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10 NEW γ DORADUS AND δ SCUTI STARS

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ABSTRACT

We present high-resolution spectroscopy and precision photometry of five new γ Doradus and five new δ Scuti variables. The five new γ Doradus variables substantially increase the number of confirmed stars of this class. All 10 stars fall in the spectral class range F0–F2, but they are cleanly separated into two groups by their luminosity and photometric periods. However, the period gap between the γ Doradus and δ Scuti stars is becoming very narrow since we confirm that HD 155154 is a γ Doradus star with the shortest periods reported to date (the shortest of its four periods is $\sim$0.312 days). We do not find any evidence in our sample for stars exhibiting both δ Scuti– *and* γ Doradus–type pulsations.

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

On-line material: machine-readable tables

1. INTRODUCTION

We present new high-resolution spectroscopy and precision photometry of five new γ Doradus and five new δ Scuti variables. δ Scuti stars are multiperiodic pulsating variables located in the lower portion of the Cepheid instability strip and have periods generally between 0.02 and 0.25 days. The δ Scuti stars have been recognized as a class for several decades, and Breger (1979, 2000) has given thorough reviews of their properties and pulsation mechanisms. The latest published catalog of δ Scuti variables contains 636 entries (Rodríguez, López-González, & Lopeź de Coca 2000) and Breger (2000) estimated that $\sim$50% of all main-sequence stars inside the instability strip are δ Scuti pulsators.

The γ Doradus stars, on the other hand, have been recognized as a class of variable stars for only a few years. Zerbi (2000) reviewed the history leading to their designation as a variable star class and discussed their physical properties. Like the δ Scuti stars, these stars typically have multiple periods, but the periods are longer, usually between 0.4 and 3 days. The latest published list of γ Doradus variables contains only 13 entries (Kaye et al. 1999a), although there are several dozen additional candidates (e.g., Handler 1999; Aerts, Eyer, & Kestens 1998). One of the 13 stars in Kaye et al. (1999a), HR 6277, has subsequently been shown to be a δ Scuti star (Kaye, Henry, & Rodríguez 2000), leaving only a dozen confirmed γ Doradus stars on the list. Handler (1999) showed that most of the γ Doradus stars lie on or near the main sequence just outside the cool boundary of the δ Scuti instability strip. However, he found the γ Doradus region overlaps that of the δ Scuti stars. The full extent of the γ Doradus domain in the H-R diagram is still unknown because of the small number of confirmed γ Doradus variables. The first models for a mechanism to drive the gravity-mode pulsations in these stars were proposed by Guzik et al. (2000).

Zerbi (2000) noted that a large fraction of the γ Doradus variables have been discovered serendipitiously, typically as variable comparison stars for other programs. Several on the list of Kaye et al. (1999a) were found in this way by Henry (1999) in a program of high-precision photometry of Sun-like stars with the T4 0.75 m and T8 0.80 m automatic photoelectric telescopes (APTs) at Fairborn Observatory in the Patagonia Mountains of southern Arizona.[2] We continue this serendipitous tradition in this paper: six of the 10 new variables were found as variable comparison stars with the same APTs. The other four stars in our sample were selected from the list of prime γ Doradus candidates in Handler (1999). Table 1 lists our 10 program stars. The V magnitudes and $B-V$ color indices in columns (3) and (4) are taken from the *Hipparcos* catalog (ESA 1997). The basic properties in columns (5)–(9) are determined below. Column (10) gives the variability type from the *Hipparcos* catalog, where only half of these new variable stars had any indication of variability. Column (11) lists the source from which the program stars were selected. All 10 stars were placed on the observing menu of the T3 0.40 m APT at Fairborn Observatory to obtain the follow-up photometric observations presented in this paper.

2. SPECTROSCOPY

2.1. *Observations*

Between 1996 October and 2001 April at least one spectrum was obtained of each program star 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.

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

TABLE 1

BASIC PROPERTIES OF PROGRAM STARS

HD (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)	Variable Star Class[b] (9)	*Hipparcos* Variable Type[a] (10)	Source (11)
277.......	...	8.37	0.379	F2	Dwarf	38	−4.6	γ Doradus	P	Handler 1999
104288...	ADS 8387 AB	7.42	0.367	F2	Giant	110	−28.7	δ Scuti	...	T8 APT
105458...	...	7.77	0.299	F2	Dwarf	40	−11.4	γ Doradus	U	Handler 1999
154443...	...	7.31	0.334	F0	Giant	37	−6.6	δ Scuti	C	T8 APT
155154...	HR 6379, NSV 8183	6.17	0.306	F1:	Dwarf	180:	69.7::	γ Doradus	U	Handler 1999
160314...	...	7.74	0.405	F2	Subgiant	59	−0.3	γ Doradus	...	T4 APT
173471...	...	7.16	0.264	F2	Giant	160	−6.1:	δ Scuti	...	T8 APT
182634...	...	7.94	0.230	F2	Giant	155	−11.1:	δ Scuti	...	T8 APT
189885...	...	7.54	0.269	F0	Giant	19	−32.9	δ Scuti	M	T4 APT
206043...	NZ Peg, HR 8276	5.77	0.314	F2	Dwarf	140	−15.2:	γ Doradus	P	Handler 1999

[a] *Hipparcos* Catalogue.
[b] This paper.

2.2. *Radial Velocities*

Radial velocities were determined in the 6385–6444 Å region with the IRAF[3] cross-correlation program FXCOR (Fitzpatrick 1993). The IAU radial velocity standards HR 5694, HR 7560, and ι Psc were used as reference stars. Their velocities of 54.4, 0.0, and 5.6 km s^{-1}, respectively, were adopted from Scarfe, Batten, & Fletcher (1990). To determine the radial velocity of each program star, a Gaussian function was fitted to the cross-correlation peak. If a peak was clearly asymmetric, the fit gave greater weight to the points in the wings of the peak than to those in the central portion to better approximate the star's velocity. Our radial velocities, which are mean values if more than one observation was made, are listed in Table 1 along with other basic properties of our program stars. Since some stars show velocity variability that may result from pulsation or duplicity, the individual velocities of all the stars are listed in Table 2. For the more slowly rotating stars (i.e., for $v \sin i \leq 60$ km s^{-1}) the individual velocities have uncertainties of 0.5–1.0 km s^{-1}. For those stars with lines broader than 100 km s^{-1}, only the least blended two or three lines were measured. The significantly smaller depth and greater width of the lines and the larger contribution of noise to the line profiles result in larger velocity uncertainties, estimated to be 2–3 km s^{-1}. Such velocities are indicated by a colon after the value. For HD 155154, the strongest lines in the observed wavelength region are extremely weak, so a double colon indicates that the velocity of this star is even more uncertain. We note that the stellar pulsations of these stars can produce asymmetric line profiles, which increase the velocity uncertainty for some of the observed velocities.

2.3. *Spectral Classes*

Strassmeier & Fekel (1990) examined red-wavelength spectra of a number of stars, including spectral type standards, and identified several temperature-sensitive and luminosity-sensitive line ratios in the 6430–6455 Å region. They used those line ratios, along with the general appearance of the spectrum, as spectral type criteria for F, G, and K stars.

The spectra of several slowly rotating late A and early F stars from the list of Abt & Morrell (1995) were obtained at KPNO with the same telescope, spectrograph, and detector as our spectra of the program stars. With a computer program developed by Huenemoerder & Barden (1984) and Barden (1985), these reference-star spectra were rotationally broadened and shifted in radial velocity and then compared with an observed spectrum of each program star. Following Strassmeier & Fekel (1990), we determined the spectral class of each program star (Table 1). However, for stars earlier than about G0, the line ratios in the 6430 Å region have little sensitivity to luminosity, so we were unable to estimate the luminosity classes of the program stars from our spectra. Instead, these are determined from the *Hipparcos*

TABLE 2

INDIVIDUAL RADIAL VELOCITIES

Date (HJD − 2,400,000)	Radial Velocity (km s^{-1})	Comments
HD 277:		
51,741.875	−4.5	
51,742.907	−4.8	
HD 104288:		
51,659.781	−28.7	Broad lines
HD 105458:		
51,731.651	−11.8	
51,735.676	−10.6	
51,742.643	−14.0	Asymmetric lines
52,017.802	−9.4	Asymmetric lines
HD 154443:		
50,362.582	−7.1	
51,350.825	−6.5	
51,740.751	−6.2	
HD 155154:		
51,734.720	69.7::	Very broad lines
HD 160314:		
50,203.892	2.8	
51,740.783	−3.0	
52,013.950	−0.7	
HD 173471:		
51,351.826	−6.1:	Broad lines
51,351.826	−5.4	Narrow cores
HD 182634:		
51,802.691	−11.1:	Very broad lines
HD 189885:		
49,968.761	−32.1	
51,731.859	−33.7	
HD 206043:		
51,737.808	−16.2:	Very broad lines
51,740.915	−14.3:	

[3] IRAF is distributed by the National Optical Astronomy Observatory.

TABLE 3

PROGRAM, COMPARISON, AND CHECK STARS

Program Star	Comparison	Check	σ_{V-C}[a] (mag)	σ_{K-C}[a] (mag)	Individual Observations[b]
HD 277..........	HD 373	HD 2774	0.0375	0.0050	Table 4A
HD 104288......	HD 104316	HD 102925	0.0070	0.0054	Table 4B
HD 105458......	HD 105123	HD 107610	0.0211	0.0064	Table 4C
HD 154443......	HD 154931	HD 155423	0.0117	0.0048	Table 4D
HD 155154......	HD 153143	HD 154099	0.0122	0.0056	Table 4E
HD 160314......	HD 158736	HD 158737	0.0087	0.0058	Table 4F
HD 173471......	HD 173088	HD 173417	0.0081	0.0049	Table 4G
HD 182634......	HD 181656	HD 184105	0.0081	0.0046	Table 4H
HD 189885......	HD 190151	HD 189090	0.0088	0.0054	Table 4I
HD 206043......	HD 205420	HD 206793	0.0185	0.0060	Table 4J

[a] In the Johnson *B* photometric band.
[b] The individual observations are given in Tables 4A–4J.

magnitudes, color indices, and parallaxes (ESA 1997) in § 5 (below).

