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Six New γ Doradus Stars

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ABSTRACT. We present high-resolution spectroscopy and precision photometry of six new γ Doradus stars, one of which was independently discovered by another group. This brings the total number of confirmed γ Doradus variables to 30. All six of these variables fall in the spectral class range F0–F2; all but one are subgiants. The six stars have between one and five photometric periods in the range 0.3–1.2 days. We find no evidence for higher frequency δ Scuti pulsations in any of these six stars. Our spectroscopic observations reveal HD 108100 to be the first confirmed γ Doradus variable with composite broad and narrow line profiles suggesting the presence of a circumstellar shell or disk. HD 221866 has the most asymmetric absorption lines of the six stars in this paper and also the largest photometric amplitude. Most of the 30 confirmed γ Doradus variables 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. However, three stars, including two of the new variables in this paper, are subgiants that lie well within the δ Scuti strip. Among the 30 confirmed γ Doradus variables, we find no correlation between the photometric periods and intrinsic color, absolute magnitude, or luminosity.

1. INTRODUCTION

We present new high-resolution spectroscopy and precise photometry of six γ Doradus variables. This paper extends the earlier study of Henry et al. (2001) that gave similar results for five new γ Doradus and five new δ Scuti variables.

The γ Doradus stars have been recognized as a new class of variable stars for only a few years. Zerbi (2000) reviewed the history leading to their designation as a variable-star class and summarized their physical properties. The γ Doradus stars typically have multiple photometric periods between 0.4 and 3 days and light curves that closely approximate sinusoids when phased with their photometric periods. Phases of the light variations are generally stable over timescales of a year or longer, but the amplitudes can vary over shorter timescales (e.g., Krisciunas et al. 1995). Radial-velocity variations of 2–4 km s^{-1} and changing spectroscopic line profiles have also been observed in some stars (e.g., Krisciunas et al. 1995; Kaye et al. 1999c; Balona et al. 1996). It is generally agreed that the photometric and spectroscpic variations arise from nonradial, *g*-mode pulsations of high order (n) and low spherical degree (l) (Kaye et al. 1999a). The first models for a mechanism to drive the gravity-mode pulsations in these stars were proposed by Guzik et al. (2000).

Although there are lists of several dozen *candidate* γ Doradus variables in the literature (e.g., Aerts, Eyer, & Kestens 1998; Handler 1999), the number of *confirmed* γ Doradus stars is still quite small. Kaye et al. (1999a) compiled a list of 12 previously confirmed γ Doradus stars, with a 13th (HR 6277) subsequently shown to be a δ Scuti star (Kaye, Henry, & Rodríguez 2000). Two new confirmations (HD 12901 and HD 48501) came from Eyer & Aerts (2000). Five more were added by Henry et al. (2001). Handler et al. (2002) confirmed HD 209295 and also claimed it to be the first example of a star exhibiting both γ Doradus and δ Scuti pulsations. Handler & Shobbrook (2002) have identified an additional five stars, and this paper also adds another five (HD 108100 was independently discovered by Breger et al. [1997] and included in the list of Kaye et al. [1999a]). This brings the current total of confirmed γ Doradus variables to 30.

A large fraction of these confirmed variables were discovered serendipitously when they were chosen as comparison stars for other programs (e.g., Henry 1999; Zerbi 2000; Henry et al. 2001). Five of the six new variables in this paper were discovered in the same way. Table 1 lists the properties of these six stars. The V magnitudes and $B-V$ color indices in columns (3) and (4) are taken from the *Hipparcos* Catalogue (ESA 1997). The basic properties in columns (5)–(8) are determined below. A colon following a value indicates greater uncertainty. Column (9) gives the variability type from the *Hipparcos* Catalogue, where only two of the six were identified as variables. Column (10) lists the source from which the program stars were selected. T4, T8, and T12 refer to three of our automatic photometric telescopes (APTs) at Fairborn Observatory in the

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TABLE 1
BASIC PROPERTIES OF THE NEW γ DORADUS STARS

HD Number (1)	Other Names (2)	V^a (mag) (3)	$B-V^a$ (mag) (4)	Spectral Class[b] (5)	Luminosity Class[b] (6)	$v \sin i^b$ (km s^{-1}) (7)	Velocity[b] (km s^{-1}) (8)	*Hipparcos* Variable Type[a] (9)	Source (10)
18995		6.72	0.342	F2	Subgiant	30	−15.8	C	T8 APT
19684		6.96	0.301	F1	Subgiant	59	6.6[c]		T12 APT
49015		7.04	0.375	F2	Dwarf	40	46.2		T8 APT[d]
99329	80 Leo, HR 4410	6.35	0.345	F2	Subgiant	140	4.0:		T12 APT
108100	DD CVn	7.12	0.368	F2	Subgiant	65	−11.5	M	T4 APT[e]
221866		7.46	0.286	F0	Subgiant	35	−10.7:	P	Handler 1999

[a] *Hipparcos* Catalogue. C = constant. M = possible microvariable with amplitude less than 0.03 mag. P = periodic variable. A blank entry signifies the star could not be classified as variable or constant.
[b] This paper.
[c] Mean velocity. Individual values are 19.8, 0.0, and 0.1 km s^{-1}.
[d] Variability announced by Henry & Henry 2000.
[e] Variability discovered independently by Breger et al. 1997.

Patagonia Mountains of southern Arizona,[2] with which we discovered them as variable comparison stars. The last star in the table was selected from the list of prime γ Doradus candidates in Handler (1999).

2. OBSERVATIONS AND ANALYSIS

2.1. Spectroscopy

Between 2000 April and 2001 April, one or more spectra were obtained of each of the six γ Doradus stars at the Kitt Peak National Observatory (KPNO) with the coudé feed telescope, coudé spectrograph, and a TI CCD detector. Each spectrogram is centered at 6430 Å and has a wavelength range of about 80 Å and a 2 pixel resolution of 0.21 Å. The typical signal-to-noise ratio of the spectra is between 100 and 250. The reduction and analysis of these spectroscopic data as well as estimates of the uncertainty in the results are described in Henry et al. (2001). The resulting radial velocities, spectral classes, and projected rotational velocities are listed in Table 1. The luminosity classes given in Table 1 were determined from the *Hipparcos* magnitudes, color indices, and parallaxes (ESA 1997) also as described in Henry et al. (2001).

[2] Further information about Fairborn Observatory can be found at http://www.fairobs.org.

TABLE 2
PROGRAM AND COMPARISON STARS

Program Star (1)	Comparison Star 1 (2)	Comparison Star 2 (3)	APT (4)	Individual Observations[a] (5)
HD 18995	HD 19521	HD 18832	T3	Table 3A
HD 19684	HD 19706	HD 19302	T12	Table 3B
HD 49015	HD 49525	HD 50277	T3	Table 3C
HD 99329	HD 98631	HD 100563	T12	Table 3D
HD 108100	HD 109615	HD 110834	T3	Table 3E
HD 221866	HD 222995	HD 222683	T3	Table 3F

[a] The individual observations are given in Tables 3A–3F.

