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Five New δ Scuti Stars

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ABSTRACT. We present high-resolution spectroscopy and precision photometry of five new, relatively bright δ Scuti stars. They were originally chosen as photometric comparison stars in our program of automated, high-precision photometry of solar-type stars and subsequently recognized as new variable stars. We conducted follow-up spectroscopic and photometric observations to determine the properties of the stars and their types of variability. All five of the stars presented here belong to the most common subgroup of low-amplitude, Population I δ Scuti variables. One of the stars, HD 10502, is the third example of a δ Scuti variable with composite broad and narrow spectroscopic line profiles suggesting the presence of a circumstellar shell or disk.

1. INTRODUCTION

We have been conducting a long-term program of automated photometry to measure brightness changes in solar-type stars and compare them to brightness changes in our own Sun (Baliunas et al. 1998; Henry 1999). Satellite observations have revealed that the Sun's total irradiance varies by about 0.001 mag in step with the 11 yr sunspot cycle (e.g., Willson & Hudson 1991; de Toma et al. 2001). The measurement of analogous variations in a sample of 350 solar-type stars with our ground-based automated telescopes requires the identification of many hundreds of comparison stars that are photometrically constant to 0.0001 mag or so. The majority of stars later than spectral class F5 do not have this level of stability (Henry 1999, his Table 5), so we are forced to seek comparisons among the early F stars. Unfortunately, this places us in the neighborhood of the δ Scuti (Breger 2000) and γ Doradus variables (Handler 1999). However, once the obvious short-term variables are culled from our comparison star sample, the remainder tend to display good long-term stability (Henry 1999, his Table 5).

The 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 day (e.g., Breger 2000). The latest published catalog of δ Scuti variables (Rodríguez, López-González, & López de Coca 2000) contains 636 entries. In this paper, we present observational results on five new δ Scuti variables discovered among our photometric comparison stars. Table 1 lists the properties of these five stars. The V magnitudes and $B-V$ color indices in columns (2) and (3) are taken from the *Hipparcos* Catalogue (ESA 1997). The basic properties in columns (4)–(7) are determined below. A colon following a value indicates greater uncertainty. Column (8) gives the variability type from the *Hipparcos* Catalogue, where none of these five stars was identified as variable. Column (9) lists the telescope with which we originally observed each star; T4, T8, and T10 refer to three of our automatic photoelectric telescopes (APTs) at Fairborn Observatory in the Patagonia Mountains of southern Arizona.[2] Our high-resolution spectroscopic observations of these stars are described below in § 2.1. Follow-up photometric observations of the first four stars were made with the T3 APT, while no further photometry was required on HD 210957. The new photometric observations are described below in § 2.2, and notes on each individual star are given in § 3.

2. OBSERVATIONS AND ANALYSIS

2.1. Spectroscopy

Between 2000 September and 2001 April, one or more spectra were obtained of four of the five δ Scuti 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

[1] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatory, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

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

TABLE 1
BASIC PROPERTIES OF THE NEW δ SCUTI STARS

HD Number (1)	V[a] (mag) (2)	$B-V$[a] (mag) (3)	Spectral Class[b] (4)	Luminosity Class[b] (5)	$v \sin i$[b] (km s^{-1}) (6)	Velocity[b] (km s^{-1}) (7)	*Hipparcos* Variable Type[a] (8)	Source (9)
10502	7.29	0.284	F1	Dwarf	120	−13.4	C	T8 APT
63874	7.41	0.309	F1:	Giant	170:	11[c]		T8 APT
117589	7.38	0.310	F1	Subgiant	70	−16.8		T4 APT
183364	7.36	0.290	F1	Giant	110	4.2		T8 APT
210957	8.01	0.226	A9[d]	Subgiant	...	0[e]	C	T10 APT

[a] *Hipparcos* Catalogue. C = constant. A blank entry signifies the star could not be classified as variable or constant.
[b] This paper.
[c] From Duflot et al. 1990.
[d] From Moore & Paddock 1950.
[e] From Fehrenbach & Burnage 1982.

from the *Hipparcos* magnitudes, color indices, and parallaxes (ESA 1997) also as described in Henry et al. (2001).