2.4. *Projected Rotational Velocities*

We have determined projected rotational velocities of our program stars in two different ways. For stars with $v \sin i \leq 60$ km s^{-1}, we used the procedure of Fekel (1997). For each star, the FWHM of several metal lines in the 6430 Å region was measured and the results averaged. An instrumental broadening of 0.21 Å was removed from the measured broadening by taking the square root of the difference between the squares of measurements of the stellar and comparison lines, resulting in the intrinsic broadening. The calibration polynomial of Fekel (1997) was used to convert this broadening in angstroms into a total line broadening in kilometers per second. Following Fekel (1997), for early F stars we adopted and removed a macroturbulence of 5 km s^{-1}.

The calibration polynomial is based on broadening values up to 50 km s^{-1}, so a second method was used to determine the projected rotational velocities of stars with significantly broader absorption lines. For these more rapidly rotating stars, reference stars of early F spectral class were rotationally broadened with the program of Huenemoerder & Barden (1984) and Barden (1985). We estimate $v \sin i$ uncertainties of 5 and 10 km s^{-1} for $v \sin i$ values near 100 and 150 km s^{-1}, respectively. For HD 160314 ($v \sin i = 59$ km s^{-1}), both methods produced essentially identical $v \sin i$ values.

3. PHOTOMETRY

3.1. *Observations*

The photometric observations analyzed in this paper were acquired between 1998 September and 2000 July with the T3 0.4 m APT at Fairborn Observatory. The 0.4 m APT uses a temperature-stabilized EMI 9924B photomultiplier tube to acquire data successively through Johnson *B* and *V* filters. Each program star was measured in the following sequence, termed a group observation: *K*, *S*, *C*, *V*, *C*, *V*, *C*, *V*, *C*, *S*, and *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 filter 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 can be found in Henry (1995).

All of our 10 program stars were observed up to five times each clear night at intervals of 2 to 3 hours for the duration of their observing seasons. This allows us to sample periods close to one day. In addition, each star was observed continuously for several hours on one night near opposition to sample periods much shorter than one day. This allows us to discriminate between the γ Doradus and the δ Scuti variables. Six of the stars were observed over two observing seasons; the other four were observed for only one season.

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 σ_{K-C} values demonstrate that all comparison and check stars are constant to $\sim$0.006 mag or better, which is approximately the limit of precision for this APT. The individual photometric observations of each star are given in Tables 4A–4J. The observations are also available on the Tennessee State University Automated Astronomy Group web site.[4]

3.2. *Period Search*

As in our previous analyses of the γ Doradus stars HD 62454 and HD 68192 (Kaye et al. 1999b) and HR 8330 (Kaye et al. 1999c), we used the method of Vaniĉek (1971), based on least-squares fitting of sinusoids, to search for

[4] http://schwab.tsuniv.edu/t3/gammador3/gammador3.html.

TABLE 4A

PHOTOMETRIC OBSERVATIONS OF HD 277

HJD	Var *B* (mag)	Var *V* (mag)	Chk *B* (mag)	Chk *V* (mag)
51,447.6493	0.591	0.601	−1.370	−2.189
51,447.7269	0.584	0.591	−1.370	−2.187
51,447.8114	0.569	0.584	−1.355	−2.177
51,447.8944	0.567	0.575	−1.357	−2.178
51,447.9792	0.548	0.564	−1.359	−2.182

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

TABLE 5

RESULTS FROM PHOTOMETRIC ANALYSIS

Star and Photometric Band (1)	Date Range (HJD − 2,450,000) (2)	N_{obs}[a] (3)	Frequency (day^{-1}) (4)	Period (days) (5)	Peak-to-Peak Amplitude (mmag) (6)	T_{min} (HJD − 2,450,000) (7)
HD 277:						
B	1447.6493–1590.5942	422[b]	1.1105 ± 0.0003	0.9005 ± 0.0002	56.7 ± 3.0	1500.884
	...	...	1.0813 ± 0.0003	0.9248 ± 0.0003	37.5 ± 3.9	1500.119
	...	...	1.3866 ± 0.0003	0.7212 ± 0.0002	23.3 ± 4.2	1500.128
V...............	1447.6493–1590.5942	415[b]	1.1106 ± 0.0003	0.9004 ± 0.0002	42.8 ± 2.4	1500.880
	...	...	1.0812 ± 0.0004	0.9249 ± 0.0003	27.3 ± 3.0	1500.114
	...	...	1.3865 ± 0.0003	0.7212 ± 0.0002	16.3 ± 3.2	1500.135
HD 104288:						
B	1121.0271–1731.6616	621	8.86297 ± 0.00003	0.1128290 ± 0.0000004	11.0 ± 0.7	1400.088
	...	...	12.09309 ± 0.00003	0.0826918 ± 0.0000002	6.6 ± 0.8	1400.070
V...............	1121.0271–1731.6616	611	8.86300 ± 0.00003	0.1128286 ± 0.0000004	8.6 ± 0.6	1400.088
	...	...	12.09293 ± 0.00004	0.0826930 ± 0.0000002	4.0 ± 0.7	1400.073
HD 105458:						
B	1485.0292–1731.6873	526	1.3208 ± 0.0002	0.7571 ± 0.0001	37.3 ± 2.1	1600.244
	...	...	0.9457 ± 0.0002	1.0574 ± 0.0003	22.4 ± 2.4	1600.676
	...	...	1.2505 ± 0.0002	0.7997 ± 0.0001	19.1 ± 2.4	1600.235
	...	...	1.4094 ± 0.0002	0.7095 ± 0.0001	10.9 ± 2.6	1600.670
	...	...	1.5524 ± 0.0002	0.6442 ± 0.0001	15.4 ± 2.5	1600.347
	...	...	1.0911 ± 0.0002	0.9165 ± 0.0002	14.3 ± 2.5	1600.543
V...............	1485.0292–1731.6873	519	1.3207 ± 0.0002	0.7572 ± 0.0001	30.5 ± 1.8	1600.239
	...	...	0.9460 ± 0.0002	1.0571 ± 0.0002	18.9 ± 2.0	1600.691
	...	...	1.2507 ± 0.0002	0.7996 ± 0.0001	16.8 ± 2.1	1600.250
	...	...	1.4096 ± 0.0002	0.7094 ± 0.0001	8.1 ± 2.2	1600.655
	...	...	1.5528 ± 0.0002	0.6440 ± 0.0001	13.3 ± 2.1	1600.354
	...	...	1.0910 ± 0.0002	0.9166 ± 0.0001	12.0 ± 2.1	1600.536
HD 154443:						
B	1207.0496–1729.6598	458	10.74096 ± 0.00004	0.0931015 ± 0.0000004	20.2 ± 1.2	1500.047
	...	...	14.27020 ± 0.00006	0.0700761 ± 0.0000003	12.4 ± 1.4	1500.026
	...	...	14.27708 ± 0.00005	0.0700423 ± 0.0000002	11.0 ± 1.5	1500.022
V...............	1207.0496–1729.6598	447	10.74099 ± 0.00005	0.0931013 ± 0.0000004	15.2 ± 1.1	1500.048
	...	...	14.27026 ± 0.00005	0.0700758 ± 0.0000002	10.7 ± 1.2	1500.025
	...	...	14.27724 ± 0.00005	0.0700415 ± 0.0000002	7.2 ± 1.3	1500.022
HD 155154:						
B	1447.5917–1731.7104	301	2.8977 ± 0.0002	0.34510 ± 0.00002	21.8 ± 1.6	1600.062
	...	...	3.0979 ± 0.0002	0.32280 ± 0.00002	20.0 ± 1.6	1600.042
	...	...	3.1999 ± 0.0002	0.31251 ± 0.00002	6.0 ± 2.0	1600.094
	...	...	3.0691 ± 0.0002	0.32583 ± 0.00002	11.2 ± 1.9	1600.125
V...............	1447.5917–1731.7104	306	2.8976 ± 0.0002	0.34511 ± 0.00002	16.4 ± 1.4	1600.066
	...	...	3.0978 ± 0.0002	0.32281 ± 0.00002	15.2 ± 1.4	1600.037
	...	...	3.2001 ± 0.0002	0.31249 ± 0.00002	5.2 ± 1.6	1600.100
	...	...	3.0686 ± 0.0002	0.32588 ± 0.00002	8.7 ± 1.6	1600.123
HD 160314:						
B	1216.0418–1731.7441	351	1.20827 ± 0.00005	0.82763 ± 0.00003	12.5 ± 1.1	1500.753
	...	...	1.18428 ± 0.00005	0.84439 ± 0.00004	12.0 ± 1.1	1500.268
V...............	1213.0514–1731.7441	346	1.20810 ± 0.00006	0.82775 ± 0.00004	10.5 ± 1.1	1500.751
	...	...	1.18423 ± 0.00005	0.84443 ± 0.00004	9.2 ± 1.1	1500.280
HD 173471:						
B	1085.5882–1731.6639	452	13.64294 ± 0.00004	0.0732980 ± 0.0000002	13.1 ± 0.9	1400.032
	...	...	10.86387 ± 0.00004	0.0920482 ± 0.0000004	9.9 ± 1.0	1400.071
	...	...	15.92651 ± 0.00005	0.0627884 ± 0.0000002	8.6 ± 1.0	1400.002
	...	...	13.27271 ± 0.00005	0.0753426 ± 0.0000003	6.7 ± 1.0	1400.069
V...............	1085.5882–1731.6639	438	13.64295 ± 0.00004	0.0732979 ± 0.0000002	9.5 ± 0.8	1400.031
	...	...	10.86389 ± 0.00004	0.0920481 ± 0.0000004	7.6 ± 0.8	1400.071
	...	...	15.92646 ± 0.00004	0.0627886 ± 0.0000002	6.4 ± 0.9	1400.001
	...	...	13.27261 ± 0.00005	0.0753431 ± 0.0000003	6.2 ± 0.9	1400.066
HD 182634:						
B	1447.6023–1731.7471	343	15.0478 ± 0.0002	0.0664549 ± 0.0000009	14.8 ± 1.1	1600.014
	...	...	13.4211 ± 0.0002	0.0745095 ± 0.0000008	5.0 ± 1.2	1600.052
V...............	1447.6023–1731.7471	338	15.0477 ± 0.0002	0.0664553 ± 0.0000007	13.1 ± 0.9	1600.013
	...	...	13.4214 ± 0.0001	0.0745079 ± 0.0000006	4.2 ± 1.1	1600.050
HD 189885:						
B	1085.6093–1730.7180	387	11.12503 ± 0.00005	0.0898874 ± 0.0000004	19.1 ± 0.8	1400.045
V...............	1085.6093–1730.7180	381	11.12505 ± 0.00004	0.0898872 ± 0.0000003	15.6 ± 0.7	1400.043