2.2. Photometry

The photometric observations analyzed in this paper were acquired between 2000 September and 2001 June with the T3 0.4 m and the T12 0.8 m APTs at Fairborn Observatory. Table 2 lists the APT used for these new observations along with the two photometric comparison stars observed with each program star. The T3 0.4 m APT observes in the Johnson *B* and *V* passbands, and its observing and data reduction procedures are described in Henry et al. (2001). The T12 0.8 m APT observes in the Strömgren *b* and *y* passbands. The observing procedures and data reduction techniques employed with this APT are identical to those for our T8 0.8 m APT described in Henry (1999). The stars observed with the T3 APT were measured up to five times each clear night at intervals of 2–3 hr for the duration of their observing seasons as well as for several hours continuously on one night near opposition. The stars observed with the T12 APT were measured up to about five times each hour for up to several hours each night throughout their observing seasons. The external precision of our differential magnitudes, defined as the standard deviation of a single differential magnitude from the seasonal mean of the differential magnitudes and determined from observations of constant pairs of stars, is ∼0.005 mag for T3 and ∼0.002 mag for T12. The individual photometric observations of each star are given in Tables 3A–3F and are also available on the Tennessee State University Automated Astronomy Group Web site.[3]

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 1 (P − C1) differential magnitudes over the frequency range

[3] See http://schwab.tsuniv.edu/papers/pasp/gammador4/gammador4.html.

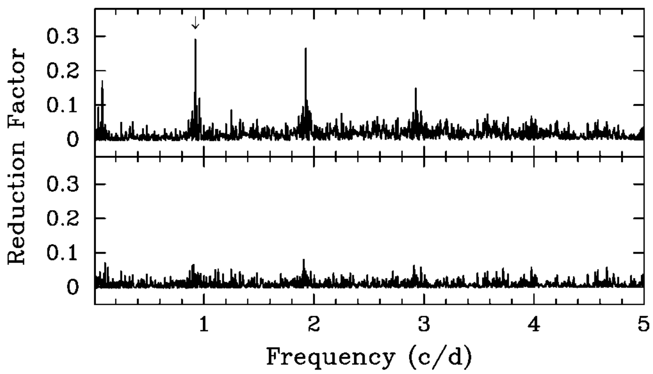

FIG. 1.—Least-squares spectra of the HD 18995 Johnson *B* data set. The arrow in the top panel indicates the single detected frequency at 0.9231 day^{-1}. The bottom panel shows the least-squares spectrum with the 0.9231 day^{-1} frequency fixed. The same frequency was confirmed in the Johnson *V* data set.

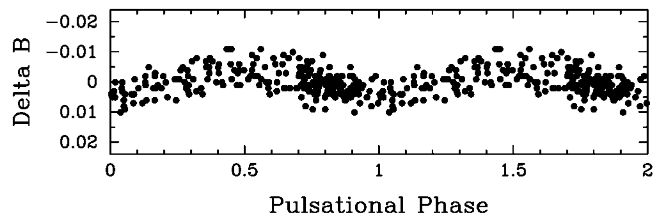

FIG. 2.—Johnson *B* photometric data for HD 18995, phased with the single frequency of 0.9231 day^{-1} and time of minimum from Table 4.

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 4. With one exception (HD 49015), the frequencies and corresponding periods are given only when they could be indentified in both passbands. The peak-to-peak amplitudes reported in column (7) of the table are determined for each frequency *without* prewhitening for the other frequencies; the amplitudes range from 25.7 down to only 1.2 mmag. The *B* (or *b*) amplitudes average 1.29 ± 0.09 times larger than those in *V* (or *y*). The times of minimum light for each frequency are given in column (8); in each case, the times of minimum in the two passbands agree within their uncertainites, so there is no detectable phase shift in our two-color photometry. The (C2 − C1) differential magnitudes were also analyzed in the same way to search for periodicities that might exist in the comparison stars. None were found in any of the 12 comparison stars. Thus, all of the periodicities reported in Table 4 can be confidently assigned to the program stars.

Least-squares spectra and phase diagrams for the *B* or *b* observations of the six program stars are shown in § 3 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}. 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.

3. RESULTS FOR INDIVIDUAL STARS

3.1. HD 18995

We classified HD 18995 as an F2 star, while its *Hipparcos* parallax indicates that the star is a subgiant. These results are similar to those of Grenier et al. (1999), who classified it as an F1 IV. We determined a moderate projected rotational velocity of 30 km s^{-1}. Our two radial velocities have a mean of −15.8 km s^{-1}, in reasonable agreement with the mean value of −19.2 ± 2.7 km s^{-1} from three velocities measured by Grenier et al. (1999).

The least-squares spectra of our *B* observations are plotted in Figure 1, and the results of the frequency analysis are given in Table 4. We find a single period of 1.0833 days in HD 18995, the only star in our present sample that appears to be monoperiodic. The observations are phased with this period and the time of minimum given in Table 4 and plotted in Figure 2, which shows a clear sinusoidal light variation. Because HD 18995 has only a single photometric period, care must be taken to eliminate rotational modulation of starspots and ellipsoidal variations induced by a binary companion as explanations of its variability before concluding that the star is pulsating. With a computed radius of 2.1 $R_\odot$ (Table 5 below) and our measured $v \sin i$ value of 30 km s^{-1}, the inclination axis would have to be very low, ~18°, if the 1.0833 day photometric period represents the stellar rotation period. This, combined with the early spectral type of the star and the high degree of stability of the light curve over 140 cycles, makes the starspot hypothesis extremely unlikely. The constancy of the radial velocites documented in the previous paragraph argues against ellipticity as the variability mechanism. The ratio of the photometric amplitude in *B* to the amplitude in *V* is 1.30, also inconsistent with spots and ellipticity but just what is observed for pulsations (see § 4 below). Thus, we confirm HD 18995 as a new γ Doradus variable.

TABLE 3A
PHOTOMETRIC OBSERVATIONS OF HD 18995

HJD −2,400,000 (1)	$(P-C1)_B$ (mag) (2)	$(P-C1)_V$ (mag) (3)	$(C2-C1)_B$ (mag) (4)	$(C2-C1)_V$ (mag) (5)
51807.9064	−0.221	−0.289	0.005	−0.753
51808.9065	99.999	99.999	99.999	−0.753
51809.8510	−0.232	−0.288	−0.006	−0.759
51809.9023	−0.229	−0.297	−0.009	−0.769
51810.8158	−0.232	−0.298	−0.004	−0.751
51810.8986	−0.230	−0.299	0.002	−0.758

NOTE.—Tables 3A–3F are presented in their entirety in the electronic edition of *PASP*. A portion of Table 3A is shown here for guidance regarding their form and content.

