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PHOTOMETRY AND SPECTROSCOPY OF 11 γ DORADUS STARS

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ABSTRACT

We have used precise photometric and high-dispersion spectroscopic observations to study 11 γ Doradus stars, 10 of them newly confirmed. Only five of these 11 γ Doradus stars appear to be single; two are primaries of double-lined spectroscopic binaries, one is the secondary of a double-lined binary, two are primaries of visual binaries and, in the case of the double-lined binary (HD 86371), either or both components could be a pulsating γ Doradus star. We have determined a preliminary orbital period of 5.32 days for the double-lined binary HD 41547. 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 4 and 94 mmag in Johnson *B* and periods between 0.38 and 1.86 days. The 11 stars have between two and five independent periods. The variability at all periods approximates a sinusoid. We provide a new tabulation of all 66 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. Among the 66 confirmed γ Doradus variables, we find no correlation between the period of the strongest pulsation mode and the $(B - V)$ color index, absolute magnitude, or luminosity.

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

Online material: machine-readable table

1. INTRODUCTION

This is the latest in a series of papers in which we have examined the spectroscopic and photometric characteristics of candidate γ Doradus stars. Recent results are described in Henry et al. (2004, 2005) and Henry & Fekel (2005). 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 mmag to a few percent (e.g., Henry et al. 2005). 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; de Cat et al. 2006). 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 54 members (Henry et al. 2005, their Table 6). These stars lie in a relatively small 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 et al. 2005, their Fig. 23). Henry et al. (2005) 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 use our precise photometric and high-dispersion spectroscopic observations to study 11 γ Doradus variables, 10 of them newly identified. With the inclusion of two additional γ Doradus stars confirmed by other authors, this brings the total number of confirmed γ Doradus stars to 66. 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

Basic data for the 11 γ Doradus stars in this study are listed in Table 1, including the sources for the 11 stars and some of their properties determined below. Three of the candidates were identified as new variable stars when we chose them as comparison stars on the T10 and T11 automated photoelectric telescopes (APTs) in our long-term monitoring program of solar-type stars (Henry 1999). One candidate, HD 41547, was discovered as a new variable after it was picked as a check star on the T3 APT for

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TABLE 1
Basic Properties of the 11 γ Doradus Stars

HD (1)	Other Names (2)	Component (3)	V[a] (mag) (4)	$B-V$[a] (mag) (5)	π[a] (mas) (6)	*Hipparcos* Variable Type[b] (7)	Source (8)	Spectral Class[c] (9)	Luminosity Class[c] (10)	$v \sin i$[c] (km s^{-1}) (11)	Velocity[c,d] (km s^{-1}) (12)
9365.........		A	8.17	0.361	8.30 ± 1.08	P	Handler (1999)	F1[e]	Dwarf[e]	80[e]	0.3
32348.......		A, B	7.24	0.343	10.82 ± 1.02	B	T10 APT				
		A	7.40	0.31				F2:	Dwarf	55:	Variable
		B	9.40	0.54				F6:	Dwarf	5:	Variable
40745.......	HR 2118, AC Lep	...	6.21	0.358	16.70 ± 0.82	P	Handler (1999)	F2	Subgiant	41	31.8
41448.......		...	7.60	0.299	10.74 ± 0.89	P	Handler (1999)	F0	Dwarf	100	29.6
41547.......	HR 2150	A, B	5.88	0.374	16.96 ± 0.86	B	T3 APT				
		A	6.41	0.35				F2	Dwarf/Subgiant	11	Variable
		B	6.91	0.42				F4–5	Dwarf/Subgiant	7	Variable
86371.......		A, B	6.62	0.314	12.85 ± 0.74	U	Handler (1999)				
		A	7.37	0.31				F1	Dwarf	10	Variable
		B	7.37	0.31				F1	Dwarf	11	Variable
89781.......		...	7.48	0.355	7.84 ± 0.85	B	T11 APT	F1:	Subgiant	120:	3.7:[f]
103751.....		...	7.97	0.397	7.93 ± 1.20	B	T10 APT	F1	Subgiant	58	2.7
144451.....		A	7.84	0.358	11.08 ± 1.07	U	Handler (1999)	F1	Dwarf	53	6.9
187615.....		...	7.95	0.300	9.49 ± 0.95	U	Handler (1999)	F1[e]	Dwarf[e]	80[e]	10.2
211699.....	PR Peg	A, B	9.13	0.382	4.07 ± 1.11	P	Handler (1999)				
		A	9.31:	0.19:				A7:	Dwarf	18:	Variable
		B	10.51:	0.36:				F2:	Dwarf	13:	Variable

[a] Single star values and combined values of binary components are from the *Hipparcos* catalog. For the individual binary components see the text.
[b] P, periodic variable; U, unresolved variable; B, star could not be classified as variable or constant.
[c] From this paper unless otherwise noted. A colon indicates greater uncertainty than usual.
[d] Velocity noted as "Variable" indicates orbital motion.
[e] Fekel et al. (2003).
[f] Star has asymmetric lines, perhaps indicating that it is a double-lined binary.

both the HD 40745 and HD 41448 observations in this paper. Six of the 11 γ Doradus candidates were taken from the list of prime candidates in Handler (1999), who identified them on the basis of his analysis of the *Hipparcos* photometry (Perryman et al. 1997), and one of the candidates, HD 187615, came from Handler's list of further candidates.

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 prime candidates (46 stars) and the further candidates (36 stars). The prime candidates consist 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 26 of Handler's 46 prime candidates and confirmed all but one of them as γ Doradus variables, demonstrating the success of his criteria for identifying the prime γ Doradus candidates. Therefore, we decided to observe all 33 of Handler's (1999) 46 prime candidates that are observable with our APTs in the Northern Hemisphere. The one prime candidate so far that could not be confirmed as a γ Doradus star is HD 173977. Fekel et al. (2003) found it to be a short-period binary and suggested that 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.

3. SPECTROSCOPY

3.1. *Observations*

For two 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 of all 11 stars between 2002 September and 2006 September. Combining the data, we have at least two spectra of each star.

For 10 of the 11 stars all of 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. For the 11th star, HD 211699, four observations were obtained at the usual red wavelength region, around 6430 Å, while the rest were acquired at 4500 Å. The blue spectrograms have a wavelength range of about 80 Å and a 2 pixel resolution of 0.22 Å. The typical signal-to-noise ratio of our spectra is between 150 and 250. Figures 1 and 2 provide sample red wavelength spectra of the SB2 binary γ Doradus candidates HD 32348 and HD 211699, respectively.

3.2. *Analysis*

The reduction and analysis of the spectroscopic data, as well as estimates of the uncertainties in the results, are described in Fekel et al. (2003). They previously provided spectral classes, $v \sin i$ values, and radial velocities for two stars in our sample. Luminosity classes were determined from the *Hipparcos* magnitudes

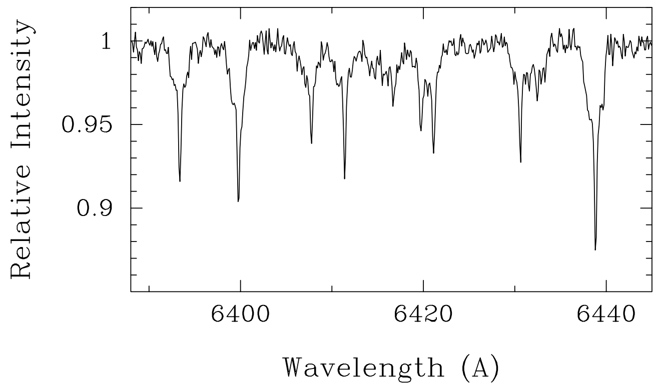

FIG. 1.—Spectrum of HD 32348 in the 6430 Å region, which shows the composite profiles of the lines. Component A is the broad-lined star, and component B is the narrow-lined star.

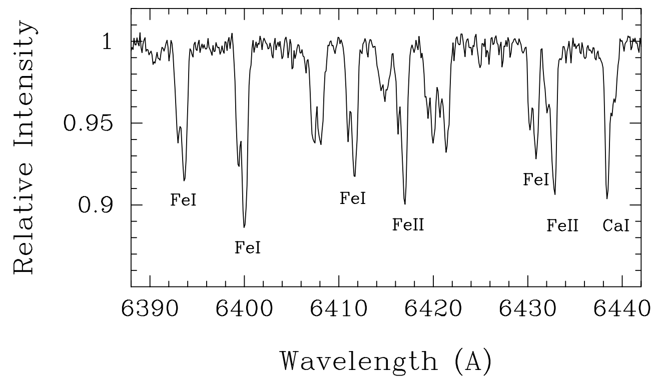

FIG. 2.—Spectrum of HD 211699 in the 6430 Å region, which shows the blended line profiles. The element and ionization stage are given for some of the lines. Component A is redshifted and has the stronger Fe I and Fe II lines. Component B is blueshifted and has the weaker lines except for the Ca I line at 6439 Å. This reversal in strength indicates that component A is an Am star.

and parallaxes (Perryman et al. 1997) as described in Fekel et al. (2003). Individual radial velocities, including the two given by Fekel et al. (2003), are listed in Table 2 along with comments about the spectra. A colon after a value indicates greater than usual uncertainty, typically because a star has very broad and shallow lines or because the star is a double-lined binary.

For single stars and single-lined binaries, the determination of basic properties is relatively straightforward. However, four stars in our sample (HD 32348, HD 41547, HD 86371, and HD 211699) show two sets of lines, making more difficult the determination of the magnitudes and colors of the individual components listed in Table 1. To obtain the individual magnitudes and colors, a V magnitude difference is needed. The spectrum addition method described in Fekel et al. (2003) produces a continuum luminosity ratio, which results in a magnitude difference that is a minimum value if the secondary has a later spectral type than the primary. If the spectral type difference is small, the continuum luminosity ratio can be adopted as the luminosity ratio from which the magnitude difference can be determined. Otherwise the continuum luminosity ratio must be adjusted for the difference in spectral types before computing a magnitude difference.

4. PHOTOMETRY

4.1. *Observations*

We acquired the photometric observations analyzed in this paper between 2003 September and 2004 December with the T3 0.4 m APT at Fairborn Observatory. This APT uses a temperature-stabilized EMI 9924B photomultiplier tube to detect photon count rates 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).

Up to five group observations of each program star were acquired 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 its opposition. This observing strategy helps to minimize 1 day aliases in our period analyses and 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 most comparison and check stars are constant to a few millimeters, which is approximately the limit of precision for this APT. Notes to Table 3 mention slight variability in two check stars, one of which (HD 41547) we show in this paper to be a new γ Doradus star. The other is a new K-type variable (HD 103484), which we do not analyze in this paper. 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 an earlier paper (Henry et al. 2001). Briefly, 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. In some cases, we find very close frequency pairs in the same star that are separated by no more than 0.02 day^{-1} or so. A conservative criterion for frequency resolution is given by Loumos & Deeming (1978) to be $1.5/T$, where T is the total range of the observations in days. Since most of our data sets span $\sim$200 days, the limit of our frequency resolution is typically around 0.0075 day^{-1}, ensuring that we can resolve such close frequencies. 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 94 down to 4 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 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. As mentioned above, two of the check

TABLE 2
Individual Radial Velocities

Star Name (1)	Date (HJD − 2,400,000) (2)	Radial Velocity ($km\ s^{-1}$) (3)	Comments (4)
HD 9365	51,741.977	−6.5	Fekel et al. (2003)
	52,903.894	−0.8	
	52,941.766	1.1	
	53,273.844	−2.3	
	53,634.858	3.6	
	53,635.870	2.7	
	53,637.938	−1.4	
	53,638.910	4.6	
	54,002.858	−1.8	
	54,003.830	3.4	
HD 32348	52,941.887	1.6	Broad component
		7.7	Narrow component
	53,274.966	7.5	Broad component
		−0.8	Narrow component
	53,634.987	1.1	Broad component
		15.1	Narrow component
	53,635.980	0.8	Broad component
		14.9	Narrow component
	53,639.960	−0.2	Broad component
		14.6	Narrow component
	54,001.924	1.1	Broad component
		7.9	Narrow component
	54,003.940	7.1	Broad component
		8.7	Narrow component
HD 40745	52,543.023	31.6	
	52,941.942	31.8	
	53,274.011	31.6	
	53,639.006	32.1	
HD 41448	52,543.011	30.1	
	52,941.957	25.9:	
	53,638.009	32.9	Asymmetric lines
HD 41547	53,637.996	6.3	SB2, primary component
		68.3	Secondary component
	53,639.000	51.8	Primary component
		16.9	Secondary component
	54,003.002	25.5	Primary component
		48.6	Secondary component
	54,003.998	−6.3	Primary component
		82.9	Secondary component
	54,004.999	14.5	Primary component
		59.9	Secondary component
	54,006.024	62.4	Primary component
		7.1	Secondary component
	54,007.021	76.4	Primary component
		−9.6	Secondary component
HD 86371	52,755.658	−41.8	SB2, components nearly identical
		28.7	
	52,756.675	−35.9	
		14.4	
	52,757.634	−24.8	
		6.4	
	52,758.641	−18.3	
		−0.5	
	52,759.615	−11.1	Single lined
	53,119.667	20.0	
		−37.5	
	53,120.666	15.0	
		−33.6	
	53,123.677	−9.8	Single lined
	53,487.657	−30.2	
		11.0	
	53,488.636	−35.5	
		6.1	
	53,490.685	−35.9	
		20.8	
	53,492.638	−32.6	
		14.8	

TABLE 2—*Continued*

Star Name (1)	Date (HJD − 2,400,000) (2)	Radial Velocity (km s^{-1}) (3)	Comments (4)
HD 89781	53,123.759	3.0:	Weak red wing not measured
	53,490.769	4.4:	Weak red wing not measured
	53,121.828	3.2	
	53,170.655	1.2	
	53,492.713	3.8	
	53,119.904	4.8	
	53,123.870	9.0	Very asymmetric lines
	53,170.767	7.4	
	53,172.791	6.4	
HD 187615	51,737.879	8.3	Fekel et al. (2003)
	53,169.949	7.4	Symmetric lines
	53,272.705	13.1	
	53,532.953	11.4	Asymmetric lines
	53,637.731	10.8	Asymmetric lines
HD 211699.....................	53,172.931	9.0	Single lined
	53,173.974	8.6	Single lined, 4500 Å
	53,636.732	1.1	Primary component
		−30.0	Secondary component
	53,637.812	0.8	Primary component
		−30.0	Secondary component
	53,638.794	2.8	Primary component, 4500 Å
		−19.3	Secondary component, 4500 Å
	53,639.729	3.7	Primary component
		−19.3	Secondary component

stars (HD 41547 and HD 103484) were found to be variable in our photometry; the remaining seven check stars and all nine comparison stars showed no evidence for variability. Thus, we can say confidently that all of the periodicities reported in Table 5 arise in the program stars.