2.2. Photometry

The photometric observations analyzed in this paper were acquired between 2000 September and 2001 July with the T3 0.4 m and the T10 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 T10 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 program star observed with the T10 APT was measured up to about five times each hour for up to several hours each night throughout its observing season. The external precision of our observations, 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 T10. The individual photometric observations of each star are given in Tables 3A–3E 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 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. The frequencies and corresponding periods are given only when they could be identified in both passbands. The peak-to-peak amplitudes reported in column (7) of the table are determined for each frequency *without* prewhitening for the other frequencies; the amplitudes range from 15.9 down to 2.2 mmag. The *B* (or *b*) amplitudes average 1.27 times larger than those in *V* (or *y*). The times of minimum light for each frequency

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

TABLE 2
PROGRAM AND COMPARISON STARS

Program Star (1)	Comparison Star 1 (2)	Comparison Star 2 (3)	APT (4)	Individual Observations[a] (5)
HD 10502	HD 10262	HD 9024	T3	Table 3A
HD 63874	HD 60105	HD 65664	T3	Table 3B
HD 117589	HD 120007	HD 118905	T3	Table 3C
HD 183364	HD 184057	HD 186377	T3	Table 3D
HD 210957	HD 208717	HD 210074	T10	Table 3E

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

TABLE 3A
PHOTOMETRIC OBSERVATIONS OF HD 10502

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)
51805.7754	0.833	0.938	0.160	0.202
51805.8613	0.847	0.953	0.163	0.200
51807.7723	0.845	0.950	0.161	0.206
51807.8566	0.846	0.953	0.156	0.193
51807.9753	0.837	0.947	0.156	0.205
51808.8934	99.999	99.999	0.158	99.999

NOTE.—Tables 3A–3E 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)
10502	*B*	1805.7754–1953.5974	196	22.9470 ± 0.0003	0.0435787 ± 0.0000006	10.5 ± 1.2	1870.008 ± 0.001
	V	1805.7754–1953.5974	197	22.9470 ± 0.0004	0.0435787 ± 0.0000008	6.8 ± 1.1	1870.008 ± 0.001
63874	*B*	1805.9922–2047.6338	391	5.4235 ± 0.0002	0.184383 ± 0.000007	15.4 ± 1.2	1900.123 ± 0.002
	V	1805.9922–2047.6338	389	5.4238 ± 0.0003	0.184373 ± 0.000010	10.9 ± 1.2	1900.123 ± 0.003
117589	*B*	1874.0377–2089.7400	452	16.0489 ± 0.0002[b]	0.0623096 ± 0.0000008[b]	4.8 ± 0.8	2000.038 ± 0.002
	V	1873.0402–2087.6832	439	16.0498 ± 0.0002[b]	0.0623061 ± 0.0000008[b]	4.4 ± 0.8	2000.039 ± 0.002
183364	*B*	1805.6245–2092.9313	287	15.6209 ± 0.0002	0.0640168 ± 0.0000006	15.9 ± 1.2	1960.060 ± 0.001
				14.7638 ± 0.0002[b]	0.0677332 ± 0.0000009[b]	5.9 ± 1.4	1960.052 ± 0.003
	V	1805.6245–2092.9313	281	15.6208 ± 0.0002	0.0640172 ± 0.0000006	11.6 ± 1.0	1960.059 ± 0.001
				14.7637 ± 0.0002[b]	0.0677337 ± 0.0000009[b]	5.6 ± 1.2	1960.050 ± 0.002
210957	*b*	1822.7036–1908.5835	439	22.6538 ± 0.0004	0.0441427 ± 0.0000008	4.9 ± 0.4	1860.035 ± 0.001
				19.1514 ± 0.0004[b]	0.0522155 ± 0.0000010[b]	3.2 ± 0.4	1860.030 ± 0.001
				21.3238 ± 0.0004[b]	0.0468960 ± 0.0000010[b]	2.6 ± 0.4	1860.020 ± 0.001
	y	1822.7036–1908.5835	439	22.6539 ± 0.0004	0.0441425 ± 0.0000008	4.2 ± 0.4	1860.035 ± 0.001
				19.1507 ± 0.0004[b]	0.0522174 ± 0.0000011[b]	2.4 ± 0.4	1860.031 ± 0.001
				21.3229 ± 0.0005[b]	0.0468979 ± 0.0000011[b]	2.2 ± 0.4	1860.019 ± 0.001

[a] The individual observations are given in Tables 3A–3E in machine-readable format available in the electronic edition of *PASP*. They are also available at http://schwab.tsuniv.edu/papers/pasp/deltasct/deltasct.html.
[b] Identification of true frequency somewhat ambiguous as a result of aliasing.

are given in column (8); in each case, the times of minimum in the two passbands agree within their uncertainties, 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 was 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.