TABLE 4
RESULTS FROM PHOTOMETRIC ANALYSIS

HD Number (1)	Photometric Band (2)	Date Range (HJD − 2,450,000) (3)	N_{obs}[a] (4)	Frequency (day^{-1}) (5)	Period (days) (6)	Peak-to-Peak Amplitude (mmag) (7)	T_{min} (HJD − 2,450,000) (8)
18995	*B*	1807.9064–1961.6070	225	0.9231 ± 0.0003	1.0833 ± 0.0004	7.3 ± 0.8	1880.742 ± 0.016
	V	1807.9064–1961.6070	217	0.9230 ± 0.0003	1.0834 ± 0.0004	5.6 ± 0.8	1880.763 ± 0.020
19684	*b*	1900.5683–1984.6285	464	2.8800 ± 0.0004	0.34722 ± 0.00005	11.3 ± 0.6	1940.102 ± 0.003
				2.7302 ± 0.0005	0.36627 ± 0.00007	8.1 ± 0.7	1940.366 ± 0.005
				2.9149 ± 0.0007	0.34306 ± 0.00008	4.9 ± 0.7	1940.093 ± 0.008
				2.8118 ± 0.0004	0.35564 ± 0.00005	3.8 ± 0.7	1940.148 ± 0.011
				2.6512 ± 0.0005	0.37719 ± 0.00007	4.9 ± 0.7	1940.220 ± 0.009
	y	1900.5683–1984.6285	464	2.8800 ± 0.0004	0.34722 ± 0.00005	9.0 ± 0.5	1940.101 ± 0.003
				2.7303 ± 0.0005	0.36626 ± 0.00007	6.4 ± 0.5	1940.368 ± 0.005
				2.9146 ± 0.0006	0.34310 ± 0.00007	3.9 ± 0.6	1940.097 ± 0.008
				2.8121 ± 0.0005	0.35561 ± 0.00006	2.9 ± 0.6	1940.147 ± 0.011
				2.6513 ± 0.0005	0.37717 ± 0.00007	3.6 ± 0.6	1940.222 ± 0.010
49015	*B*	1805.9817–2017.6336	276	1.8969 ± 0.0003	0.52718 ± 0.00008	6.2 ± 0.7	1900.262 ± 0.009
				1.9641 ± 0.0002	0.50914 ± 0.00006	5.0 ± 0.7	1900.245 ± 0.011
	V	1805.9817–2015.6325	255	1.8969 ± 0.0003	0.52718 ± 0.00008	4.7 ± 0.7	1900.261 ± 0.012
99329	*b*	1900.9102–2038.7344	669	2.2082 ± 0.0002	0.45286 ± 0.00004	11.3 ± 0.4	1975.363 ± 0.003
				1.5869 ± 0.0002[b]	0.63016 ± 0.00008[b]	4.6 ± 0.6	1975.570 ± 0.012
				2.0923 ± 0.0002[b]	0.47794 ± 0.00005[b]	5.6 ± 0.6	1975.192 ± 0.007
				1.0424 ± 0.0002[b]	0.9593 ± 0.0002[b]	1.5 ± 0.6	1975.768 ± 0.060
				1.1934 ± 0.0002[b]	0.8379 ± 0.0002[b]	3.2 ± 0.6	1975.627 ± 0.023
	y	1900.9102–2038.7344	669	2.2082 ± 0.0002	0.45286 ± 0.00004	9.0 ± 0.3	1975.366 ± 0.003
				1.5869 ± 0.0002[b]	0.63016 ± 0.00008[b]	3.6 ± 0.5	1975.570 ± 0.013
				2.0924 ± 0.0002[b]	0.47792 ± 0.00003[b]	4.6 ± 0.4	1975.196 ± 0.007
				1.0428 ± 0.0002[b]	0.9590 ± 0.0002[b]	1.2 ± 0.5	1975.776 ± 0.064
				1.1931 ± 0.0002[b]	0.8382 ± 0.0002[b]	2.6 ± 0.5	1975.642 ± 0.023
108100	*B*	1862.0330–2087.6525	488	1.3261 ± 0.0002	0.7541 ± 0.0001	18.7 ± 1.5	1975.031 ± 0.009
				1.4015 ± 0.0002	0.7135 ± 0.0001	17.8 ± 1.5	1975.331 ± 0.009
				1.3661 ± 0.0003	0.7320 ± 0.0002	12.3 ± 1.6	1975.539 ± 0.014
	V	1862.0330–2087.6525	478	1.3259 ± 0.0002	0.7542 ± 0.0001	13.9 ± 1.2	1975.016 ± 0.010
				1.4014 ± 0.0002	0.7136 ± 0.0001	11.5 ± 1.2	1975.325 ± 0.012
				1.3665 ± 0.0002	0.7318 ± 0.0001	8.8 ± 1.3	1975.546 ± 0.016
221866	*B*	1805.6721–1939.5740	181	0.8760 ± 0.0005	1.1416 ± 0.0007	25.7 ± 2.0	1875.389 ± 0.015
				0.8390 ± 0.0004	1.1919 ± 0.0006	22.3 ± 2.2	1875.308 ± 0.020
				1.7123 ± 0.0005[c]	0.5840 ± 0.0002[c]	13.7 ± 2.8	1875.302 ± 0.016
	V	1805.6721–1939.5740	183	0.8759 ± 0.0005	1.1417 ± 0.0007	21.8 ± 1.9	1875.406 ± 0.016
				0.8384 ± 0.0004	1.1927 ± 0.0006	17.6 ± 2.0	1875.308 ± 0.024
				1.7142 ± 0.0005[c]	0.5834 ± 0.0002[c]	12.4 ± 2.3	1875.250 ± 0.017

[a] The individual observations are given in Tables 3A–3F in machine-readable format available in the electronic edition of *PASP*. They are also available at http://schwab.tsuniv.edu/papers/pasp/gammador4/gammador4.html.

[b] Identification of true frequency is somewhat ambiguous as a result of aliasing.

[c] May not be an independent frequency. See § 3.6.

3.2. HD 19684

We found HD 19684 to be an F1 subgiant and determined its projected rotational velocity to be 59 km s^{-1}. Our three spectra have radial velocities that range from 0.0 to 19.8 km s^{-1}, compared to a velocity of -5 ± 4 km s^{-1} determined from six observations by Fehrenbach et al. (1987). Thus, it is probable that this star has a variable velocity and likely has a binary companion. From our spectra, we estimate that the secondary must be at least 2 mag fainter than the primary.

We detected five photometric periods in HD 19684, all between 0.3 and 0.4 day (Figs. 3 and 4; Table 4). Its multiperiodic light variations and early-F spectral classification clearly demonstrate it to be a new γ Doradus variable, although its photometric periods are shorter than most γ Doradus stars. Light variations with all five periods closely approximate sinusoids. We found no evidence for higher frequency variations that would indicate the presence of δ Scuti pulsations.

3.3. HD 49015

From our spectrum of HD 49015, we determined a spectral class of F2. The *Hipparcos* magnitude, color index, and parallax (ESA 1997) reveal HD 49015 to be a dwarf (see Table 5 below). We also determined a projected rotational velocity of 40 km s^{-1} and a radial velocity of 46.2 km s^{-1}. Our spectral classi-

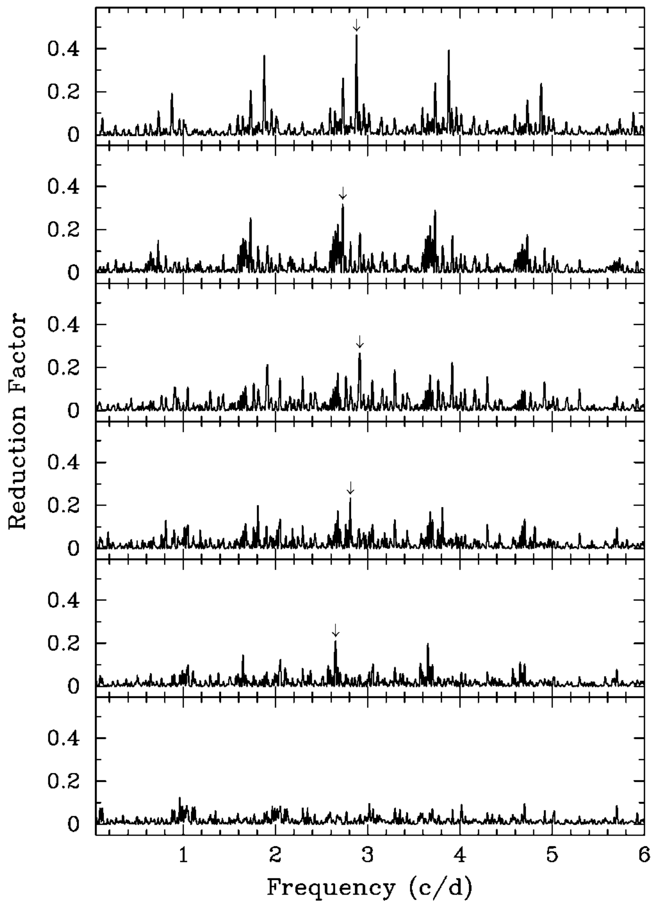

FIG. 3.—Least-squares spectra of the HD 19684 Strömgren *b* data set, showing the results of progressively fixing the five detected frequencies. The arrows indicate the five frequencies (*top to bottom*): 2.8800, 2.7302, 2.9149, 2.8118, and 2.6512 day^{-1}. All five frequencies were confirmed in the Strömgren *y* data set.