TABLE 5—*Continued*

Star and Photometric Band (1)	Date Range (HJD − 2,450,000) (2)	N_{obs}[a] (3)	Frequency (day^{-1}) (4)	Period (days) (5)	Peak-to-Peak Amplitude (mmag) (6)	T_{min} (HJD − 2,450,000) (7)
HD 206043:						
B	1447.6102–1731.8714	290	2.4323 ± 0.0001	0.41113 ± 0.00003	32.9 ± 2.5	1600.201
	...	...	2.3595 ± 0.0002	0.42382 ± 0.00004	26.5 ± 2.7	1600.076
	...	...	2.5242 ± 0.0001	0.39617 ± 0.00002	21.5 ± 2.8	1600.313
	...	...	2.5990 ± 0.0001	0.38476 ± 0.00002	12.8 ± 3.0	1600.050
	...	...	2.2657 ± 0.0002	0.44136 ± 0.00004	8.2 ± 3.0	1600.140
	...	...	2.4606 ± 0.0002	0.40640 ± 0.00003	4.1 ± 3.1	1600.228
V................	1447.6102–1731.8714	284	2.4323 ± 0.0002	0.41113 ± 0.00003	26.2 ± 1.9	1600.202
	...	...	2.3595 ± 0.0002	0.42382 ± 0.00004	22.0 ± 2.1	1600.073
	...	...	2.5243 ± 0.0002	0.39615 ± 0.00003	16.2 ± 2.3	1600.308
	...	...	2.5989 ± 0.0002	0.38478 ± 0.00003	8.8 ± 2.4	1600.037
	...	...	2.2655 ± 0.0002	0.44140 ± 0.00004	6.6 ± 2.4	1600.146
	...	...	2.4606 ± 0.0001	0.40640 ± 0.00002	4.7 ± 2.4	1600.234

[a] The individual observations are given in Tables 4A–4J. They are also available at http://schwab.tsuniv.edu/t3/gammador3/gammador3.html.

[b] Analysis does not include the 71 *BV* observations obtained on JD 2,451,451 for reasons explained in the text.

periodicities in our photometric data sets. An important feature of this technique is its ability to find multiple periodicities without prewhitening, an advantage over other techniques, especially in the low-frequency domain. This is an iterative process, in which frequencies are detected one at a time in the data. Each detected frequency, but not its associated amplitude, phase, or mean brightness level, is then introduced as a fixed parameter into a new search for additional frequencies. The new search is carried out while simultaneously fitting a single new mean brightness level along with the amplitudes and phases of all frequencies introduced as fixed parameters. In the resulting least-squares spectra, we plot the fractional reduction of the variance (reduction factor) versus trial frequency. Antonello, Mantegazza, & Poretti (1986) and Andreasen (1987) compared this method with other period-finding techniques, and Pardo & Poretti (1997) and Mantegazza (2000) described in more detail how it is used to uncover, one by one, multiple periodicities in specific data sets.

For each program star, we analyzed the $V-C$ data sets separately in each photometric band over the frequency range 0.01–30.0 day^{-1}, which corresponds to the period range 0.033–100 days. The results of these analyses are given in Table 5. The frequencies and corresponding periods are given only in cases in which they could be identified in both the *B* and *V* data sets. The peak-to-peak amplitudes reported in column (6) of the table are determined for each frequency *without* prewhitening for the other frequencies; the *V* amplitudes are generally about 3/4 as large as those in *B*.

The $K-C$ data sets were also analyzed in the same way to search for periodicities that might exist in the check and comparison stars. None were found in any of the 20 stars. Thus, all the periodicities reported in Table 5 can be assigned solely to the program stars, with one complication noted below in § 4.2 for the binary components of HD 104288.

Least-squares spectra and phase diagrams for the *B* observations of all 10 program stars are shown in Figures 1–20. Although all analyses were done over the full frequency range of 0.01–30.0 day^{-1}, the least-squares spectra are plotted here over more restricted ranges; none of the stars exhibited variability in the frequency range 20–30 day^{-1}, and several showed no 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 the *B* and *V* data sets. We generally fixed the frequencies in the order of their amplitudes from the largest to smallest, but since the Vaniĉek method does not prewhiten the data, the order in which this is done is unimportant. With all the detected frequencies fixed, the rms of the residuals was usually close to the expected precision of the observations, indicating little or no remaining variability; exceptions in two cases are discussed in § 4 below. To illustrate the lowest amplitudes, the phase diagrams are plotted for each frequency

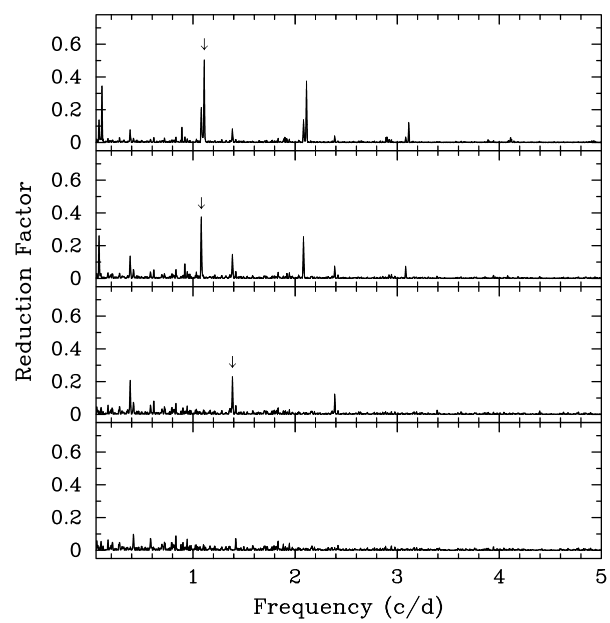

FIG. 1.—Least-squares spectra of the HD 277 *B* data set, showing the results of progressively fixing each of the detected frequencies (*arrows*). *Top*, no frequencies fixed; *second*, only the 1.1105 day^{-1} frequency has been fixed; *third*, the 1.0813 day^{-1} frequency has also been fixed; and *bottom*, the 1.3866 day^{-1} frequency has also been fixed. All three frequencies were confirmed in the *V* data set.

after the data sets were prewhitened to remove the other detected frequencies.

4. RESULTS FOR INDIVIDUAL STARS

4.1. *HD 277*

We classified HD 277 as an F2 star, and its *Hipparcos* parallax (ESA 1997) indicates that it is a dwarf. We measured a modest projected rotational velocity of 38 km s^{-1}. Two radial velocities obtained on consecutive nights (Table 2) are nearly identical and result in a mean velocity of -4.6 km s^{-1}. Duflot et al. (1992) found a velocity of -6 ± 2.7 km s^{-1}, in good agreement with our result.

The least-squares spectra of our *B* observations are given in Figure 1, and the results are summarized in Table 5. The 71 observations obtained on JD 2,451,451 are not included in this analysis for reasons explained below. Handler (1999) found periods of 0.925, 0.900, and 0.744 days in the *Hipparcos* photometry. Our first two photometric periods agree with Handler's to within the uncertainties, but our third is slightly shorter than his. These periods confirm that HD 277 is a γ Doradus variable. Although we can find no additional periodicity in our observations, the rms of our residuals in *B* after prewhitening with the three periods is 0.014 mag, compared with the 0.005 mag rms of the $K-C$ observations. This implies significant additional variability in HD 277 not explainable by sinusoidal variations at these three periods. We note that the phase curves in Figure 2 show significantly more scatter around light maximum than at light minimum, especially for the largest amplitude variation (*top*). The 71 monitoring observations from JD 2,451, 451, not included in our period analysis and not plotted in Figure 2, exhibit a brightness maximum slightly higher still than any points in the phase plot. In addition, the maximum on this night is significantly offset toward earlier phases. For these reasons, this single night of monitoring observations was not included in our period analysis of Figure 1, although it *was* used to establish that frequencies higher than those plotted are not evident in the data. This variation in the phase and level of maximum brightness of the star from cycle to cycle probably accounts for the excess rms of our residuals. Zerbi et al. (1997a, 1997b) note very similar behavior in 9 Aurigae and HD 164615, so this may be a common effect in γ Doradus stars and observationally appears similar to the Blazhko effect seen in some RR Lyrae variables (Szeidl 1976).