Figure 1 plots differential Johnson *B* or Strömgren *b* photometric observations of each of the five program stars acquired over several hours on a single night near each star's time of opposition. All five panels are plotted to the same scale and show high-frequency, low-amplitude photometric variations typical of δ Scuti variables (Rodríguez et al. 2000; Rodríguez & Breger 2001). Least-squares spectra and phase diagrams for all of the *B* or *b* observations of the five 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 the more restricted ranges where variability is found to occur. 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. The phase diagrams are plotted for each frequency after the data sets were prewhitened to remove the other detected frequencies. These phase diagrams show clear, coherent signals at all of our detected frequencies. Thus, the phase curves provide important confirmation, especially in the very low amplitude cases, that a few outliers in our data sets have not conspired to produce small peaks in our frequency spectra and thus lead to false period detections. The phase curves all closely resemble sinusoids with no obvious cycle-to-cycle amplitude variations, such as the Blazhko effect seen in some RR Lyrae and related stars.

3. RESULTS FOR INDIVIDUAL STARS

3.1. HD 10502

Our single red-wavelength spectrogram of HD 10502 shows a composite spectrum (Fig. 2). Each metal absorption line consists of a broad component with a narrow absorption feature near its center. 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 a second δ Scuti variable, HD 173741. It is possible that HD 10502 is a double-lined binary that consists of components with very different rotational velocities, but there is no evidence of duplicity in the *Hipparcos* observations (ESA 1997). Following Mantegazza & Poretti (1996), we believe it is more likely that the broad lines correspond to the photospheric spectrum of HD 10502, while the sharp absorption features result from a shell or disk surrounding the star. We determined a spectral class of F1 for the broad-lined component of HD 10502 and found a dwarf luminosity class from the *Hipparcos* parallax. The spectrum of the weak narrow lines has a similar spectral class. For HD 10502, the broad and narrow components have projected rotational velocities of 120 and 10 km s^{-1}, respec-

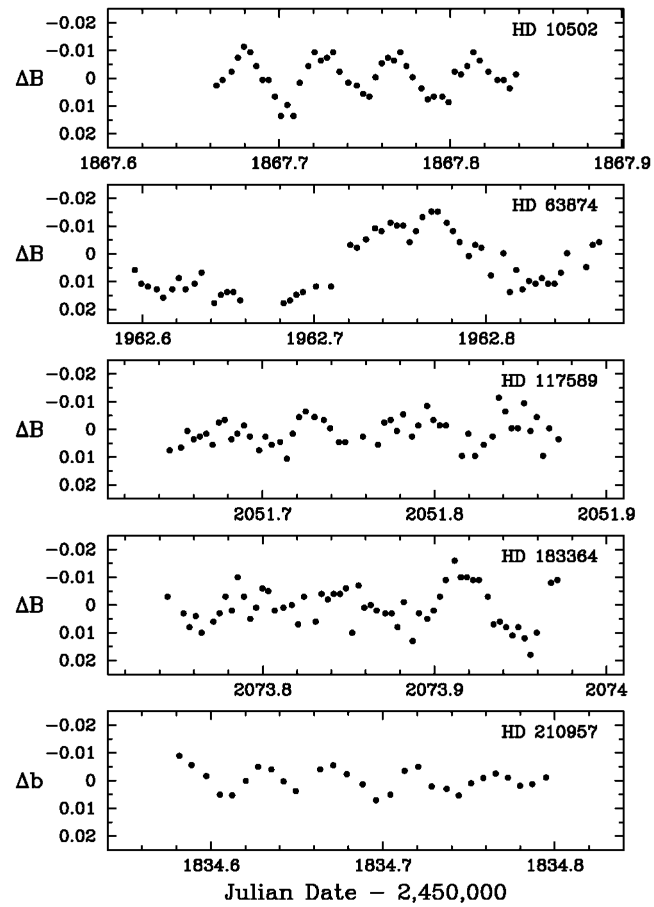

FIG. 1.—Differential Johnson *B* or Strömgren *b* photometric observations of each of the new δ Scuti stars acquired over several hours on a single night near each star's time of opposition. The differential magnitudes are computed relative to the mean brightness level for the night. All five panels are plotted to the same scale and show high-frequency, low-amplitude photometric variations typical of δ Scuti variables.

tively. The radial velocities of the two components are quite similar, −13.4 and −7.7 km s^{-1}, respectively.