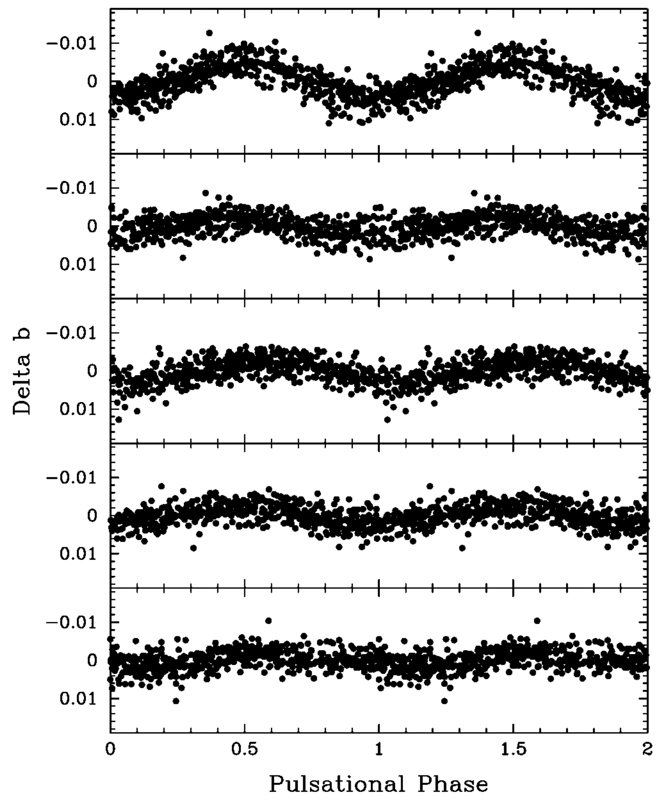

FIG. 4.—Strömgren *b* photometric data for HD 19684, phased with the five frequencies and times of minimum from Table 4. *Top to bottom*: Frequencies are 2.8800, 2.7302, 2.9149, 2.8118, and 2.6512 day^{-1}. For each panel, the data set has been prewhitened to remove the other four known frequencies.

fication is similar to the F2 IV and F0 IV spectral types of Grenier et al. (1999) and Karlsson (1969), respectively. Our single velocity is similar to the values of 41.5 ± 6.7 (Grenier et al. 1999) and 43.9 ± 0.6 km s^{-1} (Nordström et al. 1997). From three observations, however, Grenier et al. (1999) called the star's velocity variable, while from four observations Nordström et al. (1997) found the velocity to be constant. Nordström et al. (1997) also determined a $v \sin i$ value of 44 km s^{-1}, which is in good agreement with ours. The *Hipparcos* Catalogue indicates that HD 49015 is a close visible double, but the secondary component is nearly 4 mag fainter than the primary and so has no significant effect on our derived properties.

The photometric variability of HD 49015 was previously announced by Henry & Henry (2000). They found a period of 0.3452 day from a much smaller APT data set but noted that aliases at 0.5277 day and 0.2565 day were nearly as strong, making unambiguous identification of the true photometric period impossible. In our newer and much more extensive data set, we find two photometric periods at 0.52718 and 0.50914 day in the Johnson *B* observations. Therefore, it appears that the 0.3452 day period of Henry & Henry (2000) is an alias of one of the true periods. Although we could not identify the 0.50914 day period in the new *V* data set, this period seems convincing in the *B*, so we include it in our results (Figs. 5 and 6; Table 4). Light curves phased with both periods appear sinusoidal. HD 49015 is clearly a new γ Doradus star.

3.4. HD 99329 = HR 4410 = 80 Leo

Our spectrum of the bright star HD 99329 shows weak broad lines, making our analysis of its properties more uncertain than for most of the other stars in our sample. We determined a spectral class of F2, while the *Hipparcos* parallax indicates that it is a subgiant. These results are in good agreement with the F1 V and F3 IV classifications of Abt & Morrell (1995) and Cowley (1976), respectively. Our $v \sin i$ value of 140 km s^{-1} is in accord with those of Danziger & Faber (1972) and Abt & Morrell (1995), who estimated 140 and 155 km s^{-1}, respectively. Although Shajn & Albitzky (1932) claimed from four unpublished velocities that HD 99329 had a velocity range of 34 km s^{-1} and so was a spectroscopic binary, published

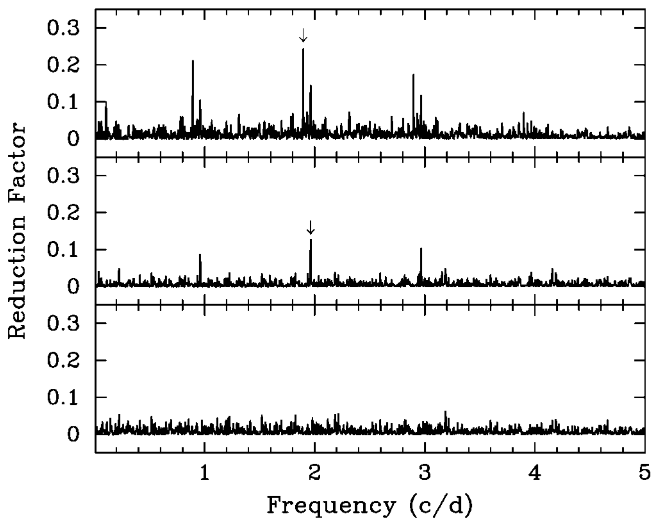

FIG. 5.—Least-squares spectra of the HD 49015 Johnson *B* data set, showing the results of progressively fixing the two detected frequencies. The arrows indicate the two frequencies at 1.8969 (*top*) and 1.9641 day^{-1} (*middle*). Only the first frequency could be confirmed in the Johnson *V* data set.