Least-squares spectra and phase diagrams for the *B* observations of the 11 program stars are shown in § 6 below. Although all 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 3
PROGRAM, COMPARISON, AND CHECK STARS

Program	Comparison	Check	$\sigma_{(V-C)}$[a] (mag)	$\sigma_{(K-C)}$[a] (mag)
HD 9365	HD 7458	HD 6210	0.0306	0.0042
HD 32348	HD 30913	HD 33336	0.0077	0.0046
HD 40745	HD 41366	HD 41547[b]	0.0088	0.0086[b]
HD 41448	HD 41366	HD 41547[b]	0.0163	0.0088[b]
HD 86371	HD 86264	HD 87096	0.0266	0.0063
HD 89781	HD 88923	HD 91181	0.0097	0.0052
HD 103751	HD 103389	HD 103484[c]	0.0144	0.0127[c]
HD 144451	HD 145100	HD 144134	0.0265	0.0071
HD 187615	HD 187402	HD 187182	0.0183	0.0048
HD 211699................	HD 211231	HD 211115	0.0434	0.0056

[a] In the Johnson *B* photometric band.
[b] The check star HD 41547 is also a new γ Doradus variable and is analyzed in this paper.
[c] The check star HD 103484 is a new K-type variable.

5. CRITERIA FOR CONFIRMING γ DORADUS VARIABILITY

Throughout our series of papers on γ Doradus stars (see § 1 for references), we have consistently 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 one cycle per day aliasing and provide the correct period identifications. This is important since the cadence of the *Hipparcos* observations, from which Handler's candidates were identified,

TABLE 4
PHOTOMETRIC OBSERVATIONS

Date (HJD − 2,400,000)	Var *B* (mag)	Var *V* (mag)	Check *B* (mag)	Check *V* (mag)
		HD 9365		
52,894.7340..............................	99.999	99.999	−1.322	−1.489
52,894.8019..............................	99.999	99.999	−1.319	−1.480
52,894.8783..............................	0.765	0.850	−1.321	−1.482
52,894.9681..............................	99.999	99.999	−1.318	−1.489
52,895.7272..............................	0.803	0.879	−1.315	−1.480
52,895.8011..............................	0.805	0.887	−1.322	−1.480

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

TABLE 5

Program Star Results from Photometric Analysis

Star Name (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)
HD 9365	*B*	2894.8783–3191.9082	374	1.5979 ± 0.0002	0.62582 ± 0.00010	75.9 ± 2.4	1.33 ± 0.06	3000.282 ± 0.003
				1.3428 ± 0.0002	0.74471 ± 0.00011	40.5 ± 4.0	1.35 ± 0.20	3000.422 ± 0.012
				1.8535 ± 0.0003	0.53952 ± 0.00009	30.5 ± 4.3	1.25 ± 0.27	3000.138 ± 0.012
	V	2894.8783–3191.9082	377	1.5979 ± 0.0002	0.62582 ± 0.00008	57.0 ± 1.9	...	3000.279 ± 0.003
				1.3427 ± 0.0002	0.74477 ± 0.00011	30.0 ± 3.1	...	3000.423 ± 0.012
				1.8531 ± 0.0002	0.53964 ± 0.00006	24.4 ± 3.2	...	3000.147 ± 0.011
HD 32348	*B*	2894.9082–3094.6164	445	1.2591 ± 0.0002	0.79422 ± 0.00013	8.5 ± 1.0	0.99 ± 0.22	3000.509 ± 0.014
				1.1346 ± 0.0002	0.88137 ± 0.00016	8.0 ± 1.0	1.45 ± 0.31	3000.766 ± 0.017
				1.1705 ± 0.0002	0.85434 ± 0.00015	6.9 ± 1.0	1.13 ± 0.31	3000.211 ± 0.019
				1.1852 ± 0.0002	0.84374 ± 0.00014	6.8 ± 1.0	1.21 ± 0.33	3000.050 ± 0.020
	V	2894.9082–3094.6164	432	1.2594 ± 0.0002	0.79403 ± 0.00016	8.6 ± 0.9	...	3000.509 ± 0.014
				1.1347 ± 0.0002	0.88129 ± 0.00016	5.5 ± 1.0	...	3000.747 ± 0.026
				1.1703 ± 0.0002	0.85448 ± 0.00018	6.1 ± 1.0	...	3000.249 ± 0.022
				1.1849 ± 0.0002	0.84395 ± 0.00014	5.6 ± 1.0	...	3000.076 ± 0.024
HD 40745	*B*	2894.9938–3094.6337	280	1.2132 ± 0.0003[a]	0.82427 ± 0.00020[a]	12.2 ± 1.3	1.05 ± 0.21	3000.069 ± 0.014
				0.7361 ± 0.0003	1.35851 ± 0.00055	8.9 ± 1.4	1.11 ± 0.32	3000.773 ± 0.035
				0.5377 ± 0.0002	1.85977 ± 0.00069	8.4 ± 1.4	1.14 ± 0.36	3000.292 ± 0.049
				2.1820 ± 0.0002	0.45830 ± 0.00004	6.3 ± 1.5	1.24 ± 0.51	3000.141 ± 0.017
	V	2894.9938–3094.6337	273	1.2138 ± 0.0002[a]	0.82386 ± 0.00017[a]	11.6 ± 1.2	...	3000.078 ± 0.013
				0.7360 ± 0.0002	1.35870 ± 0.00046	8.0 ± 1.3	...	3000.837 ± 0.034
				0.5381 ± 0.0004	1.85839 ± 0.00138	7.4 ± 1.4	...	3000.322 ± 0.050
				2.1819 ± 0.0002	0.45832 ± 0.00004	4.8 ± 1.4	...	3000.121 ± 0.020
HD 41448	*B*	2894.9975–3087.6374	306	2.3814 ± 0.0003	0.41992 ± 0.00005	37.9 ± 1.5	1.20 ± 0.08	3000.238 ± 0.003
				2.4712 ± 0.0003	0.40466 ± 0.00005	10.4 ± 2.6	1.21 ± 0.51	3000.017 ± 0.016
				2.5822 ± 0.0003	0.38727 ± 0.00004	9.0 ± 2.6	1.17 ± 0.57	3000.172 ± 0.018
				2.3419 ± 0.0003	0.42700 ± 0.00005	3.5 ± 2.6	1.35 ± 1.63	3000.244 ± 0.052
				2.1629 ± 0.0003	0.46234 ± 0.00006	9.8 ± 2.5	1.17 ± 0.52	3000.372 ± 0.020
	V	2895.9951–3091.6357	300	2.3812 ± 0.0002	0.41996 ± 0.00004	31.6 ± 1.3	...	3000.243 ± 0.003
				2.4714 ± 0.0003	0.40463 ± 0.00005	8.6 ± 2.2	...	3000.027 ± 0.017
				2.5825 ± 0.0003	0.38722 ± 0.00004	7.7 ± 2.2	...	3000.149 ± 0.018
				2.3418 ± 0.0002	0.42702 ± 0.00005	2.6 ± 2.3	...	3000.264 ± 0.059
				2.1637 ± 0.0003	0.46217 ± 0.00006	8.4 ± 2.2	...	3000.401 ± 0.019
HD 41547	*B*	2894.9975–3091.6357	272	1.2327 ± 0.0003	0.81123 ± 0.00020	11.3 ± 1.4	1.36 ± 0.27	3000.150 ± 0.015
				1.2951 ± 0.0002	0.77214 ± 0.00012	8.0 ± 1.4	2.11 ± 0.49	3000.043 ± 0.023
				1.4613 ± 0.0002	0.68432 ± 0.00012	9.4 ± 1.4	1.25 ± 0.31	3000.605 ± 0.016
	V	2894.9975–3087.6374	260	1.2334 ± 0.0003	0.81077 ± 0.00020	8.3 ± 1.2	...	3000.113 ± 0.018
				1.2959 ± 0.0003	0.77166 ± 0.00018	3.8 ± 1.2	...	3000.739 ± 0.042
				1.4609 ± 0.0002	0.68451 ± 0.00009	7.5 ± 1.2	...	3000.616 ± 0.017
HD 86371	*B*	2949.0170–3146.6547	268[b]	0.5958 ± 0.0002	1.67842 ± 0.00070	40.2 ± 4.2	1.49 ± 0.23	3000.922 ± 0.029
				0.5800 ± 0.0002	1.72414 ± 0.00074	30.3 ± 4.7	1.48 ± 0.33	3001.538 ± 0.042
				0.6715 ± 0.0003	1.48920 ± 0.00067	23.6 ± 4.8	1.28 ± 0.40	3000.870 ± 0.049
	V	2949.0170–3146.6547	260[b]	0.5960 ± 0.0002	1.67785 ± 0.00070	26.9 ± 3.4	...	3000.931 ± 0.034
				0.5798 ± 0.0003	1.72473 ± 0.00089	20.5 ± 3.6	...	3001.538 ± 0.048
				0.6710 ± 0.0003	1.49031 ± 0.00067	18.4 ± 3.6	...	3000.819 ± 0.049

TABLE 5—*Continued*

Star Name (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)
HD 89781	*B*	2925.0122–3182.6529	474	2.6274 ± 0.0002	0.38060 ± 0.00003	20.0 ± 0.9	1.14 ± 0.08	3000.216 ± 0.003
				1.7722 ± 0.0002	0.56427 ± 0.00006	12.0 ± 1.1	1.41 ± 0.21	3000.308 ± 0.009
				2.0298 ± 0.0002	0.49266 ± 0.00005	8.6 ± 1.2	1.23 ± 0.28	3000.295 ± 0.011
				2.0846 ± 0.0002	0.47971 ± 0.00005	8.6 ± 1.2	1.39 ± 0.30	3000.086 ± 0.011
	V	2925.0122–3177.6509	465	2.6274 ± 0.0002	0.38060 ± 0.00002	17.5 ± 0.7	...	3000.216 ± 0.003
				1.7721 ± 0.0002	0.56430 ± 0.00006	8.5 ± 1.0	...	3000.305 ± 0.011
				2.0304 ± 0.0002	0.49251 ± 0.00005	7.0 ± 1.0	...	3000.324 ± 0.012
				2.0851 ± 0.0002	0.47959 ± 0.00005	6.2 ± 1.0	...	3000.106 ± 0.013
HD 103751	*B*	2952.0316–3194.6496	405	0.9887 ± 0.0002	1.01143 ± 0.00020	34.5 ± 1.2	1.26 ± 0.07	3000.628 ± 0.005
				1.1185 ± 0.0002	0.89405 ± 0.00016	24.8 ± 1.7	1.25 ± 0.14	3000.756 ± 0.009
	V	2952.0316–3194.6496	376	0.9885 ± 0.0002	1.01163 ± 0.00021	27.4 ± 1.1	...	3000.620 ± 0.007
				1.1184 ± 0.0002	0.89413 ± 0.00016	19.8 ± 1.5	...	3000.761 ± 0.011
HD 144451	*B*	3041.0419–3194.6668	196	1.5970 ± 0.0004	0.62617 ± 0.00016	60.3 ± 3.3	1.32 ± 0.12	3000.147 ± 0.006
				1.6476 ± 0.0004	0.60694 ± 0.00015	52.4 ± 4.6	1.35 ± 0.18	3000.451 ± 0.007
				1.7776 ± 0.0003	0.56256 ± 0.00009	12.0 ± 5.7	3.24 ± 1.66	3000.283 ± 0.038
	V	3041.0419–3194.6668	183	1.5971 ± 0.0004	0.62613 ± 0.00014	45.8 ± 2.8		3000.148 ± 0.006
				1.6478 ± 0.0003	0.60687 ± 0.00011	38.8 ± 3.7	...	3000.464 ± 0.008
				1.7779 ± 0.0004	0.56246 ± 0.00011	3.7 ± 4.4	...	3000.309 ± 0.102
HD 187615	*B*	2894.7544–3194.8452	320	2.0078 ± 0.0002	0.49806 ± 0.00005	37.5 ± 2.4	1.23 ± 0.13	3000.379 ± 0.005
				1.9683 ± 0.0001	0.50805 ± 0.00003	31.7 ± 2.4	1.32 ± 0.16	3000.097 ± 0.006
				2.0515 ± 0.0001	0.48745 ± 0.00002	25.2 ± 2.6	1.37 ± 0.22	3000.474 ± 0.008
	V	2894.7544–3194.8452	317	2.0078 ± 0.0002	0.49806 ± 0.00005	30.6 ± 1.9	...	3000.380 ± 0.005
				1.9684 ± 0.0001	0.50803 ± 0.00003	24.1 ± 2.0	...	3000.096 ± 0.007
				2.0515 ± 0.0001	0.48745 ± 0.00002	18.4 ± 2.2	...	3000.475 ± 0.009
HD 211699..........	*B*	2894.7610–3359.6029	414	0.9328 ± 0.0002	1.07204 ± 0.00017	94.4 ± 4.0	1.29 ± 0.09	3100.661 ± 0.007
				1.1265 ± 0.0002	0.88771 ± 0.00012	45.6 ± 5.9	1.29 ± 0.27	3100.570 ± 0.018
				1.1634 ± 0.0001	0.85955 ± 0.00007	54.3 ± 5.8	1.25 ± 0.22	3100.155 ± 0.014
				0.1939 ± 0.0001[c]	5.15730 ± 0.00266[c]	33.4 ± 6.0	1.27 ± 0.36	3103.388 ± 0.152
	V	2894.7610–3359.6029	404	0.9328 ± 0.0002	1.07204 ± 0.00017	73.0 ± 3.3	...	3100.665 ± 0.008
				1.1265 ± 0.0001	0.88771 ± 0.00008	35.3 ± 4.8	...	3100.587 ± 0.019
				1.1634 ± 0.0001	0.85955 ± 0.00007	43.3 ± 4.7	...	3100.168 ± 0.014
				0.1939 ± 0.0001[c]	5.15730 ± 0.00266[c]	26.3 ± 4.8	...	3103.332 ± 0.154

Note.—The individual photometric observations are given in Table 4.

