5) and (6) of Table 6, we plot all the γ Doradus stars in the H-R diagram of Figure 23. The solid lines show the dwarf and giant sequences from Tables B1 and B2 of Gray (1992) and the subgiant sequence of Allen (1976, p. 210), all of which represent observed average values of normal stars. 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 et al. (2000), that had *Hipparcos* parallaxes with uncertainties $\leq 10\%$. The γ Doradus stars in Table 6 with V magnitudes and $B-V$ colors that were explicitly measured or determined are plotted as filled symbols. Eleven double-lined binary 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). HD 8801, the only star known to pulsate intrinsically at both γ Doradus and δ Scuti frequencies (Henry & Fekel 2005), is plotted as a circled point. The 11 new γ Doradus variables in this paper are plotted as stars.

The dashed lines in Figure 23 mark the observed boundaries of the γ Doradus instability strip, determined by Fekel et al. (2003) from the 30 confirmed γ Doradus stars in Henry & Fekel (2002). The triple-dot-dashed lines show the outer edges of the theoretical γ Doradus instability strip from Warner et al. (2003) (defined by $l=1$ on the red edge and $l=5$ on the blue edge), where we have adopted their absolute magnitude limits and converted their effective temperature limits to observed $B-V$ with the calibration of Flower (1996). With the addition of 11 new γ Doradus stars from this paper and HD 8801 from Henry & Fekel (2005), we have increased the sample of 42 γ Doradus variables in Henry & Fekel (2003) by nearly 30%. The majority of confirmed γ Doradus stars are dwarfs, with a few subgiants, and their locations straddle the cool boundary of the δ Scuti instability strip. Figure 23 shows that the enlarged sample of γ Doradus variables remains in excellent agreement with the boundaries of the γ Doradus region determined observationally by Fekel et al. (2003) and theoretically by Warner et al. (2003).

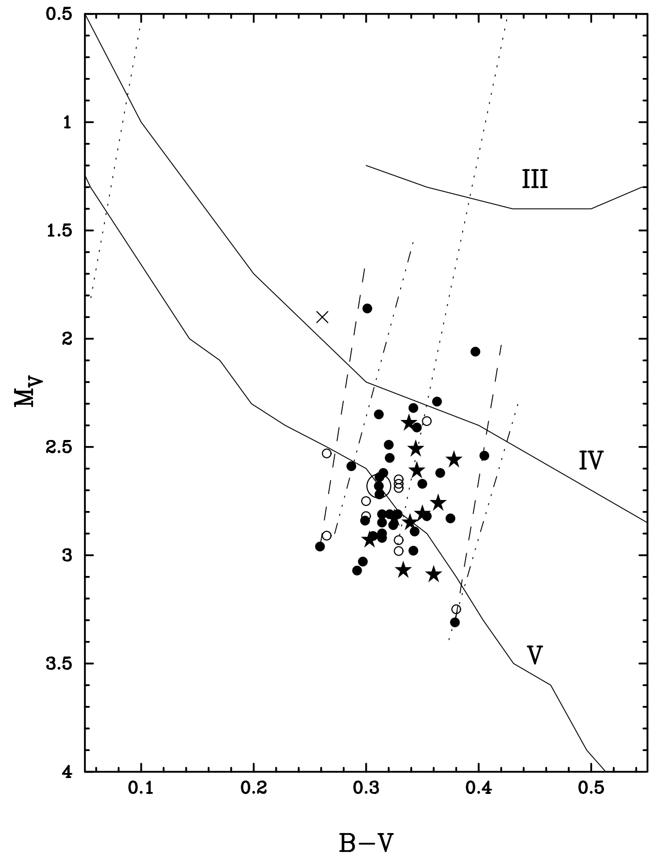

FIG. 23.—Location of all 54 confirmed γ Doradus stars (Table 6) in the H-R diagram, including the 11 stars discussed in this paper (*stars*). Solid lines indicate the observed average locations of normal main-sequence (V), subgiant (IV), and giant (III) stars in the diagram. Both components of two of the double-lined spectroscopic binaries are plotted for a total of 56 individual stars. Stars with well-determined locations in the diagram are plotted with filled symbols, while those with somewhat greater uncertainty (most of the double-lined binary components) are plotted with open symbols. One star, HD 209295, is plotted with a cross, since its γ Doradus pulsation is likely tidally excited. HD 8801, the only star known to pulsate intrinsically at both γ Doradus and δ Scuti frequencies, is plotted as a circled point. 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 outer edges of the theoretical boundaries of the γ Doradus instability strip, converted from those of Warner et al. (2003).

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