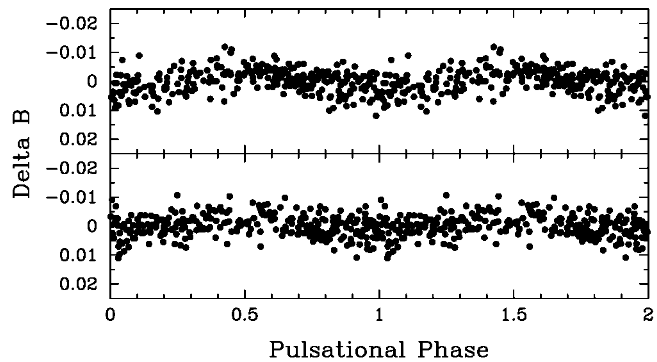

FIG. 6.—Johnson *B* photometric data for HD 49015, phased with the two frequencies and times of minimum from Table 4. The two frequencies are 1.8969 (*top*) and 1.9641 day^{-1} (*bottom*). For each panel, the data set has been prewhitened to remove the other known frequency.

average radial velocities range from −6 (Plaskett et al. 1921) to 2.1 km s^{-1} (Wilson & Joy 1950), in reasonable agreement with our value of 4.0 km s^{-1} measured from a single line. Given the broad lines of HD 99329, there is no strong evidence to suggest that the star is a spectroscopic binary.

We found five photometric periods in HD 99329, ranging from 1.0424 to 2.2082 days (Figs. 7 and 8; Table 4). Aliasing is particularly troublesome in this data set, however. As can be seen in Figure 7, identifying frequencies 2–5 is difficult because the ± 1 day^{-1} aliases are nearly as strong as the (presumed) true frequencies. We note that the analysis of the *b* and *y* observations preferred the same frequencies in every case, giving us some confidence that we identified them correctly. There is no evidence for higher frequency δ Scuti pulsations, so the star is clearly a γ Doradus variable. All five frequencies appear to be sinusoids.

3.5. HD 108100 = DD CVn

Our two red-wavelength spectra of HD 108100 show that the metal absorption lines consist of a combination of a broad component and a narrow absorption feature near its center (Fig. 9). We classify the broad-lined spectrum of HD 108100 as an F2 subgiant, close to the F2/3 V result of Grenier et al. (1999). The spectrum of the narrow lines suggests about the same spectral class. Mantegazza & Poretti (1996) found such composite absorption-line profiles in the δ Scuti variable X Caeli. They noted that the velocity of the narrow absorption core "is comparable with that of the stellar barycenter" and suggested that the narrow lines result from a circumstellar shell. Henry et al. (2001) found similar line profiles in another δ Scuti variable, HD 173741. For HD 108100, the broad and

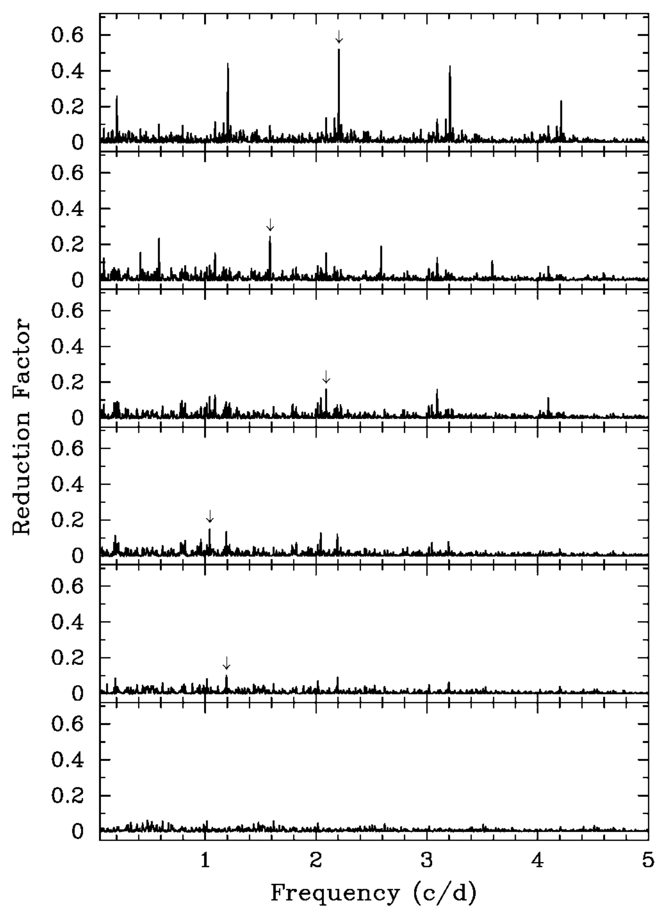

FIG. 7.—Least-squares spectra of the HD 99329 Strömgren *b* data set, showing the results of progressively fixing the five detected frequencies. The arrows indicate the five frequencies (*top to bottom*): 2.2082, 1.5869, 2.0923, 1.0424, and 1.1934 day^{-1}. All five frequencies were confirmed in the Strömgren *y* data set.

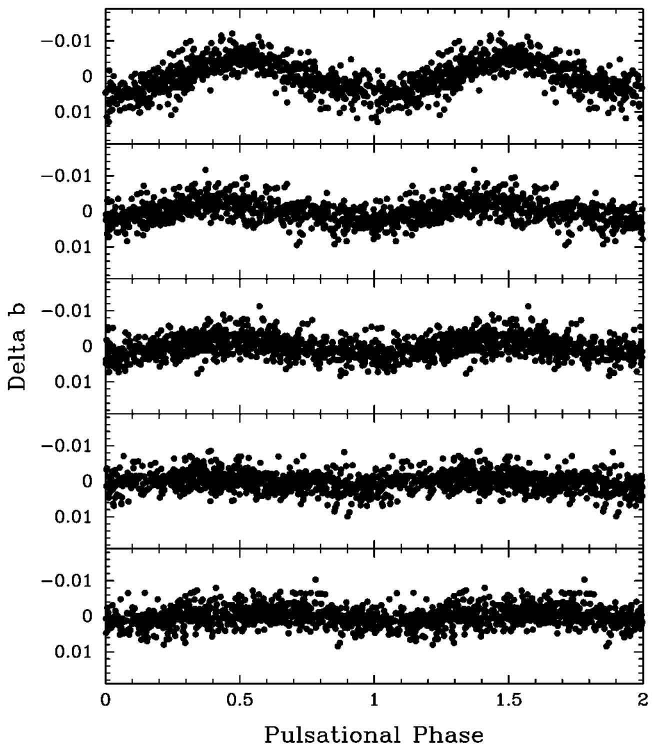

FIG. 8.—Strömgren *b* photometric data for HD 99329, phased with the five frequencies and times of minimum from Table 4. *Top to bottom*: Frequencies are 2.2082, 1.5869, 2.0923, 1.0424, and 1.1934 day^{-1}. For each panel, the data set has been prewhitened to remove the other four known frequencies.

narrow components have projected rotational velocities of 65 and 5 km s^{-1}, respectively, and quite similar mean radial velocities of -11.5 and -6.4 km s^{-1}, respectively. From six spectra, Grenier et al. (1999) found a comparable stellar velocity of -9.6 ± 4.1 km s^{-1} and concluded that HD 108100 has a variable velocity. However, a different interpretation of this complex system was provided by Nordström et al. (1997). They obtained seven high-resolution spectra centered at about 5185 Å in which they detected both the broad and narrow components seen in our spectra. They called the system a double-lined binary but concluded that no significant velocity variation was observed for either component. From their Table 6, the mean velocity for the broad-lined component is -6.6 km s^{-1}. Their individual velocity measurements of the weak, narrow absorption features are much more scattered but have an average velocity of -9.4 km s^{-1}. This is the first confirmed γ Doradus star found to have such composite line profiles. Rather than the binary model adopted by Nordström et al. (1997), we favor the explanation suggested by Mantegazza & Poretti (1996).