[a] Frequency identification uncertain due to aliasing.

[b] Analysis does not include the 39 *B* and 38 *V* observations from the monitoring night JD 2,453,080.

[c] Probably not an independent frequency. See § 6.11.

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. Our multiple spectroscopic observations can establish the absence of large-amplitude, 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 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 have a weighted mean B/V amplitude ratio of 1.27 ± 0.03, 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 identify uniquely 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 $l = 2$ and probably inconsistent with $l = 3$ (Garrido 2000). Our spectroscopic observations, obtained primarily to determine spectral class, $v \sin i$, 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 9365*

HD 9365 lies in the field of the young open cluster NGC 581 but is a nonmember (Steppe 1974). Abt (1986) examined HD 9365 in his analysis of Trapezium systems, which are multiple-star systems with components of similar separation. He classified HD 9365 as F1 V and also concluded that one of the other two components in the system, an F9 V star that is 1.5 mag fainter and 44″ away, is a physical companion. Additional spectral classifications of HD 9365 are similar: A9 V (Sowell 1987), F0 V (Jensen 1981), and F1 dwarf (Fekel et al. 2003).

From a single spectrum, Fekel et al. (2003) determined a $v \sin i$ value of 80 km s^{-1}, while Mathias et al. (2004) found a somewhat smaller value of 69 km s^{-1}. Given the line-profile variations encountered in γ Doradus pulsators, the two values are reasonably consistent.

Measuring seven objective prism plates for radial velocities, Boulon et al. (1959) found a mean velocity of 5 km s^{-1}, but they also classified the star as B3. It is thus unclear whether the spectral class is a typographical error or whether their velocities belong to another star. Liu et al. (1989) obtained four radial velocities that have a mean of -11.6 km s^{-1}. Three of their velocities have an average of -1.8 km s^{-1}, while a fourth velocity differs from that average by 39 km s^{-1}. On the basis of that large velocity difference, Liu et al. (1989) concluded that HD 9365 is apparently a spectroscopic binary. A single follow-up observation by Liu et al. (1991) produced a radial velocity of 5 km s^{-1}. In their study of candidate γ Doradus variables, Fekel et al. (2003) reported a lone velocity of -6.5 km s^{-1}. Recently, Mathias et al. (2004) collected six spectra and from their observations stated that the star has radial velocity variations ranging from -2 to 4 km s^{-1}. They concluded that the period of their observed velocity variation is consistent with the *Hipparcos* photometric period (Perryman et al. 1997) mentioned below.

We have obtained nine additional radial velocities of HD 9365. Combined with the single measurement of Fekel et al. (2003) the 10 KPNO velocities were obtained at six different epochs and have a mean velocity of 0.3 ± 1.1 km s^{-1}. Those velocities have a range of 11 km s^{-1}, but given the broad asymmetric lines of HD 9365, which make velocity measurement less precise, our velocities, as well as those of Mathias et al. (2004), show no clear indication of orbital motion. Thus, while HD 9365 appears to have velocity variability, the possibility that it is a spectroscopic binary rests on the single discrepant velocity of -41 km s^{-1} (Liu et al. 1989). Recent velocities from high-dispersion spectra are consistent with the idea that the velocity variation found for this star results from pulsation, as evidenced by the photometric variability discussed below. We conclude that HD 9365 is probably single, except for the distant physical companion mentioned above.

The *Hipparcos* mission team discovered the light variability of HD 9365 and determined a period of 0.62576 days (Perryman et al. 1997) but did not suggest a variability type. Handler (1999) included HD 9365 in his list of prime γ Doradus candidates. Wyrzykowski et al. (2002) identified six variables in the field of NGC 581, one of which was HD 9365. From their observations they determined a period of 0.6260 days, an amplitude of 0.11 mag, and concluded that it is most probably a γ Doradus variable.

We acquired over 370 new Johnson BV photometric observations of HD 9365 with the T3 APT. The least-squares spectra of our B observations are plotted in Figure 3, and the results of our period analysis are given in Table 5. We find three similar but independent periods of 0.62582, 0.74471, and 0.53952 days with peak-to-peak amplitudes in B of 76, 40, and 30 mmag, respectively. The observations are phased with these periods and the times of minimum given in Table 5 and plotted in Figure 4, 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 1.33 ± 0.06, consistent with other γ Doradus pulsators (e.g., Henry & Fekel 2003) and inconsistent with the ellipticity effect or starspots (Henry et al. 2000, their 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 9365 as a new γ Doradus variable.

6.2. *HD 32348*

HD 32348 has engendered very little past interest. Our red-wavelength spectra show that each line consists of a broad component with a weak, narrow component near its center (Fig. 1), resulting in a composite spectrum. The projected rotational velocities for components A and B are 55: and 5: km s^{-1}, respectively.

The stars appear to be slightly metal-poor, with [Fe/H] ~ -0.3. This lower-than-solar metallicity resulted in classification difficulties, since at such metallicities we have fewer reference stars available for comparison. The combined $B - V$ color of 0.343 corresponds to an F1–2 V star (Gray 1992). Using our available

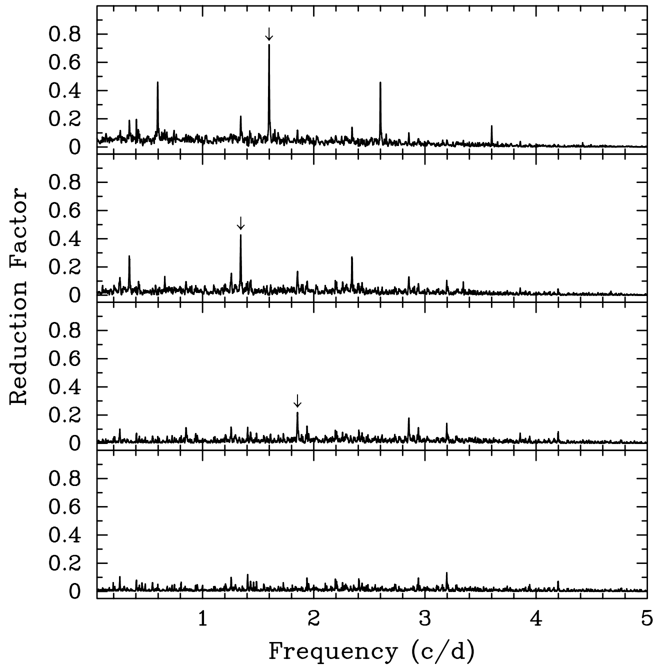

FIG. 3.—Least-squares spectra of the HD 9325 Johnson *B* data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies (*top to bottom*) 1.5979, 1.3428, and 1.8535 day^{-1}. All three frequencies were confirmed in the Johnson *V* data set.

reference stars, we have classified component A as F2: and component B as F6:. However, the minimum magnitude difference from this combination is 1.65, significantly greater than the expected difference of 0.7 mag for two such main-sequence stars (Gray 1992). This suggests that either the primary is a subgiant or the spectral subclass difference between the two components is larger.

If the spectral types are revised slightly to F0 V and F8 V and a *V* magnitude difference of 2.0 is adopted, we obtain the observed $B - V$ color of the system. The *Hipparcos* parallax then results in an absolute visual magnitude of 2.6, typical of an F0 main-sequence star (Gray 1992). Thus, we conclude that component A is a main-sequence star and that component B is as well.

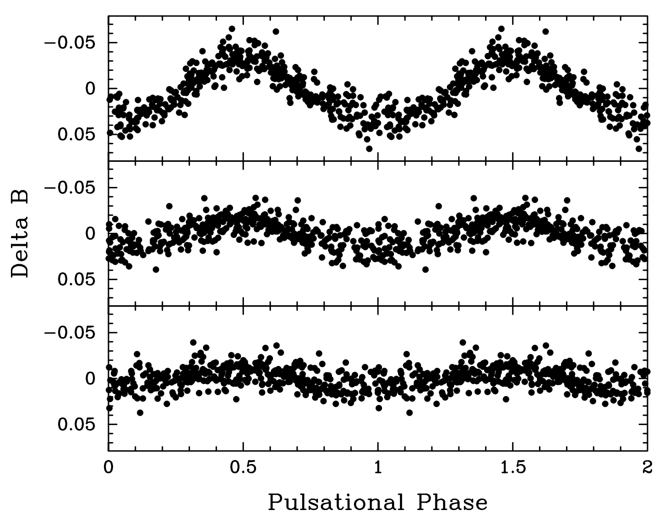

FIG. 4.—Johnson *B* photometric data for HD 9365, phased with the three frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 1.5979, 1.3428, and 1.8535 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

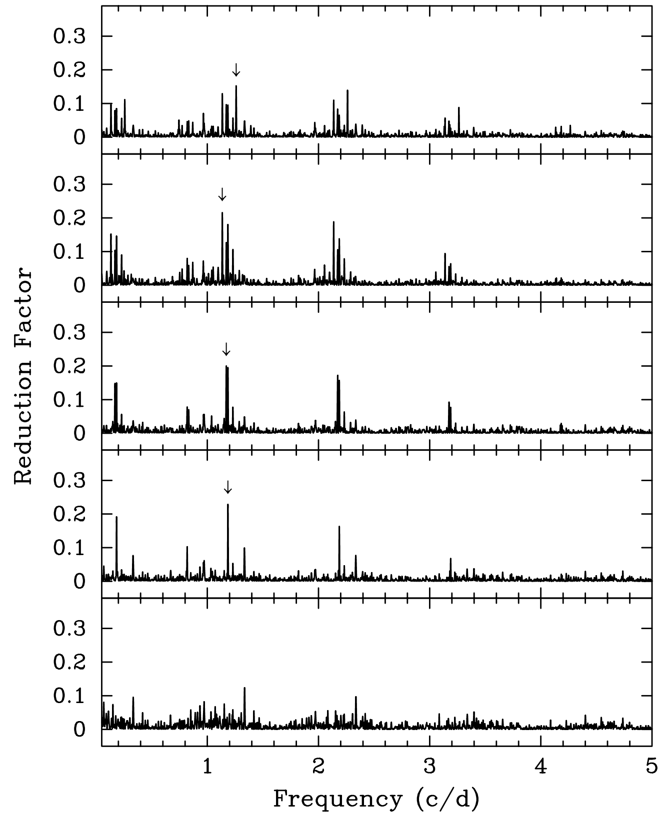

FIG. 5.—Least-squares spectra of the HD 32348 Johnson *B* data set, showing the results of progressively fixing the four detected frequencies. The arrows indicate the four frequencies (*top to bottom*) 1.2591, 1.1346, 1.1705, and 1.1852 day^{-1}. All four frequencies were confirmed in the Johnson *V* data set.

To date we have obtained seven observations of HD 32348 at four different epochs. Radial velocities of component B, the narrow-lined star, show a total velocity variation of 16 km s^{-1}, indicating that it is a spectroscopic binary. The velocity range for component A is about 8 km s^{-1}. So components A and B may make up a spectroscopic binary pair. However, since component A has a spectral type of F2 dwarf, the photometric variability determined below presumably belongs to it rather than to component B. Thus, much of the velocity variation of A could result from pulsation, making it a star with a much longer orbital period than component B. For the present we assume that components A and B form a binary system. Spectroscopic observations are continuing.

Our interest in HD 32348 began when we discovered its photometric variability with our T10 0.8 m APT after selecting it as a comparison star in our long-term monitoring program of solar-type stars (Henry 1999). Our subsequent, more intensive T3 APT observations are analyzed in this paper. We find four closely spaced periods of 0.79422, 0.88137, 0.85434, and 0.84374 days in our Johnson *B* photometry with amplitudes of 8, 8, 7, and 7 mmag, respectively (Figs. 5 and 6; Table 5). The light curve is sinusoidal when phased with each of these four periods. Figure 5 (*bottom*) suggests the possible presence of a fifth period in the same vicinity as the others, but we could not confirm this period in the *V* data. The weighted mean B/V amplitude ratio for the four periods (1.15 ± 0.15) is relatively uncertain due to the low amplitudes of the individual periods but is consistent with pulsation. Therefore, since the spectroscopic observations point to the F2 dwarf as the likely source of the photometric variability, we confirm that HD 32348A is a γ Doradus star.