4.2. *HD 104288 = ADS 8387 AB*

HD 104288 is a close visual binary with a separation of about 0."12 and components that differ in magnitude by about 0.9 mag (ESA 1997). Thus, most of the basic properties that we determined are for the composite system. Our lone spectrum shows only a single set of broad absorption lines. Our spectral class of F2 for the system is in agreement with the F2 V spectral type of Abt (1981). The *Hipparcos* parallax (ESA 1997) indicates, however, that the primary star must be a giant. We determined $v \sin i = 110$ km s^{-1}, and our velocity is -28.7 km s^{-1}.

We find two periods in our photometry (Figs. 3–4; Table 5): $\sim$0.112 and $\sim$0.083 days. The rms of the residuals in *B* after prewhitening for these two periods is 0.005 mag, which agrees with the rms of the $K-C$ observations. The ratio of the second period to the first is 0.733, very close to the 0.74–0.78 range given by Breger (1979) for the ratio of the first radial overtone to the fundamental period in δ Scuti stars. Thus, we classify HD 104288 as a new δ Scuti variable. However, we cannot be certain which component of

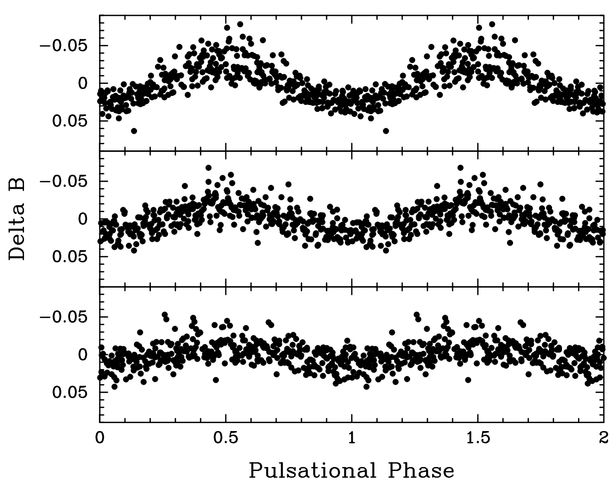

FIG. 2.—*B* photometric data for HD 277, phased with the three frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 1.1105, 1.0813, and 1.3866 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

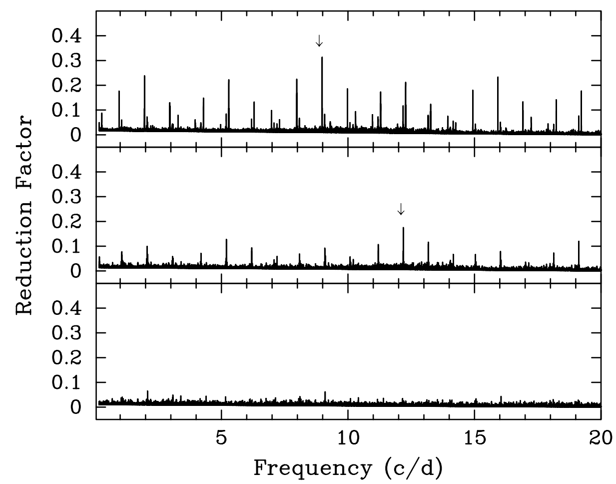

FIG. 3.—Least-squares spectra of the HD 104288 *B* data set, showing the results of progressively fixing the two detected frequencies. The arrows indicate the two frequencies at 8.86297 day^{-1} (*top*) and 12.09309 day^{-1} (*middle*). Both frequencies were confirmed in the *V* data set.

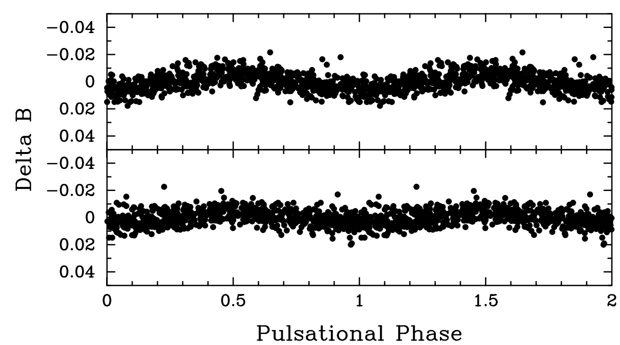

FIG. 4.—*B* photometric data for HD 104288, phased with the two frequencies and times of minimum from Table 5. The two frequencies are 8.86297 day^{-1} (*top*) and 12.09309 day^{-1} (*bottom*). For each panel, the data set has been prewhitened to remove the other known frequency.

the visual binary is the variable. Because the primary star is a giant, the secondary star 0.9 mag fainter could well be a mid- to late A dwarf or a slightly evolved early F star. Hence, it too could be a δ Scuti star and the source of the photometric variability. Dilution by the brighter primary would reduce its amplitude, but this would still be consistent with our results.

4.3. *HD 105458*

We found HD 105458 to be an F2 dwarf and determined a projected rotational velocity of 40 km s^{-1}. Previously, Grenier et al. (1999) had determined a spectral type of F0 III and, from three observations, measured a mean radial velocity of -5.6 ± 3.8 km s^{-1}. Our four spectra have a somewhat different mean radial velocity of -11.4 km s^{-1}. In two of our spectra the absorption lines are asymmetric, so the velocity variations may result from pulsation. However, given our velocity range of 4.6 km s^{-1} (Table 2) and the velocity difference between the two sets of observations, the possibility that HD 105458 is a spectroscopic binary cannot be excluded.

Handler (1999) found periods of 1.398, 0.757, and 0.687 days in the *Hipparcos* photometry. Only his second period is in common with any of the six periods found in our analysis of the APT data (Figs. 5–6; Table 5); the matching period (0.7571 days) has the largest amplitude by far. Our least-squares spectra in Figure 5 show no indication at all of Handler's other two periods. Although Handler (1999) does not indicate that any of his three periods are particularly uncertain, he does admit that searching for multiple periods in *Hipparcos* photometry can lead to spurious results. The rms of our residuals in B after prewhitening for our six periods is 0.010 mag, significantly larger than the 0.006 mag rms of the $K-C$ observations. Thus, additional, perhaps nonperiodic, variability may be occurring in HD 105458. A little excess scatter around the times of maximum is evident in the top two panels of Figure 6 that is similar to, but much less than, that seen in HD 277. Our results confirm that HD 105458 is a γ Doradus star.

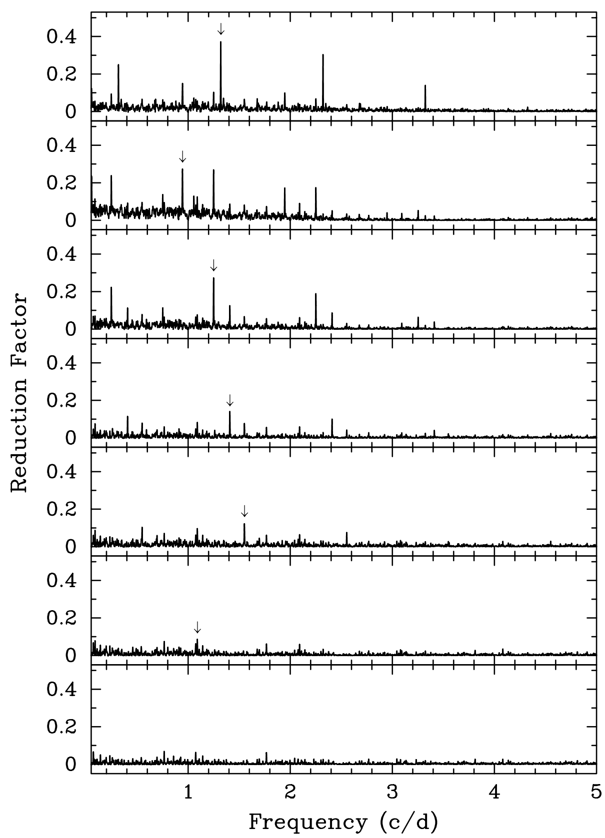

FIG. 5.—Least-squares spectra of the HD 105458 B data set, showing the results of progressively fixing the six detected frequencies. The arrows indicate the six frequencies: *top to bottom*, 1.3208, 0.9457, 1.2505, 1.4094, 1.5524, and 1.0911 day^{-1}. All six frequencies were confirmed in the V data set.

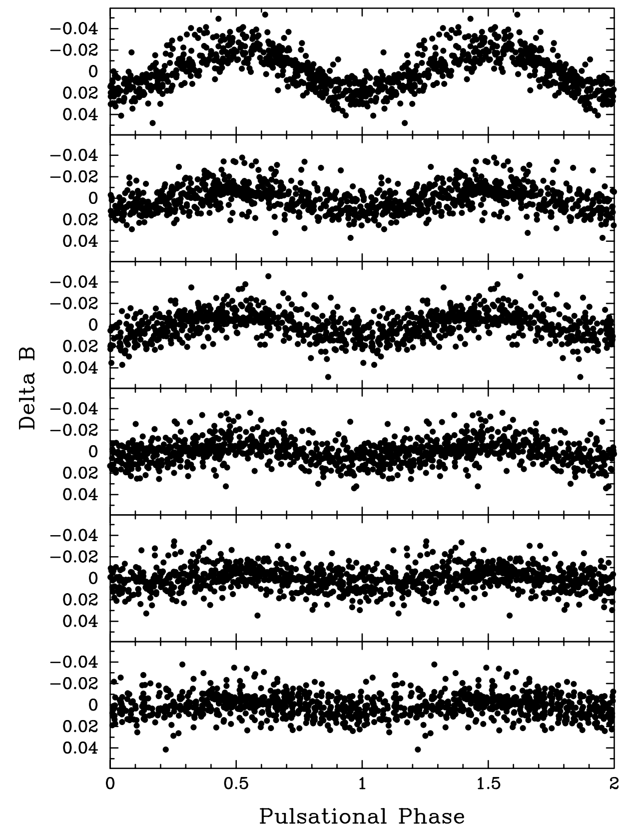

FIG. 6.—B photometric data for HD 105458, phased with the six frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 1.3208, 0.9457, 1.2505, 1.4094, 1.5524, and 1.0911 day^{-1}. For each panel, the data set has been prewhitened to remove the other five known frequencies.