HD 108100 was independently confirmed as a new γ Doradus variable by Breger et al. (1997), who made it the subject of a coordinated multilongitude observing campaign in 1996 after recognizing it as a variable comparison star used in earlier studies of the δ Scuti variable 4 CVn. They found two photometric periods of 0.757 and 0.712 day. We detect three photometric periods in our APT data, 0.7541, 0.7135, and 0.7320, thus confirming the two periods of Breger et al. (1997) and adding a third intermediate period (Figs. 10 and 11; Table 4). We see no evidence for higher frequency δ Scuti variability. Light variations at all three periods appear to be roughly si-

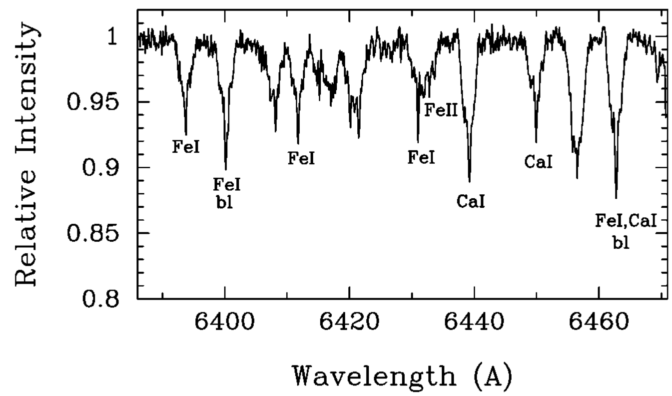

FIG. 9.—Portion of the red wavelength spectrum of HD 108100, which shows the composite profiles of all the metal lines. We attribute the broad component to the photosphere, and following Mantegazza & Poretti (1996), ascribe the narrow component to a circumstellar shell or disk rather than a binary companion. The element and ionization stage are indicated for some of the lines. The abbreviation "bl" indicates that the photospheric line is a very close blend.

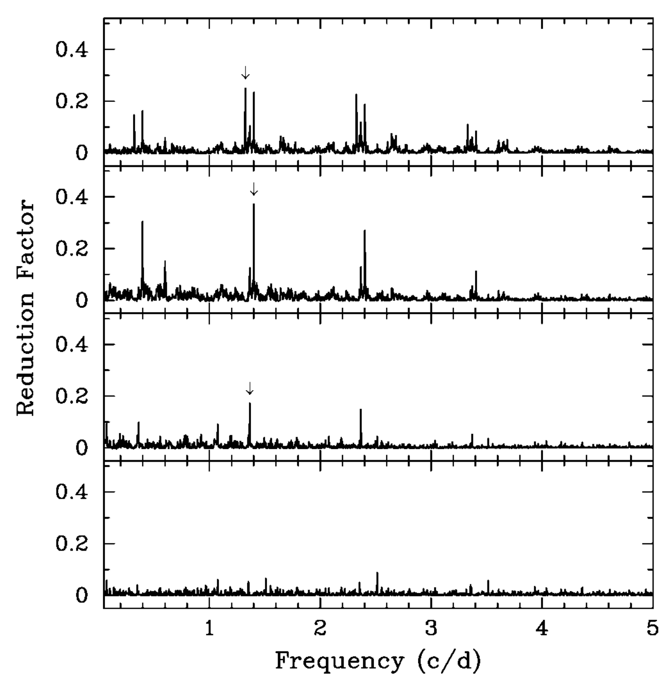

FIG. 10.—Least-squares spectra of the HD 108100 Johnson *B* data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies (*top to bottom*): 1.3261, 1.4015, and 1.3661 day^{-1}. All three frequencies were confirmed in the Johnson *V* data set.

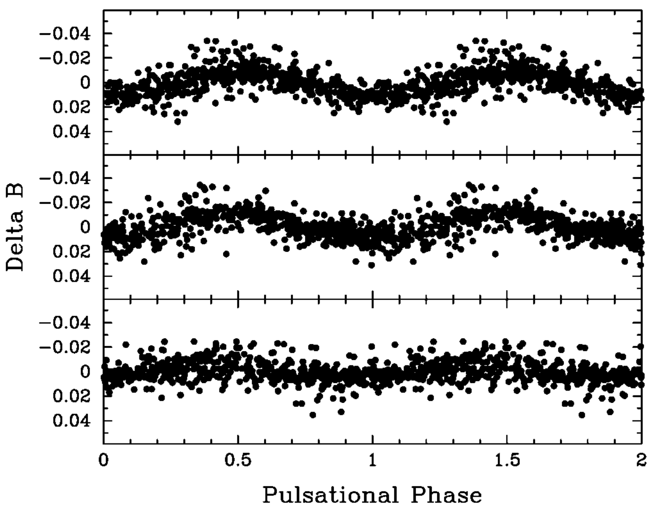

FIG. 11.—Johnson *B* photometric data for HD 108100, phased with the three frequencies and times of minimum from Table 4. *Top to bottom*: Frequencies are 1.3261, 1.4015, and 1.3661 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

nusoidal, but there is an indication of excess scatter near maximum brightness as seen in several other γ Doradus variables (see § 4 below).

3.6. HD 221866

Of the six stars in our sample, the absorption-line profiles of HD 221866 are the most asymmetric. Such asymmetries might result from pulsation or starspots, or because the star is a double-lined binary seen at a phase when the lines of the two components are only partially resolved. Figure 12 shows a portion of its red-wavelength spectrum with the element and ionization stage identified for some of the lines. Compared to

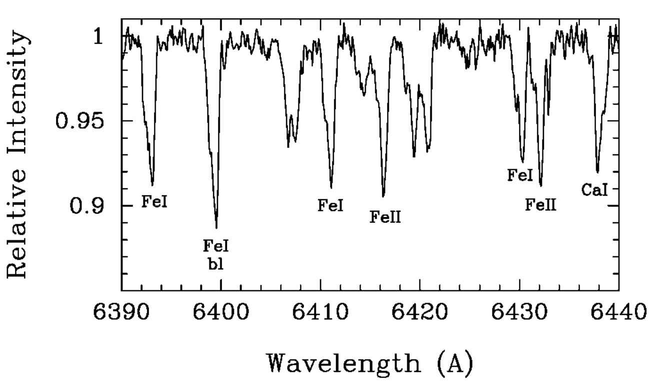

FIG. 12.—Portion of the red wavelength spectrum of HD 221866, which shows the significant asymmetries of all the absorption lines. The element and ionization stage are indicated for some of the lines. The abbreviation “bl” indicates that the line is a very close blend. Note that, compared to the other lines in the spectrum, the asymmetry of the Ca I line is in the opposite sense. The asymmetries most likely result from the nonradial pulsation of the star.