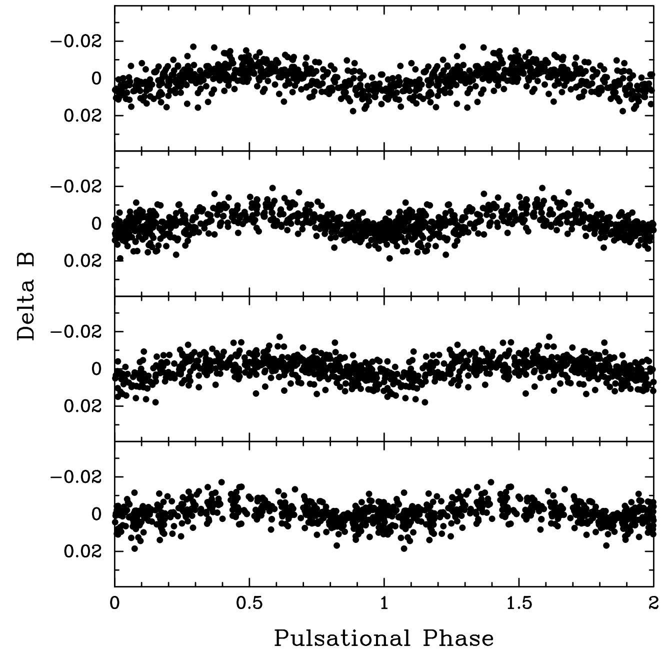

FIG. 6.—Johnson *B* photometric data for HD 32348, phased with the four frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 1.2591, 1.1346, 1.1705, and 1.1852 day^{-1}. For each panel, the data set has been prewhitened to remove the other three known frequencies.

6.3. *HD 40745 (HR 2118, AC Leporis)*

In her extensive reexamination of stars in the HD catalog, Houk (Houk & Smith-Moore 1988) classified HD 40745 as F2 IV, while Abt & Morrell (1995) called it F2 V. In agreement with those results, we have determined a spectral class of F2. The *Hipparcos* parallax (Perryman et al. 1997) leads to a subgiant luminosity class.

Danziger & Faber (1972) estimated a $v \sin i$ value of 50 km s^{-1}, which Wolff & Simon (1997) revised to 40 km s^{-1}. Abt & Morrell (1995) found $v \sin i = 33$ km s^{-1}, which Royer et al. (2002) rescaled to 42 km s^{-1}. From high-resolution spectra Mathias et al. (2004) and de Cat et al. (2006) also determined the projected rotational velocity of HD 40745, obtaining 37 and 39 km s^{-1}, respectively. Our mean from four observations is 41 km s^{-1} and so is in good agreement with previous values.

From a single spectrum Grenier et al. (1999) computed a radial velocity of 29.9 km s^{-1}, while Nordström et al. (2004) measured a velocity of 28.0 km s^{-1}, also from just one observation. Recently, de Cat et al. (2006) obtained eight spectra and determined a mean velocity of 31.8 km s^{-1} (P. de Cat 2006, private communication). Our four spectra result in an identical mean velocity of 31.8 ± 0.1 km s^{-1}. Taken together, the 14 velocities have a range of 5 km s^{-1}, consistent with pulsation as its cause (e.g., Fekel & Henry 2003; Mathias et al. 2004). Thus, we assume that HD 40745 is a single star.

The *Hipparcos* mission team discovered HD 40745 to be variable with a period of 0.82415 days (Perryman et al. 1997). Aerts et al. (1998) reanalyzed that photometry and found periods of 0.8752 and 0.8920 days. They identified the star as a member of the γ Doradus class of variables. As a result, Kazarovets et al. (2000) provided it with the variable-star name AC Lep and tentatively classified it as a γ Doradus variable. At about the same time Handler (1999) also noted the star in his list of prime γ Doradus candidates. Handler & Shobbrook (2002) obtained three nights of photometric observations that showed variability consistent with that found in the *Hipparcos* observations, supporting its designation as a prime γ Doradus candidate.

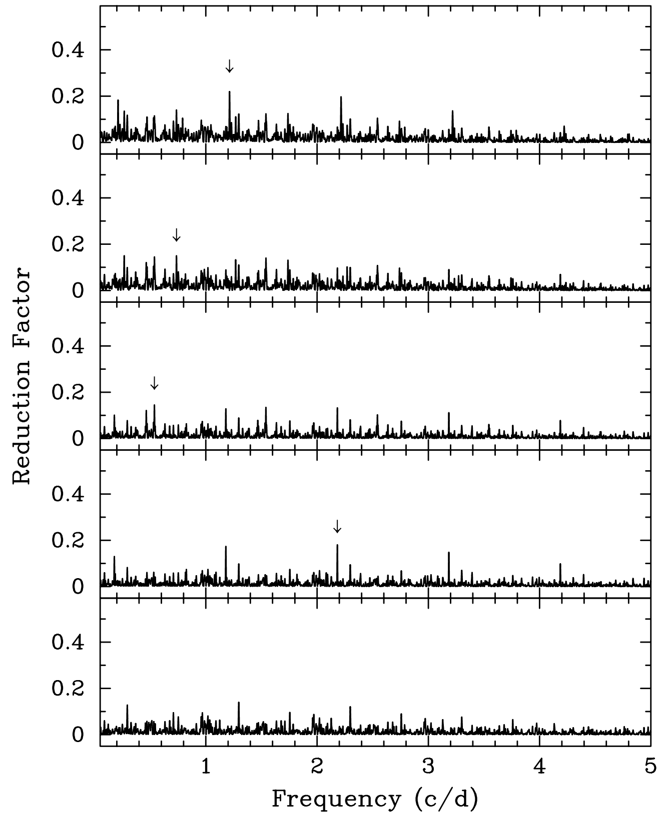

FIG. 7.—Least-squares spectra of the HD 40745 Johnson *B* data set, showing the results of progressively fixing the four detected frequencies. The arrows indicate the four frequencies (*top to bottom*) 1.2132, 0.7361, 0.5377, and 2.1820 day^{-1}. All four frequencies were confirmed in the Johnson *V* data set.

Our new HD 40745 APT photometric data set contains more than 270 Johnson *BV* observations acquired over 200 days. The least-squares spectra of the *B* observations are plotted in Figure 7, and the results of our period analysis are given in Table 5. We find four periods of 0.82427, 1.35851, 1.85977, and 0.45830 days with peak-to-peak amplitudes in *B* of 12, 9, 8, and 6 mmag, respectively. The first of these periods agrees with the *Hipparcos* result. Although our four periods range over a factor of 4, no linear combinations of the four frequencies are evident within their uncertainties. However, given the low amplitudes involved, it is possible that we have misidentified one or two of the true frequencies and picked an alias instead. All of our HD 40745 observations are phased with the four periods and the times of minimum given in Table 5 and plotted in Figure 8; the light curves phased with all four periods closely resemble sinusoids. The individual *B*/*V* amplitude ratios have a weighted mean of 1.33 ± 0.06, indicative of γ Doradus pulsation. Given the star's F2 subgiant classification, the multiple periods in the γ Doradus period range, and the *B*/*V* amplitude ratio, we confirm previous claims that HD 40745 is a γ Doradus variable.

6.4. *HD 41448*

Houk (Houk & Smith-Moore 1988) classified HD 41448 as A9 V. Mathias et al. (2004) obtained two spectra and found a projected rotational velocity of 93 km s^{-1}, while de Cat et al. (2006) recently determined a value of 106 ± 3 km s^{-1}. We have obtained three spectra from which we determined a spectral class of F0, while the *Hipparcos* parallax leads to a dwarf luminosity class. We found $v \sin i = 100$ km s^{-1}, in reasonable accord with the above two determinations. De Cat et al. (2006) obtained 12 velocities

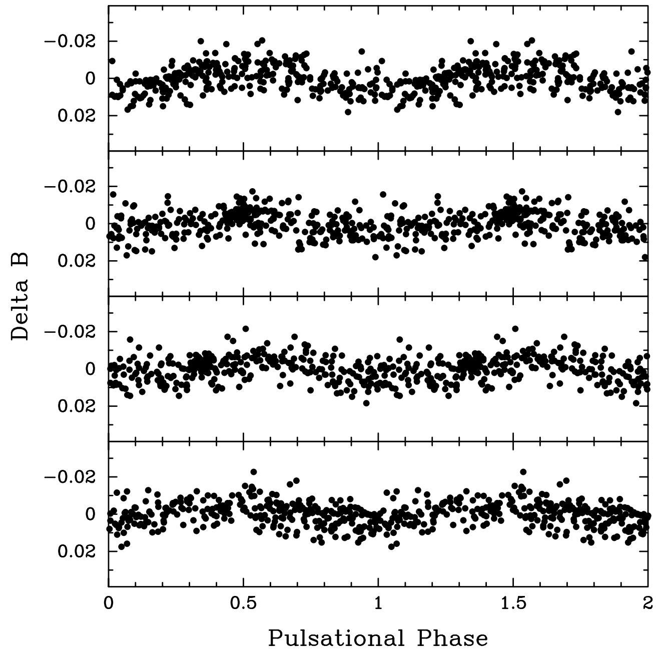

FIG. 8.—Johnson *B* photometric data for HD 40745, phased with the four frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 1.2132, 0.7361, 0.5377, and 2.1820 day^{-1}. For each panel, the data set has been prewhitened to remove the other three known frequencies.

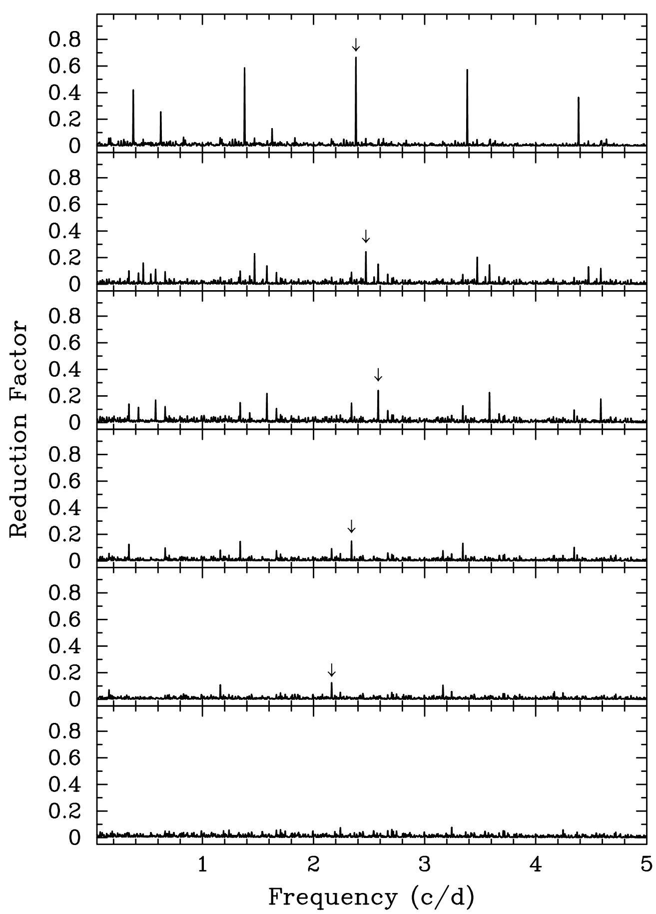

FIG. 9.—Least-squares spectra of the HD 41448 Johnson *B* data set, showing the results of progressively fixing the five detected frequencies. The arrows indicate the five frequencies (*top to bottom*) 2.3814, 2.4712, 2.5822, 2.3419, and 2.1629 day^{-1}. All five frequencies were confirmed in the Johnson *V* data set.

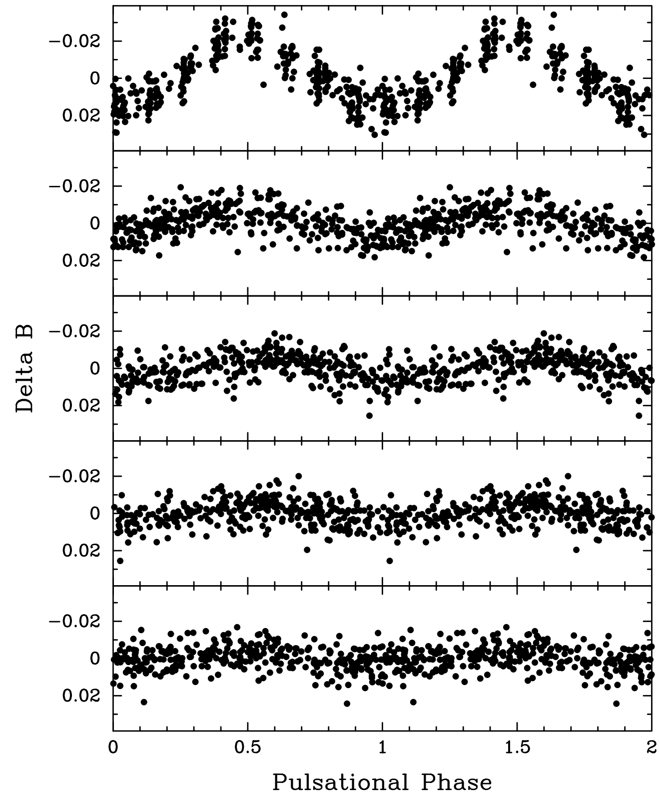

FIG. 10.—Johnson *B* photometric data for HD 41448, phased with the five frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 2.3814, 2.4712, 2.5822, 2.3419, and 2.1629 day^{-1}. For each panel, the data set has been prewhitened to remove the other four known frequencies.

over a 10 day period and found a mean velocity of 26.9 km s^{-1} (P. de Cat 2006, private communication). Our three velocities, measured from a single unblended line in each spectrum, result in an average velocity of 29.6 ± 2.0 km s^{-1} and have a range of 7 km s^{-1}. Thus, the two average velocities are in reasonable agreement. Given our difficulty in measuring the radial velocity because of the star's rapid rotation and line asymmetries, the range of the velocity variation is consistent with pulsation. Thus, the star is probably single.