4.4. *HD 154443*

Between 1996 October and 2000 July we obtained three spectra of HD 154443. We determined a spectral class of F0 for this giant star, a result in reasonable agreement with Grenier et al. (1999), who found a spectral type of F0 IV. For HD 154443 we computed $v \sin i = 37$ km s^{-1}. Our three velocities have an average of -6.6 km s^{-1} and show no evidence of variability. Our mean is, however, rather different from that of Grenier et al. (1999), who found a velocity of -13.4 ± 2.0 km s^{-1} from three spectra. This velocity difference suggests that its velocity is variable.

We find three photometric periods in the APT data (Figs. 7–8; Table 5), all less than 0.1 days, with the second and third periods being very close to each other. After prewhitening for these three periods, the rms of the residuals in B is 0.007 mag, not quite down to the rms of 0.005 mag for the $K-C$ observations. The period ratios of the second to the first and the third to the first are 0.753 and 0.752, respectively, both within the range of 0.74–0.78 given by Breger (1979) for the ratio of the first radial overtone to the funda-

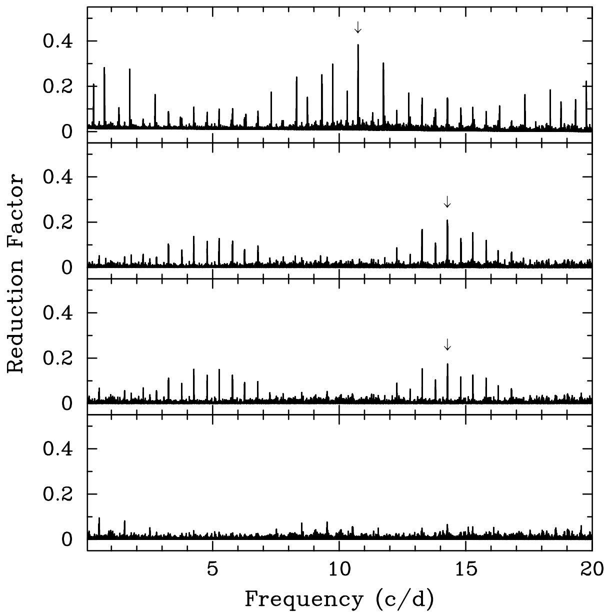

FIG. 7.—Least-squares spectra of the HD 154443 *B* data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies: *top to bottom*, 10.74096, 14.27020, and 14.27708 day^{-1}. All three frequencies were confirmed in the *V* data set.

mental period in δ Scuti stars. Therefore, we classify HD 154443 as a new δ Scuti star.

4.5. *HD 155154 = HR 6379 = NSV 8183*

Our sole spectrum of the bright star HD 155154 shows very weak, broad lines, making the analysis of its properties significantly more uncertain than that for any of the other stars in our sample. Our $v \sin i$ value of 180 ± 20 km s^{-1} is between those of Abt & Morrell (1995) and Danziger & Faber (1972), who estimated 145 and 200 km s^{-1}, respectively. We classified the star as an F1: dwarf, which is in reasonable agreement with previous results of A9 V (Abt & Morrell 1995), F0 IVn (Cowley & Fraquelli 1974), and F0 Vn (Cowley & Bidelman 1979). Our radial velocity of -69.7 km s^{-1} was determined from the measurement of a single line. It is quite different from the value found by Harper (1937), so perhaps the star is a binary. He noted that the "lines are broad and fuzzy as if complex." His three velocities have a range of nearly 26 km s^{-1} and a mean of 0.1 km s^{-1}.

Breger (1969) recognized HD 155154 as a short-term variable from 2.7 hr of photometric monitoring but did not assign a variability type. Handler (1999) found periods of 0.345, 0.323, and 0.294 days in the *Hipparcos* photometry and therefore placed the star on his list of prime γ Doradus candidates. The first two of Handler's periods match the first two of the four periods we find in the APT data (Figs. 9–10; Table 5). We see no evidence for Handler's 0.294 day period but instead find periods of 0.313 and 0.326 days. Our observed periods confirm HD 155154 to be a γ Doradus star with some of the shortest known periods. The rms of the APT observations after prewhitening for the four detected periods is 0.006 mag, the same as the rms of the $K-C$ observations.

4.6. *HD 160314*

We classified HD 160314 as an F2 star, while the *Hipparcos* parallax indicates that it is subgiant. These results are in good agreement with the F2 V–IV spectral type of Grenier et al. (1999). We determined a moderate projected rotational velocity of 59 km s^{-1}. Our three radial velocities have a mean of -0.3 km s^{-1} and a velocity range of nearly 6 km s^{-1} (Table 2). From three measurements Grenier et al. (1999) found a slightly different average velocity of -4.5 ± 1.3 km s^{-1}. Since our spectra show that the absorption lines are asymmetric, the velocity variability may result from line profile changes associated with the pulsation mechanism rather than binary motion. Additional radial velocities will be necessary to identify the cause of velocity variability.

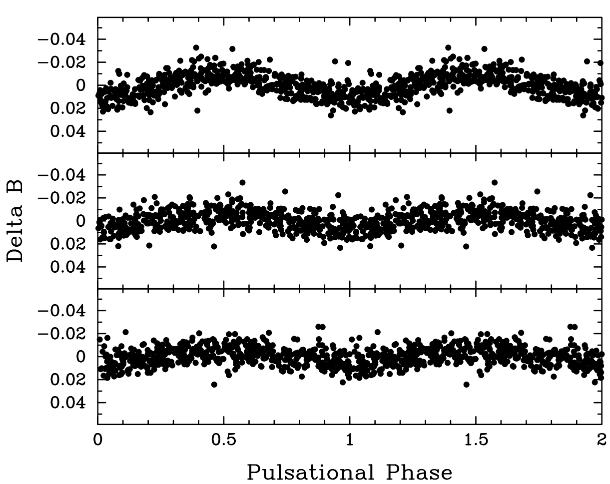

FIG. 8.—*B* photometric data for HD 154443, phased with the three frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 10.74096, 14.27020, and 14.27708 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

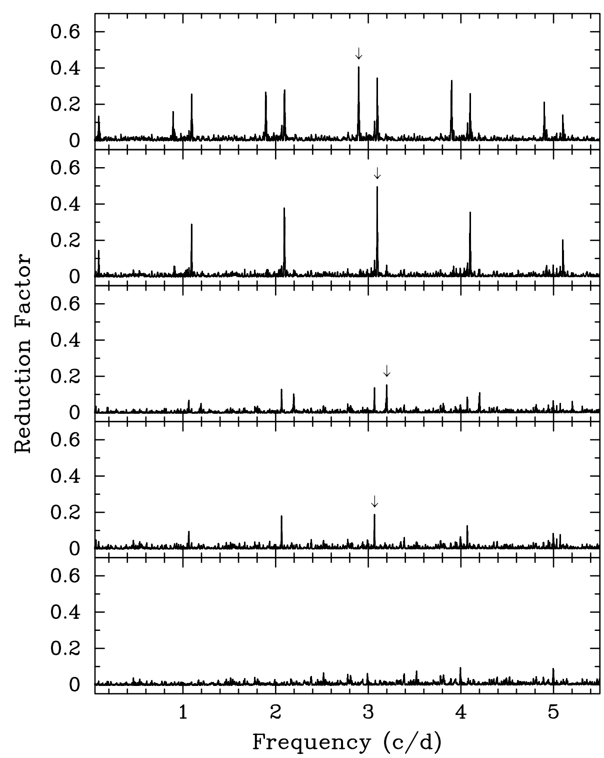

FIG. 9.—Least-squares spectra of the HD 155154 *B* data set, showing the results of progressively fixing the four detected frequencies. The arrows indicate the four frequencies: *top to bottom*, 2.8977, 3.0979, 3.1999, and 3.0691 day^{-1}. All four frequencies were confirmed in the *V* data set.

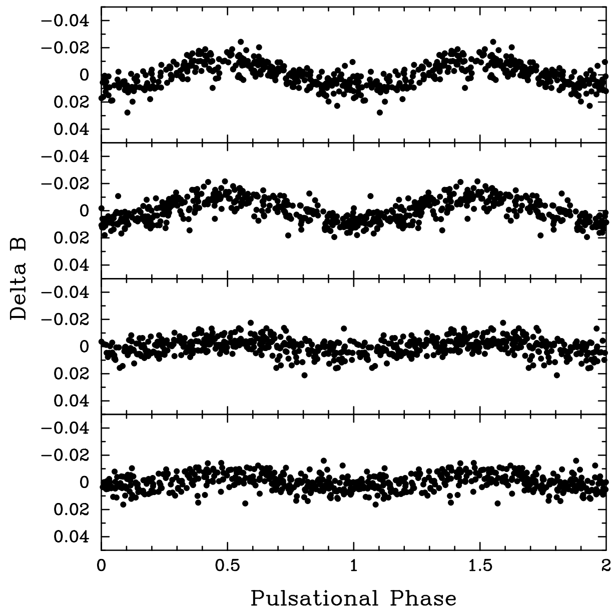

FIG. 10.—B photometric data for HD 155154, phased with the four frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 2.8977, 3.0979, 3.1999, and 3.0691 day^{-1}. For each panel, the data set has been prewhitened to remove the other three known frequencies.