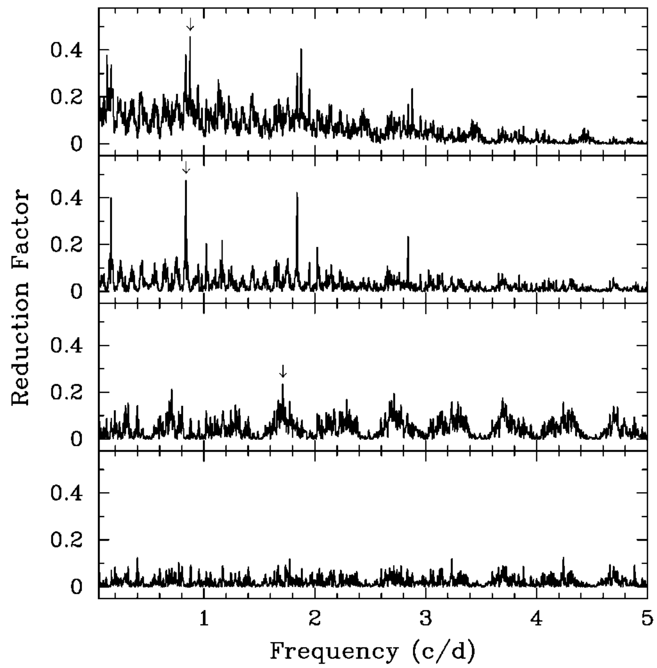

FIG. 13.—Least-squares spectra of the HD 221866 Johnson *B* data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies (*top to bottom*): 0.8760, 0.8390, and 1.7123 day^{-1}. All three frequencies were confirmed in the Johnson *V* data set.

the Fe I and Fe II lines in the spectrum, the asymmetry of the Ca I feature at 6439.1 Å is in the opposite sense. The lower excitation potential of the Ca I line and the Fe I line at 6393.6 Å are nearly identical. If the asymmetries resulted from starspots or the partially resolved lines of a double-lined binary, we

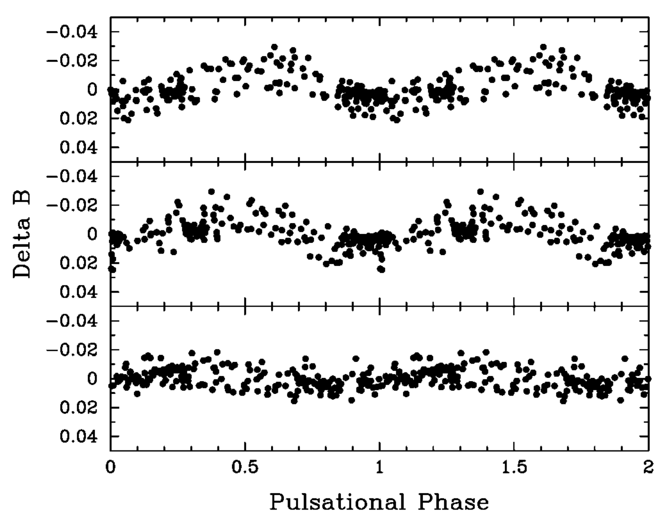

FIG. 14.—Johnson *B* photometric data for HD 221866, phased with the three frequencies and times of minimum from Table 4. *Top to bottom*: Frequencies are 0.8760, 0.8390, and 1.7123 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

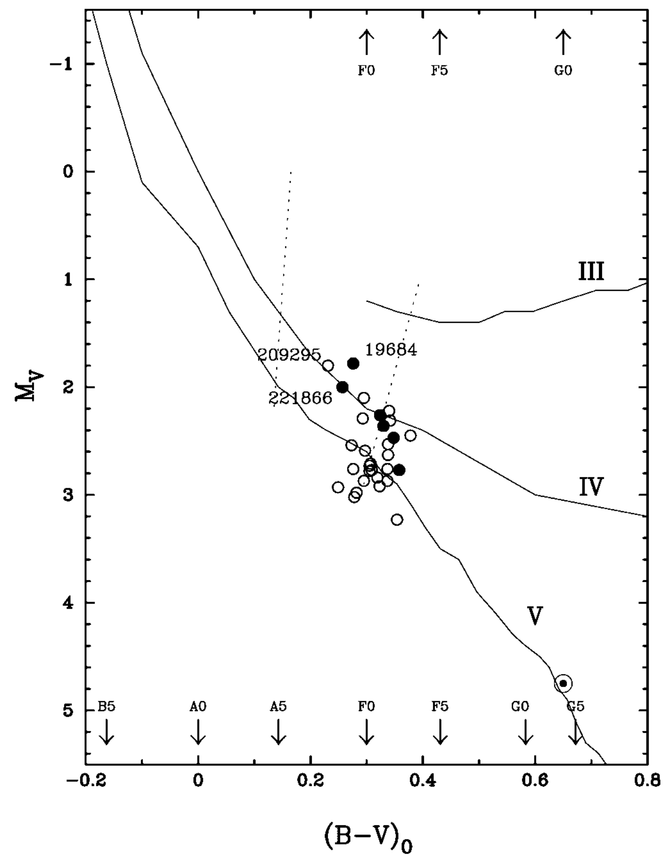

FIG. 15.—Previously confirmed γ Doradus variables in the H-R diagram (*open circles*) along with the new variables in this paper (*filled circles*). The dotted lines indicate the boundaries of the δ Scuti instability strip. The Sun's position is shown at lower right. Three stars near the center of the δ Scuti instability strip are labeled with their HD numbers.

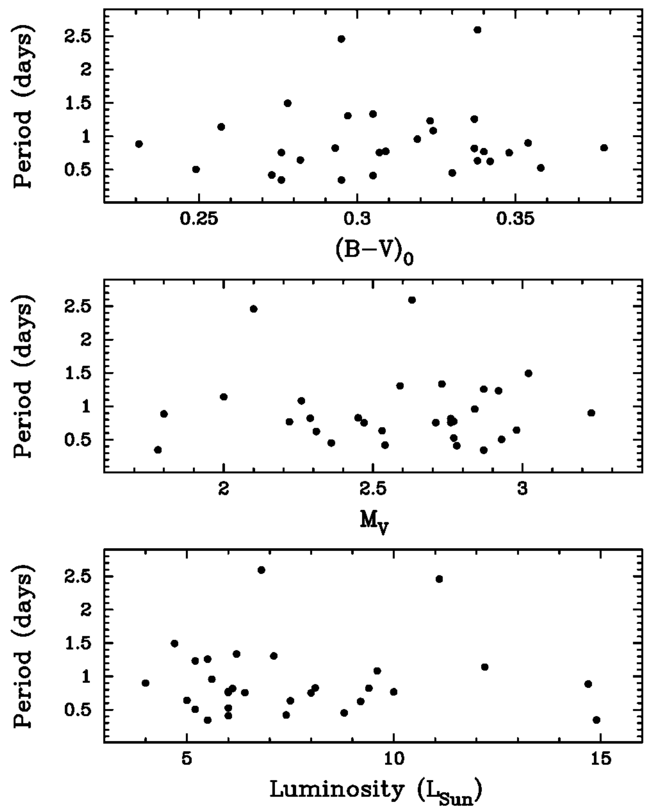

FIG. 16.—Highest amplitude period for each of the 30 confirmed γ Doradus variables from Table 5 plotted against $(B-V)_0$ (*top*), M_V (*middle*), and luminosity (*bottom*).

would expect to see similar line asymmetries for the two lines. Since that is not the case (and we do not expect starspots on such a hot star), we believe that the line asymmetries result from nonradial pulsations of this star.

For HD 221866, such asymmetries make the measurement of its radial and rotational velocity as well as the determination of its spectral class more uncertain than the other stars in our sample that have similar projected rotational velocities but much more symmetric lines. We classified HD 221866 as F0 and concluded from its *Hipparcos* parallax that it is a subgiant. We found a projected rotational velocity of 35 km s^{-1} and a radial velocity of -10.7 km s^{-1}.