The *Hipparcos* mission team discovered the light variability of HD 41448 and was able to determine a period of 0.419912 days (Perryman et al. 1997), but they did not identify a variability type. Handler (1999), however, called it a prime γ Doradus candidate, based on the work of Eyer (1998). Because of its proximity in the sky to HD 40745, Handler & Shobbrook (2002) observed HD 41448 in the same photometric group. Analysis of their data resulted in the same general conclusions as those for HD 40745. Thus, they retained the star as a prime γ Doradus candidate.

We obtained over 300 *BV* photometric observations of HD 41448 with the T3 APT. We find five closely spaced, independent periods of 0.41992, 0.40466, 0.38727, 0.42700, and 0.46234 days with amplitudes of 38, 10, 9, 4, and 10 mmag, respectively (Figs. 9 and 10; Table 5). Our highest-amplitude period of 0.41992 days agrees well with the *Hipparcos* value cited above; all five light curves in Figure 10 closely resemble sinusoids. The weighted mean *B*/*V* amplitude ratio for these five periods is 1.20 ± 0.08, indicating the photometric variability is due to pulsation. Therefore, given the F0 V spectral type, multiperiodic photometric variations in the γ Doradus period range, and the *B*/*V* amplitude ratio, we confirm HD 41448 as a γ Doradus variable.

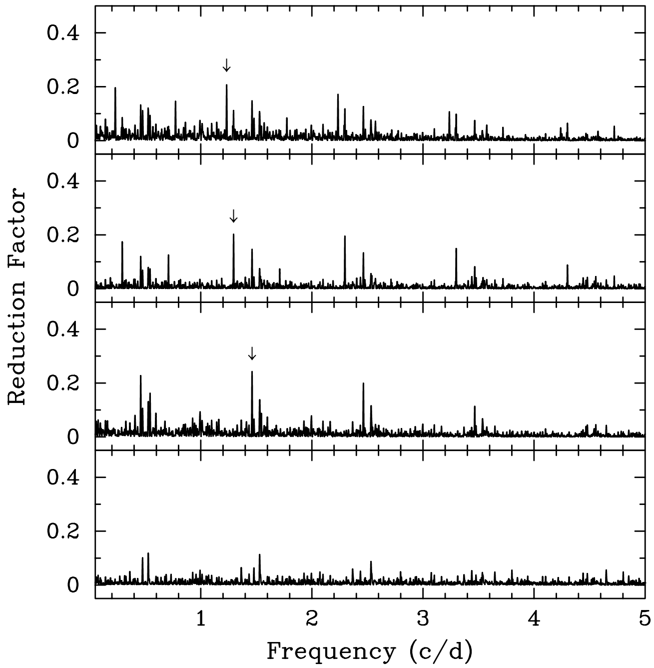

FIG. 11.—Least-squares spectra of the HD 41547 Johnson *B* data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies (*top to bottom*) 1.2327, 1.2951, and 1.4613 day^{-1}. All three frequencies were confirmed in the Johnson *V* data set.

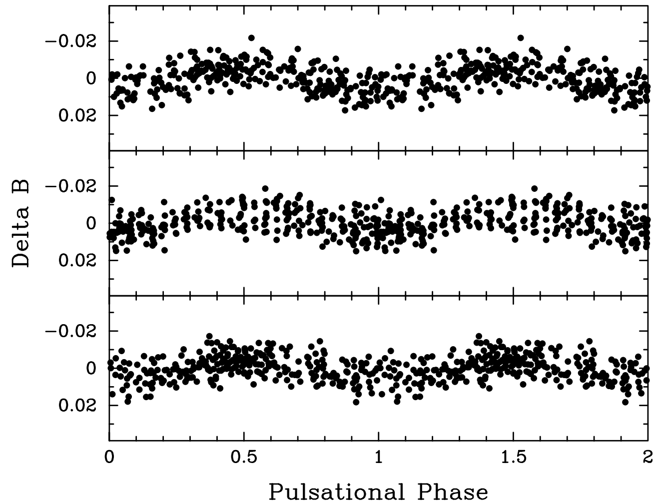

FIG. 12.—Johnson *B* photometric data for HD 41547, phased with the three frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 1.2327, 1.2951, and 1.4613 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

6.5. *HD 41547 (HR 2150)*

At Mount Wilson Observatory Christie & Wilson (1938) obtained three spectra of HD 41547, one of which showed double lines with a velocity separation of 82 km s^{-1} (Christie & Wilson 1938; Abt 1970). Our seven red-wavelength spectra show two components of roughly similar strength. We classify the stars as F2 and F4–5, and the *Hipparcos* parallax indicates that they are both dwarfs or subgiants. From our spectrum addition results the magnitude difference in *V* is 0.5 with an estimated uncertainty of 0.1 mag.

The lines of the primary change in width and strength with its $v \sin i$ value varying from 9 to 12 km s^{-1}, producing an average value of 11 km s^{-1}. The $v \sin i$ of the secondary has a mean of 7 km s^{-1}. The line-shape variability appears to be greater for the primary suggesting that it is a γ Doradus variable while the secondary is not. Additional spectra will be needed to confirm this preliminary result.

From our seven spectra we have obtained a preliminary orbit with a period of 5.32 days and a nearly circular orbit. Minimum masses are 0.21 and 0.19 $M_{\odot}$ for the primary and secondary, respectively. Adopting a canonical value of 1.45 $M_{\odot}$ (Gray 1992) for the primary results in an orbital inclination of about 30°. We are continuing observations to improve the orbit elements.

Both Balona & Stobie (1980) and Balona et al. (2001) used HD 41547 as one of their photometric comparison stars for the δ Scuti variable 1 Mon without commenting on any low-amplitude variability in the comparison stars. We also chose HD 41547 as our check star for both our HD 40745 and HD 41448 group observations (Table 3). Analysis of both groups showed that HD 41547 is also a possible γ Doradus variable. The data analyzed for this paper are the $(K - C)$ differential magnitudes from the HD 41448 group (Table 4). We detect three closely spaced, independent periods of 0.81123, 0.77214, and 0.68432 days with *B* amplitudes of 11, 8, and 9 mmag, respectively (Figs. 11 and 12; Table 5). The light variability at all three periods resembles a sinusoid. The weighted mean B/V amplitude ratio for the periods is 1.43 ± 0.19, indicating pulsational variability. Given these photometric results and the spectroscopic results discussed above, we confirm that the F2 component of HD 41547 is a γ Doradus star.

6.6. *HD 86371*

Houk (Houk & Smith-Moore 1988) classified HD 86371 as F0 V. Grenier et al. (1999) obtained three spectra of HD 86371, two of which showed double lines with a velocity separation of about 47 km s^{-1}. Mathias et al. (2004) determined $v \sin i$ values of 11 and 6 km s^{-1} for the two components.

Our red-wavelength spectra show that the lines of the two components are nearly identical in both strength and broadening. While there are times when the lines of the two components appear slightly unequal in depth, the depth change is compensated for by increased line broadening of the weaker component, so the equivalent widths remain essentially unchanged. This changing shape of the lines is presumably caused by pulsation. We classify the two nearly identical components as F1. That the stars are dwarfs is indicated by the *Hipparcos* parallax (Perryman et al. 1997), combined with the apparent visual magnitude, which has been increased by 0.75 to account for duplicity. Our individual $v \sin i$ values range from 8 to 14 km s^{-1}, but the mean values for components A and B, assuming that we have correctly identified those components, are 10.5 and 11.1 km s^{-1}, respectively. Our 12 spectra indicate that the velocities of the two stars change slowly, and we have obtained a preliminary orbital period of 26.7 days. Observations are underway to confirm this period and determine other orbital elements.

Handler (1999) listed the star among his prime γ Doradus candidates, with a period of 2.459 days and with additional variability around 1.1 days. Although Handler & Shobbrook (2002) obtained only one night of photometry for HD 86371 and could not recover the *Hipparcos* periodicity, they concluded from its complicated light curve and color-amplitude ratio that HD 86371 is a confirmed member of the γ Doradus class of variables. Because of the similarity of the stars and their line-width variability as discussed above, it appears that both components could be γ Doradus variables.

Our *BV* photometry from the T3 APT reveals three closely spaced periods of 1.67842, 1.72414, and 1.48920 days with

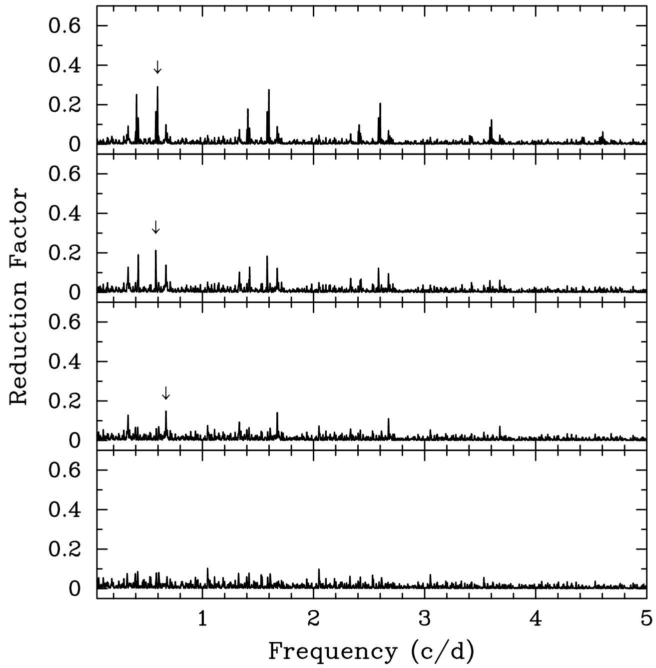

FIG. 13.—Least-squares spectra of the HD 86371 Johnson *B* data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies (*top to bottom*) 0.5958, 0.5800, and 0.6715 day^{-1}. All three frequencies were confirmed in the Johnson *V* data set.

amplitudes of 40, 30, and 24 mmag, respectively (Figs. 13 and 14; Table 5). These periods are quite different from those derived from the sparser *Hipparcos* photometry. However, the *Hipparcos* period of 2.459 days is a 1 day alias of our 1.67842 day period. While all three periods give approximately sinusoidal phase curves, there is some suggestion of cycle-to-cycle variation in the level of maximum brightness (seen as increased scatter around the maximum of the phase curve). This is 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 of the B/V amplitude ratio is 1.45 ± 0.17, indicating that the photometric variability is due to pulsation. Thus, we can confirm that HD 86371 is a γ Doradus star but, given the similarity of its two components, we cannot say whether the photometric variability arises from component A or B or both. Spectroscopic analyses, such as those by Mathias et al. (2004) and de Cat et al. (2006) may be able to determine which period or periods belong to which component.

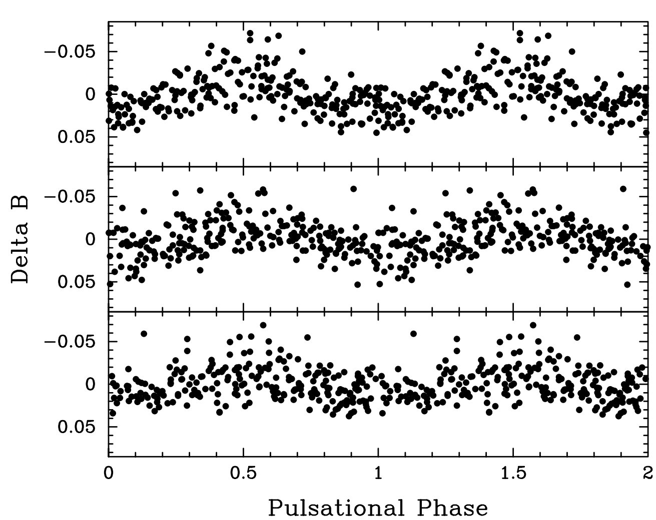

FIG. 14.—Johnson *B* photometric data for HD 86371, phased with the three frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 0.5958, 0.5800, and 0.6715 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

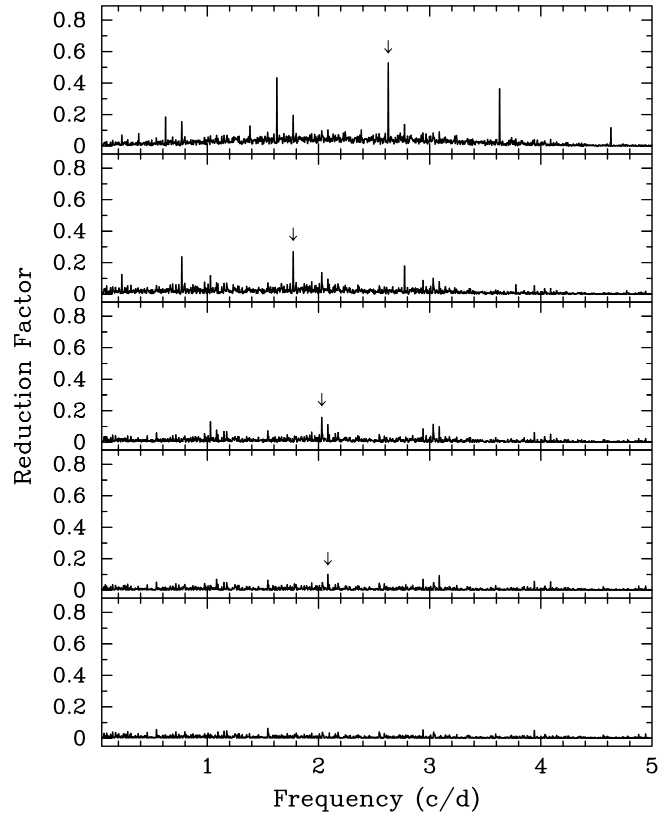

FIG. 15.—Least-squares spectra of the HD 89781 Johnson *B* data set, showing the results of progressively fixing the four detected frequencies. The arrows indicate the four frequencies (*top to bottom*) 2.6274, 1.7722, 2.0298, and 2.0846 day^{-1}. All four frequencies were confirmed in the Johnson *V* data set.