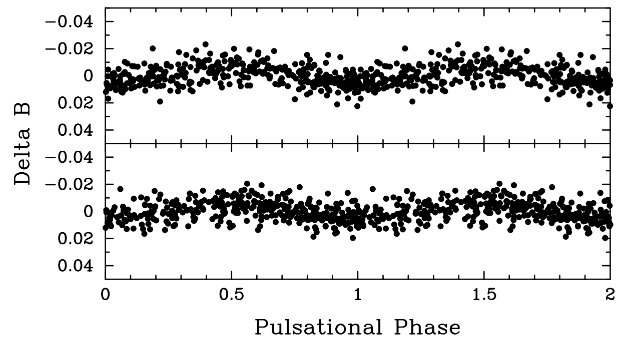

FIG. 12.—B photometric data for HD 160314, phased with the two frequencies and times of minimum from Table 5. The two frequencies are 1.20827 day^{-1} (*top*) and 1.18428 day^{-1} (*bottom*). For each panel, the data set has been prewhitened to remove the other known frequency.

Slight night-to-night photometric variability in HD 160314 was suspected in one of two observing seasons by Lockwood, Skiff, & Radick (1997). We find periods of ∼0.828 and ∼0.844 in our photometry (Figs. 11–12; Table 5). Based on these periods, we classify the star as a new γ Doradus variable. After prewhitening the observations with these two periods, the rms of the residuals in B is 0.007 mag, close to the rms of 0.006 mag in the $K-C$ observations.

4.7. *HD 173471*

Our red-wavelength spectrum of HD 173471 shows that the neutral metal absorption lines consist of a combination of a broad component and a narrow absorption feature near its center. Initially, we suspected that this superposition indicated that the system consisted of two stars, one broad lined and the other narrow lined. A search of the literature produced no reference to any previous discovery of duplicity. Mantegazza & Poretti (1996) have found similar absorption line profiles in the spectrum of the δ Scuti variable X Caeli. They noted that the velocity of the narrow absorption core "is comparable with that of the stellar barycenter," suggested that the narrow lines resulted from a circumstellar shell, and commented that such a shell would be a new discovery for a δ Scuti star. HD 173471 appears to be a second example of this. The radial velocities of the broad and narrow components are also nearly identical, -6.1 and -5.4 km s^{-1}, respectively. From four spectra Grenier et al. (1999) found a similar velocity of -6.4 ± 2.5 km s^{-1}. The star is rapidly rotating with $v \sin i = 160$ km s^{-1}. We classify it as an F2 giant, while Grenier et al. (1999) found a somewhat different spectral type of A9 V.

We find four photometric periods, all shorter than 0.1 days, in our APT data (Figs. 13–14; Table 5), indicating that the star is a δ Scuti variable. None of the period ratios fall within the 0.74–0.78 range given by Breger (1979). However, some of the ratios are quite close to typical δ Scuti period ratios for radial pulsations in higher overtones (Breger 1979), indicating that our longest period for HD 173471 may be the first overtone rather than the fundamental. Prewhitening the B observations with the four detected periods leaves residuals with an rms of 0.005 mag, identical to the rms of the $K-C$ observations.

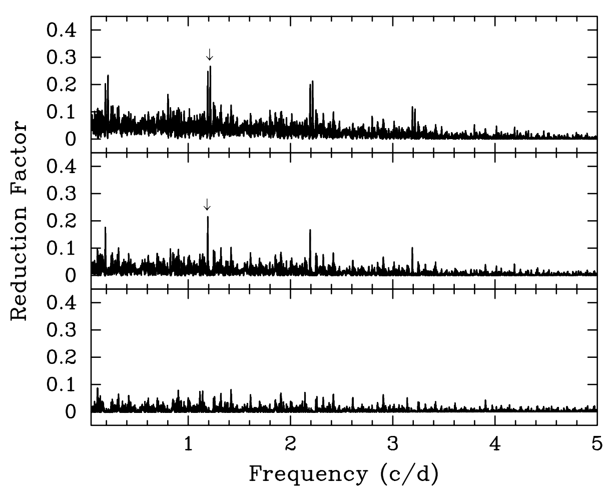

FIG. 11.—Least-squares spectra of the HD 160314 B data set, showing the results of progressively fixing the two detected frequencies. The arrows indicate the two frequencies at 1.20827 day^{-1} (*top*) and 1.18428 day^{-1} (*middle*). Both frequencies were confirmed in the V data set.

4.8. *HD 182634*

We classified HD 182634 as an F2 giant. It has a projected rotational velocity of 155 km s^{-1}. From our single spectrum its radial velocity is -11.1 km s^{-1}.

We found two photometric periods, both less than 0.1 days (Figs. 15–16; Table 5), indicating that HD 182634 is a δ Scuti star. The bottom panel of the least-squares spectrum in Figure 15 suggests that another low-amplitude period may be present, but aliasing makes it impossible to know which period might be the correct one. The period ratio of our two detected periods is 1.121 or 0.892, depending on the sense of the ratio. Neither ratio closely matches any of the period ratios from Breger (1979) for radial modes in δ Scuti stars. However, only a minority of δ Scuti variables are pure radial pulsators (Breger 2000); most pulsate with a large number of nonradial p-modes. Prewhitening for the two periods gives residuals in B of 0.006 mag, which is not much larger than the rms of 0.005 mag for the $K-C$ observations.

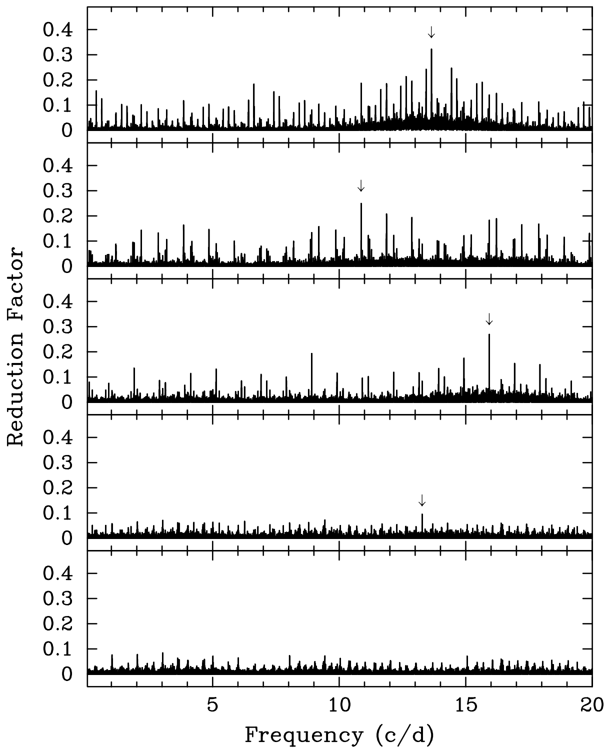

FIG. 13.—Least-squares spectra of the HD 173471 *B* data set, showing the results of progressively fixing the four detected frequencies. The arrows indicate the four frequencies: *top to bottom*, 13.64294, 10.86387, 15.92651, and 13.27271 day^{-1}. All four frequencies were confirmed in the *V* data set.

4.9. *HD 189885*

Of the 10 stars in our sample, HD 189885 has the narrowest lines, from which we obtained $v \sin i = 19.3$ km s^{-1}. We classified the star as F0 and concluded from its *Hipparcos* parallax (ESA 1997) that it is a giant. The average velocity of our two spectra is -32.9 km s^{-1}.

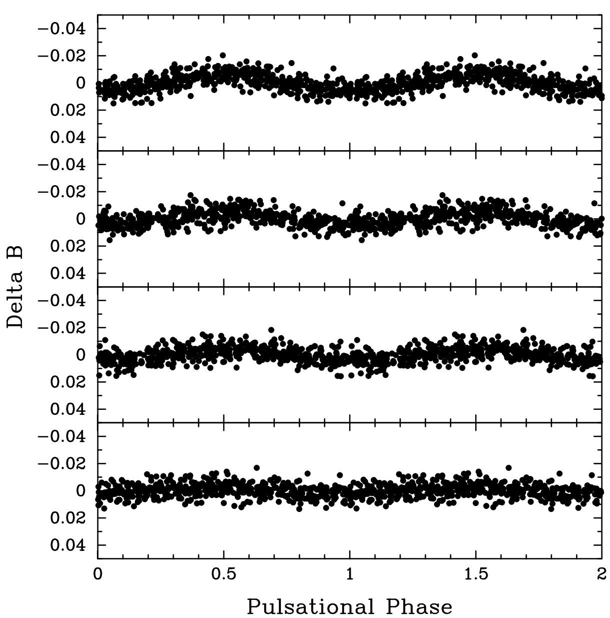

FIG. 14.—*B* photometric data for HD 173471, phased with the four frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 13.64294, 10.86387, 15.92651, and 13.27271 day^{-1}. For each panel, the data set has been prewhitened to remove the other three known frequencies.