This star appears on the list of prime γ Doradus candidates of Handler (1999), where he gives photometric periods of 1.140 and 0.589 days from his analysis of the *Hipparcos* photometry. We find periods of 1.1416, 1.1919, and 0.5840 days in our Johnson *B* photometry (Figs. 13 and 14; Table 4). Thus, we confirm Handler's two periods and add a third. We note that our 0.5840 day period is approximately half of the 1.1416 day period, although not strictly so within their uncertainties, so we wonder if this period is a harmonic of the longer one. Indeed, we see in the top panel of Figure 13 that the light variability of the 1.1416 day period appears to be slightly nonsinusoidal, so we might expect to find the first harmonic in the frequency spectrum. Alternatively, the third frequency is approximately equal to the sum of the first two, within 2–3 standard deviations, further suggesting that it may not be an independent frequency. We find no evidence of higher frequency δ Scuti variations in this star. Given the multiple frequencies, the asymmetric line profiles, and the absence of frequencies in the δ Scuti range, we confirm that HD 221866 is a γ Doradus star. In addition to having the most asymmetric absorption lines of the stars in our sample, it has the largest photometric amplitude as well.

4. DISCUSSION

We have added five new variables to the list of confirmed γ Doradus stars and independently confirmed a sixth star, bringing the total number of known γ Doradus variables to 30. Table 5 lists these 30 stars along with some of their physical properties. The $(B-V)_0$ unreddened mean color indices, absolute magnitudes, luminosities, and radii in columns (3)–(6) were computed from the *Hipparcos* mean magnitudes, mean

TABLE 5
DERIVED PROPERTIES OF γ DORADUS STARS

HD Number (1)	Other Names (2)	$(B-V)_0$ (mag) (3)	M_V (mag) (4)	L ($L_\odot$) (5)	R ($R_\odot$) (6)	Period (days) (7)	References (8)
277		0.354	3.23	4.0	1.4	0.9005	1
12901		0.293	2.29	9.4	1.9	0.82270	2
18995		0.324	2.26	9.6	2.1	1.0833	3
19684		0.276	1.78	14.9	2.4	0.34722	3
27290	γ Dor, HR 1338	0.307	2.71	6.4	1.6	0.7570	4
32537	V398 Aur, 9 Aur, HR 1637	0.337	2.87	5.5	1.6	1.2582	5
48501	HR 2481	0.309	2.77	6.0	1.6	0.7750[a]	2
49015		0.358	2.77	6.0	1.7	0.52718	3
55892	QW Pup, HR 2740	0.319	2.84	5.6	1.6	0.9584	6
62454	DO Lyn	0.342	2.31	9.2	2.1	0.62447	7
65526	V769 Mon	0.282	2.98	5.0	1.4	0.644	8
68192	KO UMa	0.340	2.22	10.0	2.1	0.7691	7
86371		0.295	2.10	11.1	2.1	2.459	8
99329	80 Leo, HR 4410	0.330	2.36	8.8	2.0	0.45286	3
105458		0.276	2.76	6.0	1.5	0.7571	2
108100	DD CVn	0.348	2.47	8.0	1.9	0.7541	3, 9
139095		0.338	2.53	7.5	1.9	0.634	8
155154	HR 6379	0.295	2.87	5.5	1.5	0.34510	1
160314		0.378	2.45	8.1	2.0	0.82763	1
164615	V2118 Oph	0.337	2.76	6.1	1.7	0.8117	10, 11
165645	HR 6767	0.273	2.54	7.4	1.7	0.42132	12
167858	V2502 Oph, HR 6844	0.297	2.59	7.1	1.7	1.307	8
181998		0.305	2.73	6.2	1.6	1.334	8
206043	NZ Peg, HR 8276	0.305	2.78	6.0	1.6	0.41113	1
207223	V372 Peg, HR 8330	0.338	2.63	6.8	1.8	2.59381	13
209295		0.231	1.80	14.7	2.2	0.88547	14
218396	V342 Peg, HR 8799	0.249	2.93	5.2	1.4	0.5053	15
221866		0.257	2.00	12.2	2.1	1.1416	3
224638	BT Psc	0.323	2.92	5.2	1.5	1.2323	16
224945	BU Psc	0.278	3.02	4.7	1.4	1.4943	16

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

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

apparent color indices, and parallaxes (ESA 1997) with the procedure outlined in Henry et al. (2001). Most of these stars are multiperiodic, so the period given in column (7) is the one with the largest photometric amplitude. Column (8) gives the literature reference establishing each star as a γ Doradus variable.

We plot the 30 confirmed γ Doradus variables in the H-R diagram in Figure 15. Most lie in a fairly tight region of the diagram, on or just above the main sequence, that slightly overlaps the cool edge of the δ Scuti instability strip. Three γ Doradus variables, including two from this paper, lie somewhat farther within the δ Scuti strip and are labeled by name in Figure 15. These three stars also have slightly higher luminosities than the rest of the γ Doradus stars (Table 5). Handler et al. (2002) have suggested that HD 209295 is not a normal γ Doradus star since its pulsations may be excited by a short-period binary companion in an eccentric 3.1 day orbit. However, we have shown in this paper that HD 19684 and HD 221866 *are* γ Doradus pulsators and so extend the overlap region between the γ Doradus and the δ Scuti pulsators. A larger sample of γ Doradus stars is needed to map the full extent of the region in the H-R diagram occupied by these stars.

Breger (2000), in his Figure 4, and Handler & Shobbrook (2002), in their Figure 8, have shown that the incidence of δ Scuti pulsations within the lower instability strip reaches a broad peak roughly one-third of the way in from the red edge. The three stars labeled in Figure 15 lie in just this location and so, a priori, would have ranked as the best candidates among the confirmed γ Doradus variables to exhibit *both* γ Doradus and δ Scuti pulsations. Indeed, Handler et al. (2002) have just announced the detection of both kinds of pulsation in HD 209295, although their interpretation is complicated by the presence of the binary companion. However, as described in

§ 2.2 above, our period analyses in this paper covered the frequency range 0.01–30.0 day^{-1}, and none of the stars revealed high-frequency variations above a few cycles per day, including HD 19684 and HD 221866. Thus, we cannot identify any additional stars with both kinds of pulsation.

We noted in § 2.2 that the *B*/*V* or *b*/*y* amplitude ratios of the six stars in this paper averaged 1.29 ± 0.09. This amplitude ratio is significantly different from the ratio of ∼1.13 observed for starspot variability or ∼1.00 for ellipticity variations (Henry et al. 2000, their Table 8). It corresponds to a $(b-y)/y$ or $(B-V)/V$ ratio of 0.29 and closely matches the $(b-y)/y$ ratios observed in other γ Doradus variables and expected from pulsation models (Garrido 2000).

Henry et al. (2001) found that the light curve of one of their five new γ Doradus stars (HD 277) exhibited excess scatter around maximum brightness. This effect, similar to the Blazhko effect observed in some RR Lyrae variables (Szeidl 1976), is also seen in several other γ Doradus variables (e.g., 9 Aurigae = V398 Aur: Zerbi et al. 1997a; HD 164615 = V2118 Oph: Zerbi et al. 1997b; HR 8799 = V342 Peg: Zerbi et al. 1999). In our current sample of six new variables, none shows the effect to the extent seen in HD 277. However, there is some suggestion of excess scatter around maximum in the light curve of HD 108100 (Fig. 11, *top panel*).

Finally, in Figure 16, we plot the largest amplitude photometric period for each star in Table 5 against its $(B-V)_0$, M_V, and luminosity. No correlations have yet become evident between any of these parameters. This is not too surprising given (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.

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