6.7. *HD 89781*

Grenier et al. (1999) obtained three 80 Å mm^{-1} spectrograms of HD 89781. They classified the star as F0 IV and found a mean velocity of 14.0 ± 6.8 km s^{-1}. The large uncertainty led them to conclude that the star has a variable velocity.

We acquired two spectra of this star, both of which show significant redward line asymmetries that either belong to a second component or are the result of pulsation. Unfortunately, the large rotational broadening, which we determined to be $v \sin i = 120$: km s^{-1}, makes analysis of the properties of HD 89781 more uncertain than usual. We find a spectral class of F1:, and the *Hipparcos* parallax (Perryman et al. 1997) leads to a subgiant luminosity class. Our two velocities have an average of 3.7 ± 0.7 km s^{-1}, which is 10 km s^{-1} less than the mean of Grenier et al. (1999). From this limited number of radial velocities and the asymmetry of the line profiles, we conclude that HD 89781 *might* be a spectroscopic binary, but we consider it a single star until we have further evidence of its duplicity.

The photometric variability of HD 89781 was first discovered with the T10 APT after we chose it as a comparison star for our solar-type star monitoring program (Henry 1999). Our more intensive follow-up measurements from the T3 APT are presented and analyzed in this paper. We find four similar, independent periods of 0.38060, 0.56427, 0.49266, and 0.47971 days with *B* amplitudes of 20, 12, 9, and 9 mmag, respectively (Figs. 15 and

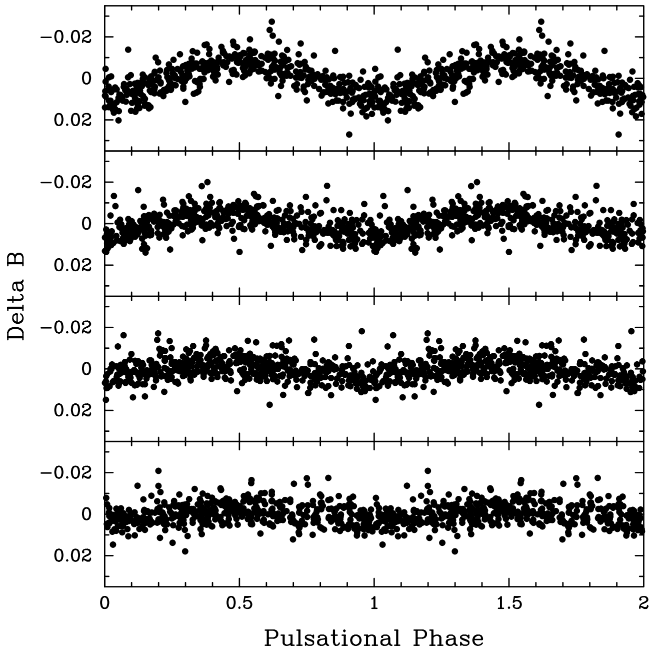

FIG. 16.—Johnson *B* photometric data for HD 89781, phased with the four frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 2.6274, 1.7722, 2.0298, and 2.0846 day^{-1}. For each panel, the data set has been prewhitened to remove the other three known frequencies.

16; Table 5). All four light curves in Figure 16 closely resemble a sinusoid. The weighted mean *B*/*V* amplitude ratio of these four periods is 1.19 ± 0.07, consistent with pulsation. Based on this spectroscopic and photometric evidence, we confirm HD 89781 to be a γ Doradus star.

6.8. *HD 103751*

HD 103751 is a previously obscure star with no references in the bibliography section of SIMBAD. The *Hipparcos* and Tycho catalog (Perryman et al. 1997) is the primary source of basic information about it. We obtained three spectra of the star and determined a spectral class of F1, while the *Hipparcos* parallax (Perryman et al. 1997) results in a subgiant luminosity classification. HD 103751 has a moderate projected rotational velocity of 58 km s^{-1}. Its mean velocity of 2.7 ± 0.8 km s^{-1} shows little variability, suggesting that the star is single.

HD 103751 was discovered to be a variable comparison star with the T10 APT in our solar-type star monitoring program (Henry 1999). Our more intensive follow-up measurements from the T3 APT are presented and analyzed here. We find two independent periods of 1.01143 and 0.89405 days with *B* amplitudes of 34 and 25 mmag, respectively (Figs. 17 and 18; Table 5). Both light curves in Figure 18 closely resemble a sinusoid with a slight indication of increased scatter around the maximum brightness in both panels, similar to the Blazhko effect noted above in HD 86371. The weighted mean *B*/*V* amplitude ratio of these two periods is 1.26 ± 0.06, indicating the presence of pulsation. Based on the spectroscopic and photometric evidence, we confirm HD 103751 to be a γ Doradus variable.

6.9. *HD 144451*

The only previous spectral type of HD 144451 is that of Houk (Houk & Smith-Moore 1988), who classified it F0 V. We found a spectral class of F1, while the *Hipparcos* parallax indicates a dwarf luminosity class. Nordström et al. (1997) determined a $v \sin i$ value of 54.1 km s^{-1} in accord with our result of 53 km s^{-1}.

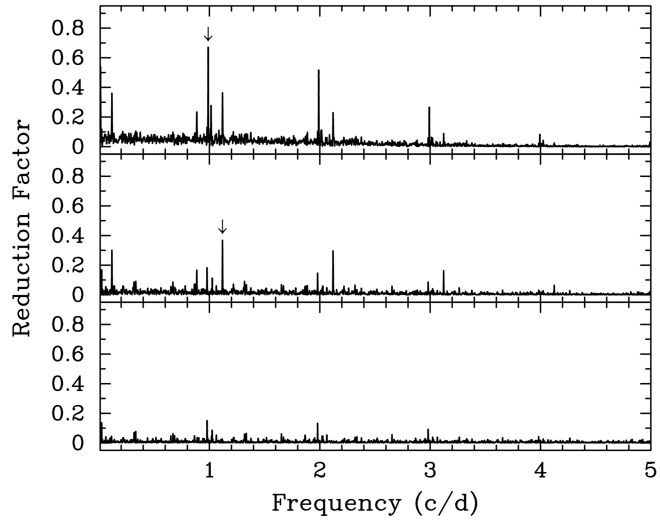

FIG. 17.—Least-squares spectra of the HD 103751 Johnson *B* data set, showing the results of fixing the two detected frequencies. The arrows indicate the two frequencies at 0.9887 day^{-1} (*top*) and 1.1185 day^{-1} (*middle*). Both frequencies were confirmed in the Johnson *V* data set.

From three observations Nordström et al. (1997) measured a mean velocity of 7.1 km s^{-1}. That average is in excellent agreement with our four KPNO velocities, which have a mean of 6.9 ± 0.9 km s^{-1}. Thus, we conclude that the star is single except for a visual companion that is 3.5 mag fainter and separated by 1.9″.

HD 144451 is a prime γ Doradus candidate from Handler (1999); he found periods of 0.442 and 0.553 days from the *Hipparcos* photometry. Our more numerous APT observations reveal three closely spaced periods of 0.62617, 0.60694, and 0.56256 days with amplitudes of 60, 52, and 12 mmag, respectively (Figs. 19 and 20; Table 5). All three periods closely approximate sinusoids. Only our third (weakest) period agrees approximately with the *Hipparcos* results. The weighted mean of the *B*/*V* amplitude ratio is 1.34 ± 0.10, indicating the photometric variability is due to pulsation. Thus, we confirm that HD 144451 is a γ Doradus variable.

6.10. *HD 187615*

Handler (1999) included HD 187615 in his list of further γ Doradus candidates. Although he found two periods of 0.498 and 0.508 days from his analysis of the *Hipparcos* photometry, Handler (1999) commented that the light variability might possibly result from starspots. In their survey of possible γ Doradus

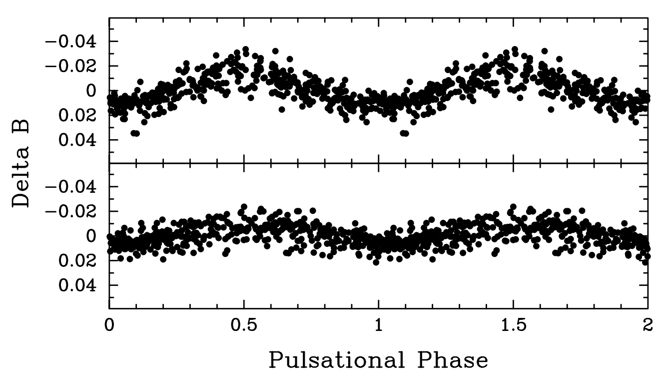

FIG. 18.—Johnson *B* photometric data for HD 103751, phased with the two frequencies and times of minimum from Table 5. The two frequencies are 0.9887 day^{-1} (*top*) and 1.1185 day^{-1} (*bottom*). For each panel, the data set has been prewhitened to remove the other known frequency.

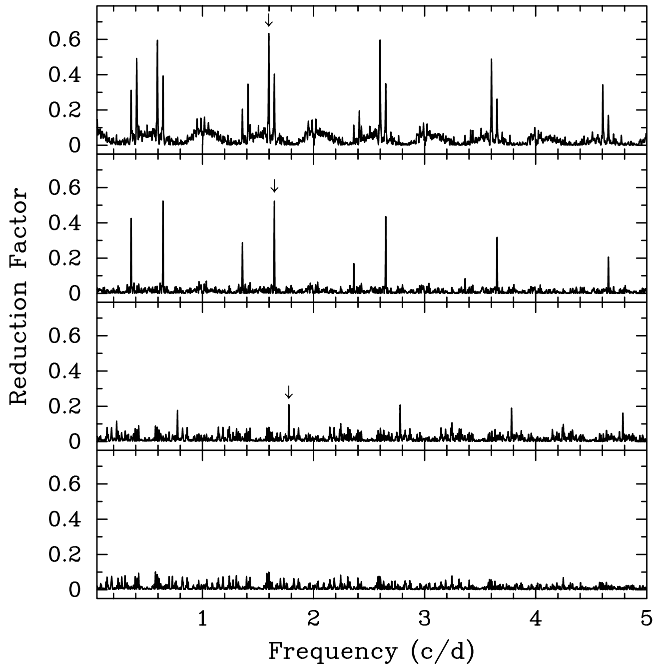

FIG. 19.— Least-squares spectra of the HD 144451 Johnson *B* data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies (*top to bottom*) 1.5970, 1.6476, and 1.7776 day^{-1}. All three frequencies were confirmed in the Johnson *V* data set.

variables Fekel et al. (2003) obtained a single spectrum of HD 187615. They classified the star as F1 and noted that the *Hipparcos* parallax indicates that the star is a dwarf. They determined a radial velocity of 8.3 km s^{-1} and a $v \sin i$ value of 80 km s^{-1}. Our velocities from four additional KPNO spectra, combined with the lone velocity of Fekel et al. (2003) result in an average of 10.2 $\pm$ 1.0 km s^{-1}, suggesting that the star is single.

Our APT observations of HD 187615 reveal three independent, closely spaced periods of 0.49806, 0.50805, and 0.48745 days with amplitudes of 38, 32, and 25 mmag, respectively (Figs. 21 and 22; Table 5). The first two periods match the periods found in the *Hipparcos* data by Handler (1999). All three periods closely approximate sinusoids. The weighted mean of the *B*/*V* amplitude ratio is 1.28 $\pm$ 0.09, indicating that the photometric variability is due to pulsation. Thus, we confirm that HD 187615 is a γ Doradus star.

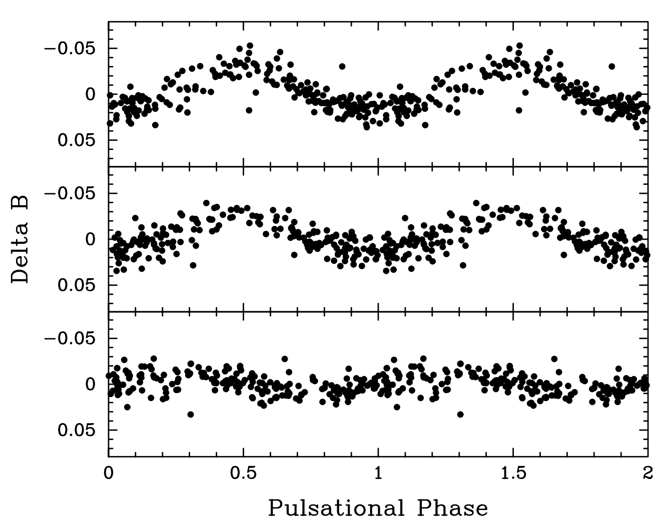

FIG. 20.—Johnson *B* photometric data for HD 144451, phased with the three frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 1.5970, 1.6476, and 1.7776 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

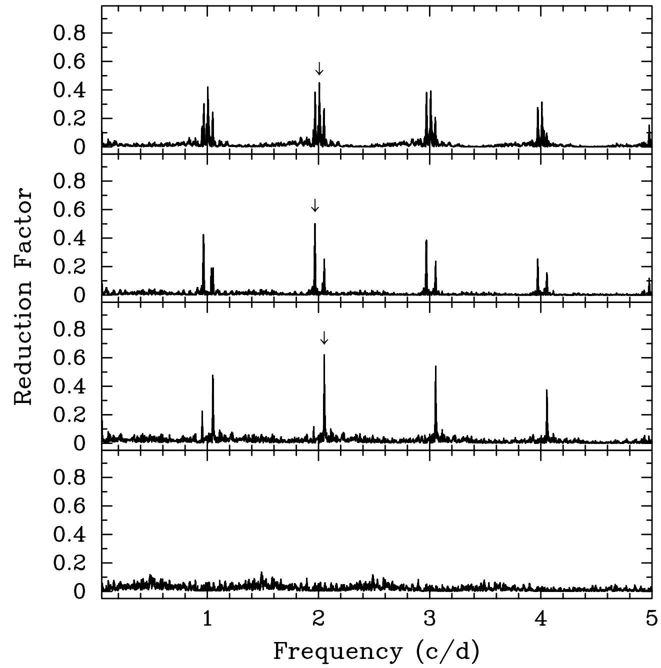

FIG. 21.— Least-squares spectra of the HD 187615 Johnson *B* data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies (*top to bottom*) 2.0078, 1.9683, and 2.0515 day^{-1}. All three frequencies were confirmed in the Johnson *V* data set.