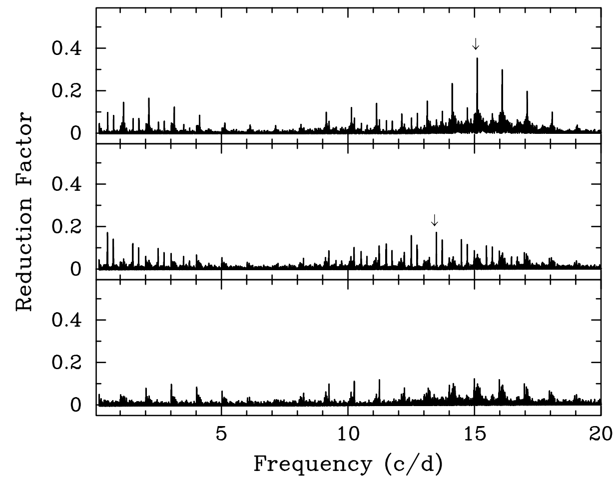

FIG. 15.—Least-squares spectra of the HD 182634 *B* data set, showing the results of progressively fixing the two detected frequencies. The arrows indicate the two frequencies at 15.0478 day^{-1} (*top*) and 13.4211 day^{-1} (*middle*). Both frequencies were confirmed in the *V* data set. At least one additional low-amplitude frequency is probably present, but aliasing prevents us from determining its correct value.

HD 189885 is the only star in our sample with a single period (Figs. 17–18; Table 5). We identify it as a δ Scuti variable since the period is ~ 0.090 days. If this star is a radial pulsator, then equation (5) of Stellingwerf (1979) suggests that the star is pulsating in the first or second overtone; we do not know the bolometric magnitude and effective temperature accurately enough to identify the

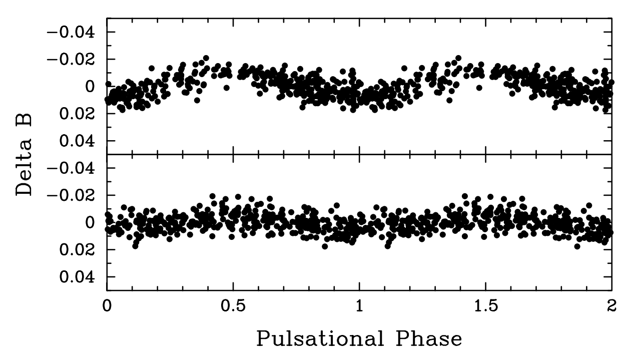

FIG. 16.—*B* photometric data for HD 182634, phased with the two frequencies and times of minimum from Table 5. The two frequencies are 15.0478 day^{-1} (*top*) and 13.4211 day^{-1} (*bottom*). For each panel, the data set has been prewhitened to remove the other known frequency.

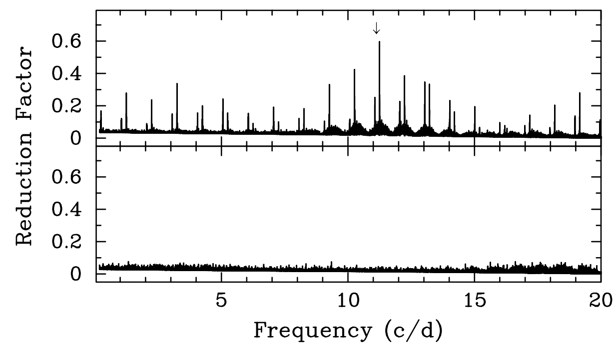

FIG. 17.—Least-squares spectra of the HD 189885 *B* data sets. *Top*: single detected frequency at 11.12503 day^{-1}. The same frequency was confirmed in the *V* data set.

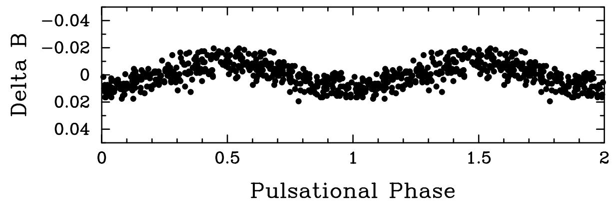

FIG. 18.—B photometric data for HD 189885, phased with the single frequency of 11.12503 day^{-1} and time of minimum from Table 5.

mode uniquely. Breger (2000), however, states that it is "likely that the so-called monoperiodic variables with low amplitudes are not radial pulsators." In any case, the constancy of our two radial velocity measures, the narrow spectral lines, and the short period are all inconsistent with the possibility of ellipsoidal variations or starspots as the cause of photometric variability in this star. The rms of the residuals in B after prewhitening for this period is 0.005 mag, which matches the rms of the $K-C$ observations.

4.10. *HD 206043 = HR 8276 = NZ Peg*

Because HD 206043 is a relatively bright star, it has been included in various surveys of late A and early F stars. Our classification of F2 dwarf is identical to that of Cowley & Fraquelli (1974) and Cowley (1976), while Gray & Garrison (1989) and Abt & Morrell (1995) gave it a slightly earlier spectral class of F0. Our $v \sin i$ value of 140 km s^{-1} is in accord with the results of Danziger & Faber (1972) and Abt & Morrell (1995), who estimated 130 and 135 km s^{-1}, respectively. From two observations we determined an average radial velocity of -15.2 km s^{-1}. This velocity is in good agreement with the mean value of Fehrenbach et al. (1997), who obtained -13 ± 2.7 km s^{-1} from five observations.

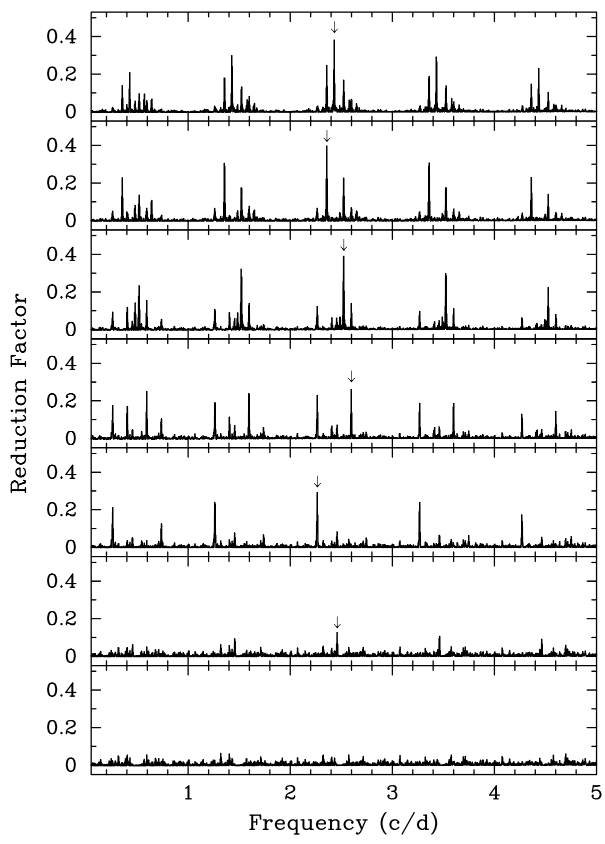

FIG. 19.—Least-squares spectra of the HD 206043 B data set, showing the results of progressively fixing the six detected frequencies. The arrows indicate the six frequencies: *top to bottom*, 2.4323, 2.3595, 2.5242, 2.5990, 2.2657, and 2.4606 day^{-1}. All six frequencies were confirmed in the V data set.

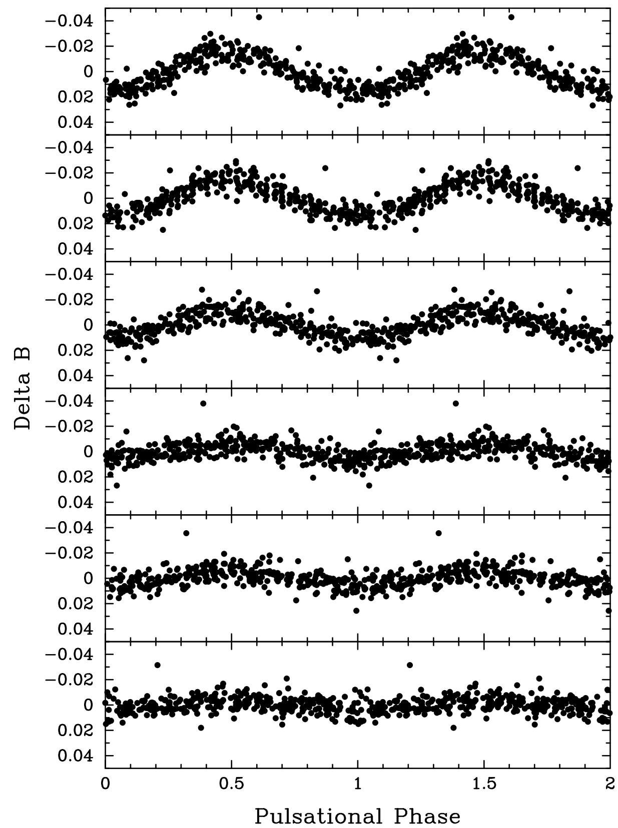

FIG. 20.—B photometric data for HD 206043, phased with the six frequencies and times of minimum from Table 5. *Top to bottom*: Frequencies are 2.4323, 2.3595, 2.5242, 2.5990, 2.2657, and 2.4606 day^{-1}. For each panel, the data set has been prewhitened to remove the other five known frequencies.

Handler (1999) found periods of 0.416, 0.407, and 0.458 days in the *Hipparcos* photometry. If we assume uncertainties in these periods of a few thousandths of a day, then Handler's first and second periods are consistent with our first and sixth periods from the APT photometry (Figs. 19–20; Table 5), and his third period agrees with our fifth period to within 2–3 standard deviations. Prewhitening the APT data with our six periods leaves residuals with an rms of 0.006 mag in B, which is the same as the rms of the $K-C$ observations. The observed periods confirm that HD 206043 is a γ Doradus variable rather than the δ Scuti classification given in SIMBAD.