6.11. *HD 211699 (PR Pegasi)*

Handler (1999) drew attention to HD 211699 as a prime γ Doradus candidate. Mathias et al. (2004) obtained 21 spectra of it and found HD 211699 to be a slow rotator with $v \sin i =$ 12 km s^{-1}. They also noted that the star had line-profile variations and that its radial velocity ranged from 5 to 10 km s^{-1}. Mathias et al. (2004) concluded that the observed velocity variation had a period that was consistent with the *Hipparcos* photometric period (Perryman et al. 1997) mentioned below.

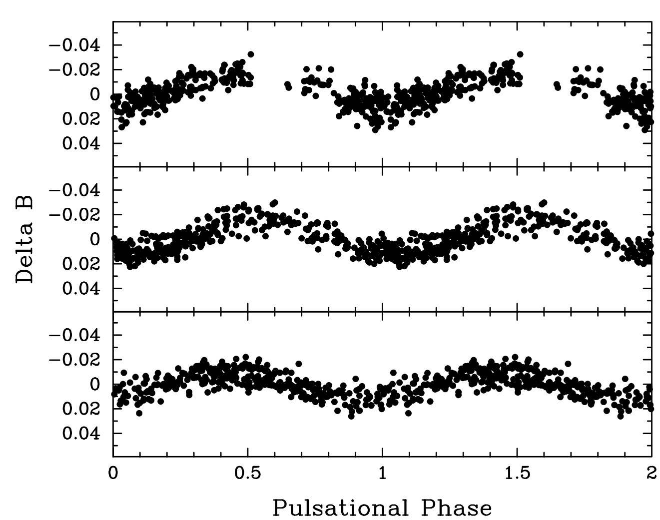

FIG. 22.— Johnson *B* photometric data for HD 187615, phased with the three frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 2.0078, 1.9683, and 2.0515 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

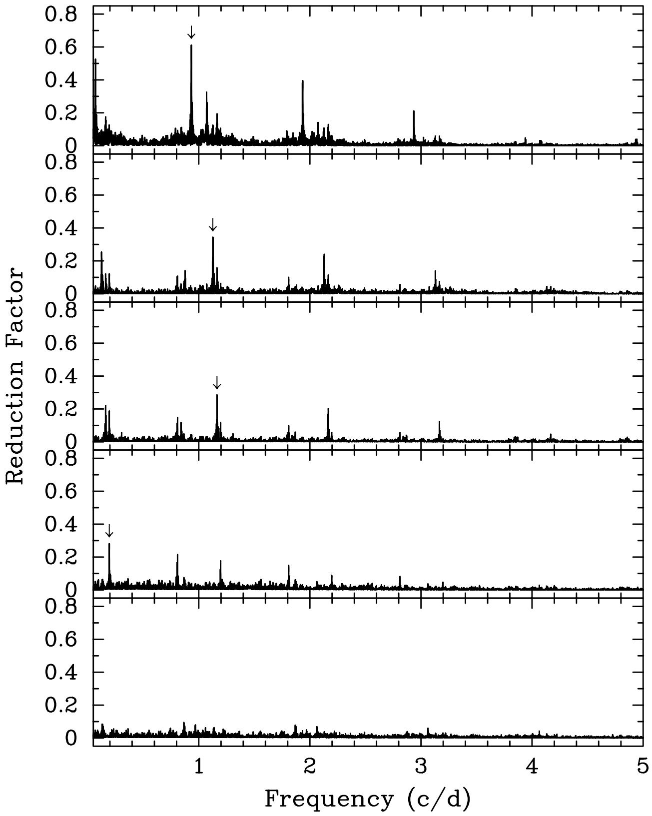

FIG. 23.—Least-squares spectra of the HD 211699 Johnson B data set, showing the results of progressively fixing the four detected frequencies. The arrows indicate the four frequencies (*top to bottom*) 0.9328, 1.1265, 1.1634, and 0.1939 day^{-1}. All four frequencies were confirmed in the Johnson V data set.

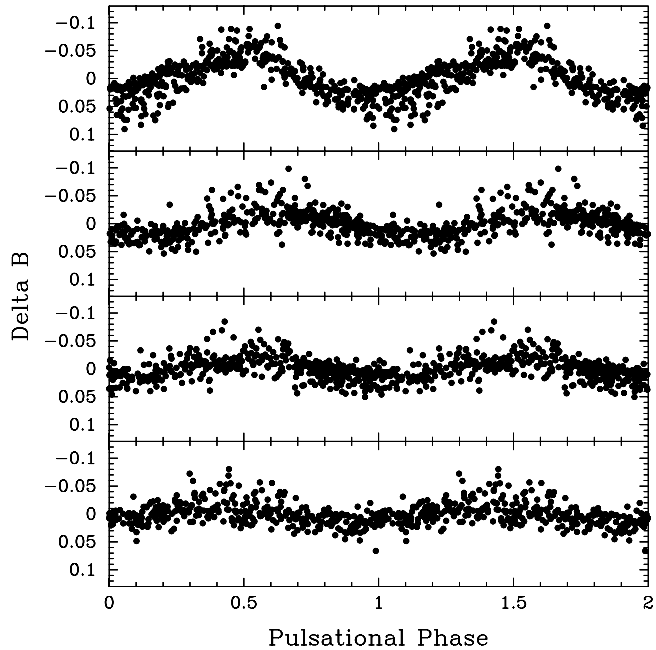

FIG. 24.—Johnson B photometric data for HD 211699, phased with the four frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 0.9328, 1.1265, 1.1634, and 0.1939 day^{-1}. For each panel, the data set has been prewhitened to remove the other three known frequencies.

In 2004 June we initially obtained two spectra of the star, one at 6430 Å and one at 4500 Å. Then, in 2004 September and October, we participated in a multisite observing campaign on HD 211699 coordinated by P. Mathias (Mathias et al. 2006) and obtained 15 spectrograms at 4500 Å during three consecutive nights. Finally, in 2005 September, we obtained four additional observations, three at 6430 Å and one at 4500 Å.

Figure 2 shows a red-wavelength spectrum that was acquired during the observing run of 2005 September. That spectrum shows obvious line asymmetries with the redward portion of the iron lines being stronger than the blueward portion, while the calcium line at 6439 Å has the asymmetry reversed. This spectrum of HD 211699 is very similar in appearance to that of another γ Doradus variable, HD 221866 (see Henry & Fekel 2002, their Fig. 12). Kaye et al. (2004) demonstrated that HD 221866 is a double-lined spectroscopic binary with a rather long period of 135 days, high eccentricity of 0.68, and an Am star primary. They concluded that the early F secondary star was the source of the photometric variations and was therefore the γ Doradus component of HD 221866. Thus, we conclude that HD 211699 is also a long-period double-lined spectroscopic binary with an Am star primary.

The *Hipparcos* parallax of the HD 211699 system, $0.00407'' \pm 0.00111''$, is small and has an uncertainty of 27%. The corresponding distance is 246 ± 72 pc, suggesting that the star is likely to be somewhat reddened. As part of an extensive effort to map interstellar reddening within 300 pc of the Sun, Perry & Johnston (1982) observed HD 211699 in the Strömgren *uvby* system and Hβ. They determined an unreddened V magnitude of 9.00, which is 0.13 mag brighter than the observed value given in the *Hipparcos* catalog. The Hβ magnitude of 2.768 and $(b-y)_0$ of 0.187 (Perry & Johnston 1982) indicate, according to the calibration of Crawford (1979) a spectral type of F0 V for the combined system.

From a red-wavelength spectrum with partially resolved lines, we determined spectral classes of A3 and A8 for the calcium and iron lines of the primary, respectively. Such a spectral class difference is typical of Am stars (e.g., Abt & Morrell 1995). We have no information on the hydrogen spectral class and so simply adopt A7, since it is intermediate between our calcium- and metal-line results. We estimate a spectral class of F2: for the secondary. The minimum magnitude difference at 6430 Å from our spectrum-addition fit is 0.99 mag. We estimate an approximate V magnitude difference of 1.2. Although the *Hipparcos* parallax suggests that both stars are probably dwarfs, the parallax uncertainty is large. From Johnson (1966) we adopt $B-V$ colors corresponding to spectral types of A7 V and F2 V for the components. Our $v \sin i$ values are 18: and 13: km s^{-1} for the primary and secondary, respectively. We caution that some of the preliminary derived properties of the two components are not particularly consistent, and all the properties of this system will need to be redetermined once a spectrum having completely resolved lines is obtained.

The *Hipparcos* mission team discovered HD 211699 to be variable with a period of 1.07207 days (Perryman et al. 1997) but did not suggest a variable-star type. Kazarovets et al. (1999) assigned it the variable-star name PR Peg and tentatively classified it as a Cepheid variable. Handler & Shobbrook (2002) observed it on four nights as part of their survey for δ Scuti pulsators among known and candidate γ Doradus variables. They reported night-to-night light variations with a color-amplitude ratio that was consistent with pulsation. They detected no light variations of the δ Scuti type and so retained this star as a γ Doradus candidate.

Our APT observations of HD 211699 reveal three closely spaced, independent periods of 1.07204, 0.88771, and 0.85955 days, as well as a fourth period of 5.15730 days (Figs. 23 and 24; Table 5). The first period agrees closely with the *Hipparcos* period, while the fourth period is probably not an independent

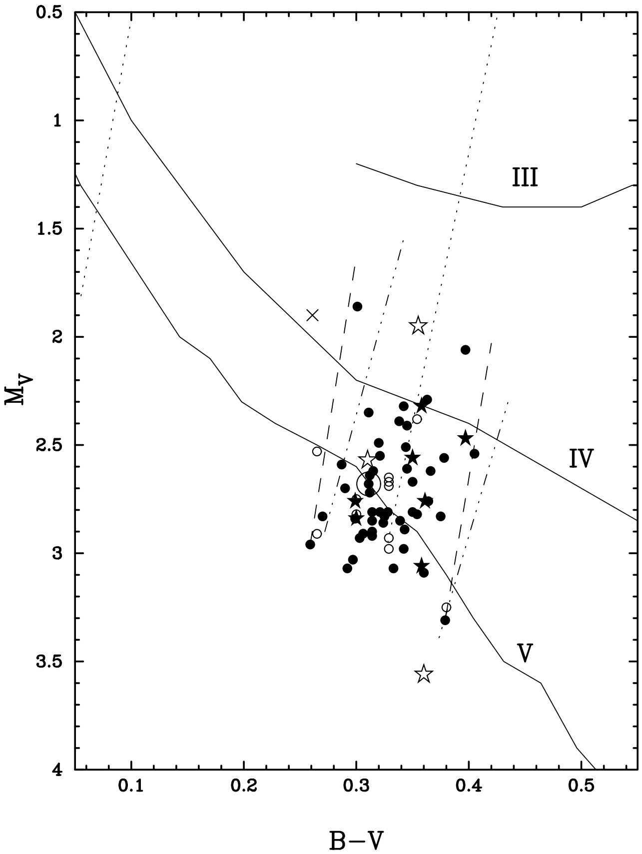

FIG. 25.—Location of all 66 confirmed γ Doradus stars (Table 6) in the H-R diagram, including the 10 new stars discussed in this paper (*star symbols*). Solid lines indicate the observed average locations of normal main-sequence (V), subgiant (IV), and giant (III) stars in the diagram. Both components of two of the double-lined spectroscopic binaries are plotted for a total of 68 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 dot. 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).

pulsation period since its frequency is precisely the difference of the first two frequencies. The B amplitudes of the four periods are 94, 46, 54, and 33 mmag, respectively. All four periods closely resemble sinusoids. The weighted mean B/V amplitude ratio of the four periods is 1.28 ± 0.08, consistent with pulsation. Since the Am primary of HD 211699, with an assumed $B - V$ color index of 0.19 (see above), lies well outside the nominal γ Doradus instability strip (Fig. 25), the F2 secondary is likely to be the variable star. Thus, the HD 211699 binary system is very similar to the HD 221866 system, and we confirm HD 211699B as a γ Doradus variable.

7. DISCUSSION

In Table 6, we list all 66 γ Doradus stars that have been confirmed to date, including the 10 new stars in this paper and HD 218427 and HD 239276, confirmed by Rodríguez et al. (2006a) and Rodríguez et al. (2006b), respectively. The list includes 36 single stars, 6 single-lined spectroscopic binaries, 14 double-lined binaries, and 12 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 211699, however, is a double-lined system for which we have shown in § 6.11 (above) 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 (§ 6.6 above) and HD 113867 (Henry & Fekel 2003) 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 68 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, $B - V$ 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. The final column gives the literature reference(s) confirming each star as a γ Doradus variable.

In many cases, 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 due to 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 0.38 to 1.86 days, entirely within the period range of previously known γ Doradus variables. As mentioned in § 1, none of these 11 stars exhibited evidence for pulsation in the δ Scuti period range.

Two recent spectroscopic surveys have been useful in extending the number of γ Doradus candidates and confirmed members of the class. Mathias et al. (2004) conducted a 2 yr high-resolution spectroscopic survey of 59 candidates with the Aurélie spectrograph on the 1.52 m telescope at the Observatoire de Haute-Provence. The candidates were mainly culled from the *Hipparcos* mission, and more than 60% of them showed line-profile variations. The vast majority of those now have good ground-based photometric data sets confirming them as γ Doradus stars, and they appear in our Table 6. De Cat et al. (2006) surveyed 37 southern γ Doradus candidates with the CORALIE spectrograph on the

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	Henry et al. (2001)
2842	. . .	Single	7.99	0.325	2.83	5.7	1.6	0.65070	Henry et al. (2005)
7169A	HDS 160	VB, SB2	7.42	0.329	2.98	5.0	1.5	0.5486	Henry & Fekel (2003)
8801	HR 418, ADS 1151A	VB	6.42	0.311	2.68	6.5	1.7	0.40331	Henry & Fekel (2005)
9365A	. . .	VB	8.17	0.361	2.76	6.1	1.7	0.62582	This paper
12901	. . .	Single	6.74	0.311	2.35	8.9	1.9	0.82270	Eyer & Aerts (2000)
17310A	. . .	SB1	7.76	0.378	2.56	7.3	1.9	2.13584	Henry et al. (2005)
18995	. . .	Single	6.72	0.342	2.32	9.1	2.1	1.0833	Henry & Fekel (2002)
19684A	. . .	SB1	6.96	0.301	1.86	13.8	2.4	0.34722	Henry & Fekel (2002)
23874A	ADS 2785A	VB, SB2	8.45	0.329	2.67	6.6	1.7	0.4432	Henry & Fekel (2003)
27290	γ Dor, HR 1338	Single	4.26	0.312	2.72	6.3	1.6	0.7570	Balona et al. (1994)
32348A	. . .	SB2	7.40	0.31	2.57	7.2	1.7	0.79422	This paper
32537A	V398 Aur, 9 Aur, HR 1637, ADS 3675A	VB	4.98	0.343	2.89	5.4	1.6	1.2582	Zerbi et al. (1997a)
40745	HR 2118, AC Lep	Single	6.21	0.358	2.32	9.1	2.1	0.82427	This paper
41448	. . .	Single	7.60	0.299	2.76	6.1	1.6	0.41992	This paper
41547A	HR 2150	SB2	6.41	0.35	2.56	7.3	1.9	0.81123	This paper
48271	. . .	Single	7.49	0.315	2.62	6.9	1.7	1.0959	Henry & Fekel (2003)
48501A	HR 2481, ADS 5377A	VB	6.26	0.321	2.81	5.8	1.6	0.7750[c]	Eyer & Aerts (2000)
49015A	. . .	VB	7.04	0.375	2.83	5.7	1.7	0.52718	Henry & Fekel (2002)
55892	QW Pup, HR 2740	Single	4.49	0.324	2.86	5.5	1.6	0.9584	Perryman et al. (1997)
62454A	DO Lyn	SB2	7.43	0.329	2.67	6.6	1.7	0.62447	Kaye et al. (1999b)
64729	. . .	Single	7.57	0.321	2.55	7.4	1.8	0.7248	Henry & Fekel (2003)
65526	V769 Mon	Single	6.98	0.297	3.03	4.7	1.4	0.644	Handler & Shobbrook (2002)
68192	KO UMa	Single	7.15	0.363	2.29	9.4	2.1	0.7691	Kaye et al. (1999b)
69715A	BDS 4550A	VB	7.18	0.360	3.09	4.5	1.5	0.40707	Henry et al. (2005)
70645A	. . .	SB1	8.12	0.344	2.51	7.7	1.9	1.10314	Mathias et al. (2004), Henry et al. (2005)
80731A	. . .	SB1	8.46	0.345	2.61	7.0	1.8	1.11595	Mathias et al. (2004), Henry et al. (2005)
86358A	HR 3936	SB2	6.87	0.300	2.75	6.1	1.6	0.7753	Henry & Fekel (2003)
86371A:	. . .	SB2	7.37	0.314	2.91	5.3	1.5	1.6784	Handler & Shobbrook (2002), this paper
86371B:	. . .	SB2	7.37	0.314	2.91	5.3	1.5	1.6784	Handler & Shobbrook (2002), this paper
89781	. . .	Single:	7.48	0.355	1.95	12.8	2.5	0.38060	This paper
99329	80 Leo, HR 4410	Single	6.35	0.345	2.41	8.4	2.0	0.45286	Henry & Fekel (2002)
100215A	. . .	SB2	8.08	0.265	2.91	5.3	1.4	0.7564	Henry & Fekel (2003)
103751	. . .	Single	7.97	0.397	2.47	8.0	2.1	1.01143	This paper
105085A	. . .	SB2	7.59	0.300	2.82	5.7	1.5	0.6879	Henry & Fekel (2003)
105458	. . .	Single	7.77	0.299	2.84	5.6	1.5	0.7571	Henry et al. (2001)
108100A	DD CVn	SB2	7.27	0.329	2.68	6.5	1.7	0.7541	Breger et al. (1997), Henry & Fekel (2002)
112429	IR Dra, 8 Dra, HR 4916	Single	5.23	0.303	2.93	5.2	1.5	0.42450	Henry et al. (2005)
113867A:	. . .	SB2	7.40	0.265	2.53	7.5	1.7	1.1252	Henry & Fekel (2003)
113867B:	. . .	SB2	7.80	0.329	2.93	5.2	1.5	1.1252	Henry & Fekel (2003)
115466	LP Vir, 58 Vir	Single	6.89	0.338	2.39	8.5	2.0	0.83022	Henry et al. (2005)
124248	MU Vir, 97 Vir	Single	7.15	0.333	3.07	4.6	1.4	0.76144	Henry et al. (2005)
139095	CF UMa, HR 4550	Single	7.91	0.366	2.62	7.0	1.9	0.634	Handler & Shobbrook (2002)
144451A	. . .	VB	7.84	0.358	3.06	4.6	1.5	0.62617	This paper
152896	V645 Her	Single	7.55	0.314	2.85	5.6	1.5	0.7472	Henry & Fekel (2003)
155154	HR 6379	Single	6.17	0.306	2.91	5.3	1.5	0.34510	Henry et al. (2001)
160295A	V2381 Oph	SB2	7.87	0.354	2.38	8.6	2.0	0.7553	Henry & Fekel (2003)
160314A	. . .	VB	7.74	0.405	2.54	7.5	2.0	0.82763	Henry et al. (2001)
164615	V2118 Oph	Single	7.03	0.354	2.82	5.8	1.7	0.8117	Zerbi et al. (1997b), Hatzes (1998)
165645A	HR 6767, ADS 11054A	VB	6.38	0.287	2.59	7.1	1.7	0.4210	Henry & Fekel (2003)
166233A	73 Oph, HR 6795, ADS 11111A	VB	6.03	0.320	2.49	7.8	1.8	0.61439	Fekel & Henry (2003)
167858A	V2502 Oph, HR 6844	SB1	6.62	0.312	2.64	6.8	1.7	1.307	Handler & Shobbrook (2002), Fekel & Henry (2003)
171244	. . .	Single	7.75	0.397	2.06	11.7	2.5	1.0040	Henry & Fekel (2003)
175337	. . .	Single	7.39	0.364	2.76	6.1	1.7	0.78691	Mathias et al. (2004), Henry et al. (2005)
181998	. . .	Single	7.67	0.328	2.81	5.8	1.6	1.334	Handler & Shobbrook (2002)
187615	. . .	Single	7.95	0.300	2.84	5.6	1.5	0.49806	This paper
195068/9	V2121 Cyg, 43 Cyg, HR 7828	Single	5.73	0.339	2.85	5.6	1.6	0.79955	Mathias et al. (2004), Henry et al. (2005)
206043	NZ Peg, HR 8276	Single	5.77	0.314	2.81	5.8	1.6	0.41113	Henry et al. (2001)
207223	V372 Peg, HR 8330	Single	6.18	0.350	2.67	6.6	1.8	2.59381	Kaye et al. (1999c)
209295A	. . .	SB1	7.33	0.261	1.90	13.4	2.2	0.88547	Handler et al. (2002)
211699B	PR Peg	SB2	10.51	0.36	3.56	2.9	1.2	1.07204	This paper
213617	39 Peg, HR 8586	Single	6.43	0.350	2.81	5.8	1.7	0.75574	Henry et al. (2005)
218396	V342 Peg, HR 8799	Single	5.97	0.259	2.96	5.0	1.4	0.5053	Zerbi et al. (1999)

TABLE 6—*Continued*

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)
218427	. . .	Single	8.17	0.29	2.70	6.6	1.8	0.7504	Rodríguez et al. (2006a)
221866B	. . .	SB2	8.62	0.380	3.25	3.9	1.4	1.1416	Henry & Fekel (2002), Kaye et al. (2004)
224638	BT Psc	Single	7.49	0.342	2.98	4.9	1.5	1.2323	Mantegazza et al. (1994)
224945	BU Psc	Single	6.93	0.292	3.07	4.5	1.4	1.4943	Mantegazza et al. (1994)
239276	. . .	Single	9.09	0.27	2.83	5.8	1.6	0.4747	Rodríguez et al. (2006b)

[a] Colon indicates component A and/or B could be the γ Doradus star.
[b] VB: visual binary or double star; SB: spectroscopic binary.
[c] Also has period of 10.959 days with a slightly larger amplitude.

1.2 m EULER telescope at La Silla, Chile. Line-profile variations were clearly seen in 17 stars; to date, eight of those stars have sufficient ground-based photometry to confirm them as γ Doradus variables, so they also appear in Table 6.

We have now studied all 33 of the 46 Handler (1999) prime γ Doradus candidates that are observable with our APTs in southern Arizona. Only one, HD 173977, did not turn out to be a γ Doradus variable (see § 2 above), although it did posses a low-amplitude period in the right period range. Thus, we have enjoyed a phenomenal 97% success rate in our search for γ Doradus stars from among Handler's prime candidates, validating his selection criteria. Clearly, precision photometric observations of his remaining 13 southerly prime candidates will yield additional γ Doradus variables.

Handler's further candidate list in the same paper contains 36 additional candidates "whose nature remains uncertain." HD 187615 is confirmed as a γ Doradus star in this paper, while HD 213617 was confirmed by Henry et al. (2005). Martín et al. (2003), Mathias et al. (2004), and our own as-yet unpublished observations of HD 63436 show it to be a γ Doradus variable. Handler & Shobbrook (2002) confirmed HD 12901, HD 139095, and HD 181998 and showed that HD 113357, HD 188032, and HD 189631 were probable γ Doradus stars. Out of a total of 18 of the 36 further candidates that have been examined photometrically, six confirmed and three probable γ Doradus variables have emerged. Therefore, up to ~50% of Handler's total sample of further candidates may eventually be found to be γ Doradus stars as well.

We plot all 66 of the confirmed γ Doradus stars in the H-R diagram of Figure 25 using the $B-V$ color indexes and absolute magnitudes in columns (5) and (6) of Table 6. 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. Thirteen double-lined binary components and one possible binary 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; 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 10 new γ Doradus variables in this paper are plotted as stars.

The dashed lines in Figure 25 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 in this paper of 12 new confirmed γ Doradus stars, we have increased the sample of 54 γ Doradus variables in Henry et al. (2005) by 22% to 66 stars. The majority of confirmed γ Doradus stars are

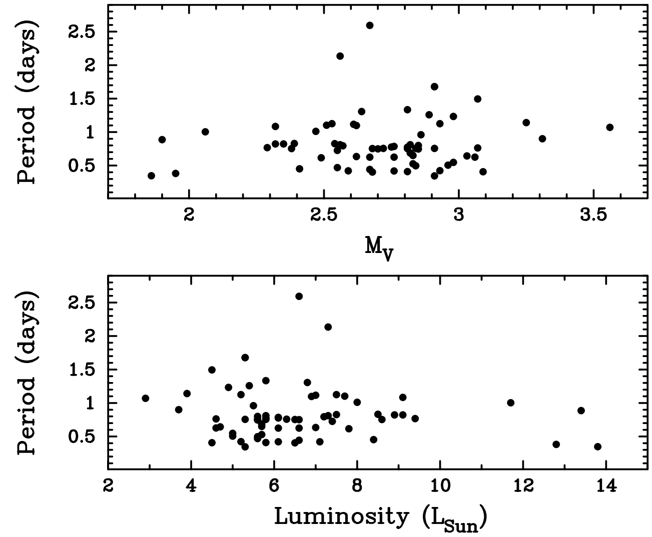

FIG. 26.—Highest-amplitude period for each of the 66 confirmed γ Doradus variables from Table 6 plotted against $(B-V)$ (*top*), M_V (*middle*), and luminosity (*bottom*). The period of the strongest pulsation mode in these stars seems completely uncorrelated with these parameters.

dwarfs, a few are subgiants, and their location straddles the cool boundary of the δ Scuti instability strip. Figure 25 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).

In Henry & Fekel (2002) we looked for correlations between the period of the strongest pulsation mode in each of the 30 confirmed γ Doradus variables known at that time and $(B - V)$ color index, absolute magnitude, and luminosity (see their Fig. 16). No correlations were found; possible explanations given were (1) the still small number of known γ Doradus variables, (2) the fact that multiple modes are possible in any given star, and (3) the observed factor of 2–3 spread in periods within many individual stars. With more than twice the number of γ Doradus variables now known (Table 6), we re-created the correlation plots of Henry & Fekel (2002) in Figure 26. Although the density of points is higher in these plots, they nonetheless look very similar to Figure 16 of Henry & Fekel (2002). No correlations are observed.

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