5. DISCUSSION

In this paper, we have presented the results of new photometry and spectroscopy of 10 new γ Doradus and δ Scuti variables. The variability class of each of these 10 stars has been determined, and they should be considered additions to the appropriate catalog (for the γ Doradus variables, Kaye et al. 1999a; for the δ Scuti variables, Rodríguez et al. 2000). Photometric variations attributed to starspots or the ellipticity effect in binary systems can be eliminated in these stars for a variety of reasons, including the high stability of the light curves, the multiple periods observed, the lack of substantial convective envelopes, and the lack of high-amplitude changes in the radial velocities. We also note the following:

1. Our results on the five γ Doradus variables in this paper are consistent with the definition of this class given by Kaye et al. (1999a). Thus, these five stars provide a significant increase in the number of confirmed variables in this class.

2. In our sample, the γ Doradus variables and the δ Scuti variables separate themselves in the H-R diagram by absolute magnitude, although not by spectral class (Fig. 21). As we stated in § 2.3 (above), we were unable to determine the luminosity classes of these stars from our spectra because stars earlier than G0 have little sensitivity to luminosity in our observed spectral region. However, since all 10 stars appear in the *Hipparcos* catalog (ESA 1997), we can use the *Hipparcos* magnitudes, color indices, and parallaxes to calculate each star's luminosity directly. Table 6 gives the results. Columns (2) and (3) list $(B-V)_0$ and M_V, respectively, computed with the *Hipparcos* data and the adopted interstellar extinction relation of Henry et al. (2000). Each luminosity in column (4) was determined from M_V, the bolometric correction of Flower (1996), and an assumed $M_{\rm bol}$ of 4.75 for the Sun. The radii in column (5) were then computed by assuming the $(B-V)_0$ versus $T_{\rm eff}$ relationship of Flower (1996). The values for HD 104288 refer to the brighter star of the visual double and are somewhat uncertain because we do not have separate magnitudes and colors for the two components. These results were used to determine our luminosity classes in Table 1 and in each of the subsections of § 4. In our 10 star sample, all the giants (i.e., those stars with $M_V < 2$) are δ Scuti stars; less luminous objects (i.e., those having $M_V > 2$) are γ Doradus stars. Each of our new δ Scuti variables lies well within the empirically determined classical δ Scuti instability strip (Breger 1979), and all the new γ Doradus variables lie within the observationally determined domain of the γ Doradus variables identified by Handler (1999).

TABLE 6

DERIVED PROPERTIES OF PROGRAM STARS

Program Star (HD) (1)	$(B-V)_0$ (mag) (2)	M_V (mag) (3)	L ($L_\odot$) (4)	R ($R_\odot$) (5)
277	0.354	3.23	4.0	1.4
104288	0.320:	0.81:	37.0:	4.0:
105458	0.276	2.76	6.0	1.5
154443	0.285	0.64	42.8	4.1
155154	0.295	2.87	5.5	1.5
160314	0.378	2.45	8.1	2.0
173471	0.229	1.27	23.8	2.8
182634	0.172	0.84	35.8	3.2
189885	0.227	1.19	25.7	2.9
206043	0.305	2.78	6.0	1.6

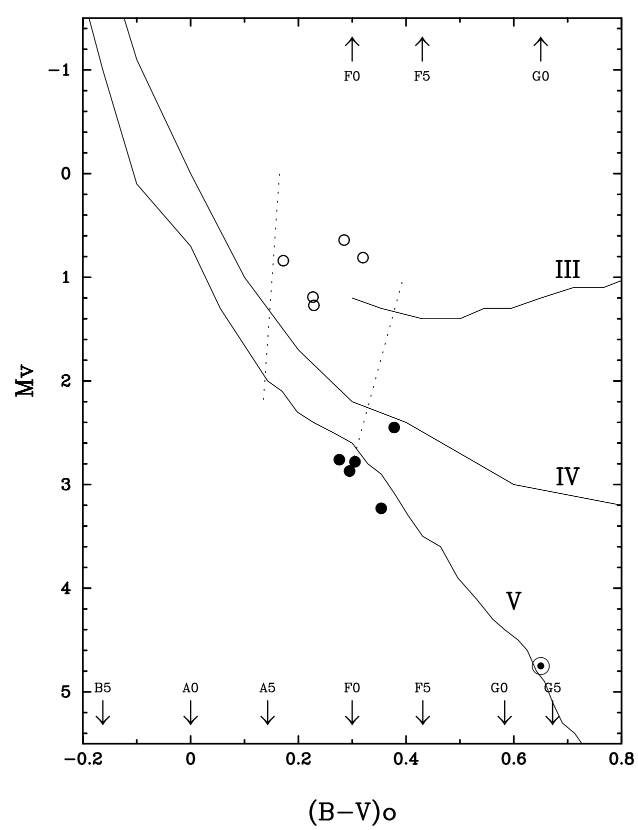

FIG. 21.—Plot of 10 program stars in the H-R diagram, showing the five δ Scuti variables, all with photometric periods less than 0.1 days (*open circles*) and the five γ Doradus variables, all with periods longer than 0.3 days (*filled circles*). The dotted lines indicate the boundaries of the δ Scuti instability strip. The Sun's position is shown at lower right.

3. The δ Scuti and γ Doradus stars in our sample are also cleanly separated in the period domain. Those stars that have periods shorter than the radial fundamental (roughly 0.25 days in this part of the H-R diagram) are δ Scuti stars (as expected for *p*-modes); those with longer periods are γ Doradus variables (as expected for *g*-modes). We do not find any evidence in our sample for stars exhibiting both δ Scuti– *and* γ Doradus–type pulsations (Breger & Beichbuchner 1996), and, to date, only weak evidence for this exists in a couple stars (Breger 2000). However, the portion of the H-R diagram in which we would expect these objects to occur is not sampled in our study. Given that the domains of the γ Doradus and δ Scuti variables in the H-R diagram appear to overlap and that the pulsation-driving mechanisms in the two types of stars may operate at different depths (Guzik et al. 2000), it may be possible for both types of pulsation to coexist in the same star.

4. The excess scatter at maximum brightness observed in some γ Doradus variables is confirmed within our sample, but does not seem to be a function of projected rotational velocity. We note a large amount of excess scatter at maximum light in only one γ Doradus object—HD 277 ($v \sin i = 38$ km s^{-1}); other γ Doradus variables with similar projected rotational velocities do not show such strong scatter (e.g., HD 105458; $v \sin i = 40$ km s^{-1}), nor do γ Doradus stars with much higher projected rotational velocities (e.g., HD 155154, $v \sin i = 180$ km s^{-1}). This kind of excess scatter at maximum brightness is well documented in the γ Doradus stars 9 Aurigae = V398 Aur (Zerbi et al. 1997a), HD 164615 = V2118 Oph (Zerbi et al. 1997b), and HR 8799 = V342 Peg (Zerbi et al. 1999).

5. For the four program stars from Handler's list of prime γ Doradus candidates (Handler 1999), photometric analyses of our APT data confirmed the majority of the periods found in the *Hipparcos* photometry. Furthermore, we have confirmed all four of these as γ Doradus stars. That some of Handler's periods were not detected in our APT observations illustrates the utility of follow-up photometric monitoring of Handler's candidates, as also recommended

by Zerbi (2000). However, based on our results, most of Handler's prime candidates are likely to be confirmed as γ Doradus stars.

6. When considering the periods present in our new δ Scuti stars, we sometimes see periods that correspond to the ratio of the radial fundamental and first overtone (HD 104288 and HD 154443) or the first and second overtones (HD 173471). However, in the case of HD 182634, this is not the case, so the observed modes may be nonradial *p*-modes or modes of mixed character. We detect only one period in HD 189885, but we do not have enough information about the star to characterize the pulsation.

7. The results presented in § 4, along with other recent results, indicate that the period gap observed between the γ Doradus and δ Scuti variables is narrowing. Of the 636 δ Scuti stars listed in the catalog of Rodríguez et al. (2000), the 14 stars with the longest periods fall within the range 0.25–0.29 days (Rodríguez & Breger 2001). However, Rodríguez & Breger (2001) also list three AC And–type variables with longer periods up to 0.7 days that may be evolved δ Scuti stars. The number of confirmed γ Doradus stars is much smaller than the number of δ Scuti stars. Previously, the shortest known γ Doradus period was 0.421 days (HD 165645; Kaye 1998). Martín & Rodríguez (2000) present two γ Doradus candidates with still shorter periods (H1284 and S29, both in the Pleiades cluster with $P = 0.3389$ and $P = 0.3896$ days, respectively). Henry & Henry (2000) analyzed photometry of the γ Doradus candidate HD 49015 and found a tentative period of 0.3452 days. HD 155154 (§ 4.5 above) now represents the star with the shortest periods observed in any confirmed γ Doradus star ($P = 0.313$ days is the shortest of its four periods; see Table 5 and Figs. 9–10). Therefore, the period gap between the γ Doradus and the δ Scuti variables may still be real and due to the different pulsation mechanisms of the two classes of variable stars, but much narrower than originally thought. More likely, however, as more γ Doradus stars are identified, even shorter periods may be found (down to the radial fundamental), and the period gap may disappear entirely.

8. It is generally agreed that the observed γ Doradus variability is due to high-order (n), low spherical degree (l) g-modes (Kaye et al. 1999a). From simple geometric arguments, we can make the a priori assumption that the vast majority of the modes that have been photometrically observed to date are characterized by $1 \leq l \leq 4$; modes of higher spherical degree are likely to have very small amplitudes. However, such modes (of degree $\sim$6–10) may be present in some stars (see, e.g., HD 160314 in § 4.6, above; see also 38 Eri in Balona 2000). Mode identification in γ Doradus stars is still in its infancy; there has been only one detailed paper on this to date (Aerts & Kaye 2001).

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