Our Johnson *B* differential magnitudes for the night of JD 2,451,867 are shown in the top panel of Figure 1. Least-squares spectra of the complete *B* data set are given in Figure 3, and the results of the frequency analysis are listed in Table 4. We find only a single period of 0.0435787 day with a peak-to-peak amplitude of 10.5 mmag in *B*. The observations are phased with this period and the time of minimum from Table 4 and plotted in Figure 4.

3.2. HD 63874

Our red-wavelength spectrum of HD 63874 shows weak, very broad lines, making our analysis of its properties more uncertain (indicated by a colon after the appropriate value) than those of the other stars in our sample. We classified HD 63874 as an F1: star, while its *Hipparcos* parallax indicates that the star

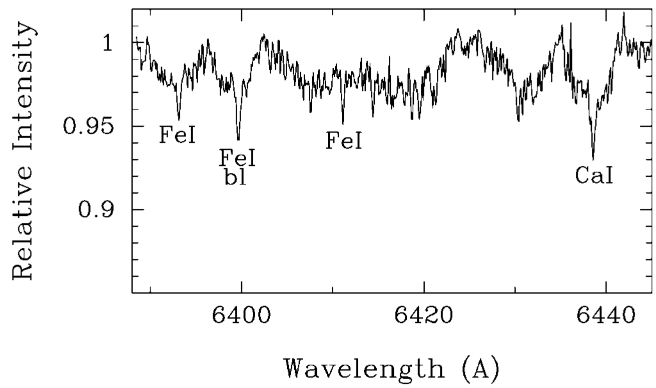

FIG. 2.—Portion of the red-wavelength spectrum of HD 10502, which shows the composite profiles of all the metal lines. We attribute the broad component to the photosphere and, following Mantegazza & Poretti (1996), ascribe the narrow component to a circumstellar shell or disk rather than a binary companion. 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.

is a giant. Its projected rotational velocity is 170: km s^{-1}. The lines in the 6430 Å region are so weak and blended that they do not produce a measurable cross-correlation peak. However, Duflot et al. (1990) determined a mean radial velocity of 11 ± 2.6 km s^{-1} from five observations.

Our Johnson *B* photometry for the night of JD 2,451,962 is shown in Figure 1 (*second panel*). We detect a single period of 0.184383 day in the complete data set (Figs. 5 and 6, Table 4). The amplitude in *B* is 15.4 mmag.

3.3. HD 117589

From our only spectrum, we found a spectral class of F1 for HD 117589, while its *Hipparcos* parallax indicates that it is a subgiant. The combined result is similar to the spectral type of F0 III found by Grenier et al. (1999). Our two velocities differ by 0.4 km s^{-1} and have an average of −16.8 km s^{-1}. This mean velocity agrees with the value of −17.9 ± 1.5 km s^{-1},

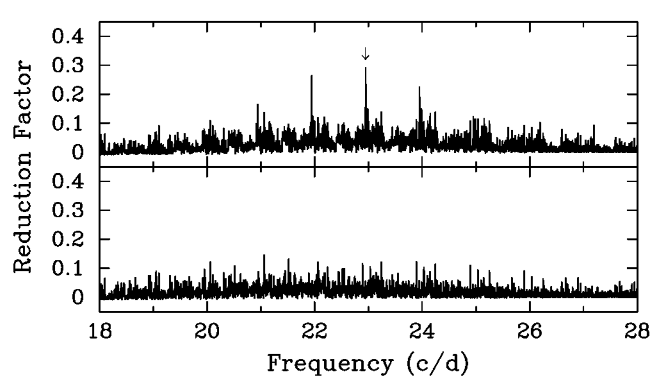

FIG. 3.—Least-squares spectra of the HD 10502 *B* data set. The arrow in the top panel indicates the single detected frequency at 22.9470 day^{-1}. The same frequency was confirmed in the *V* data set.

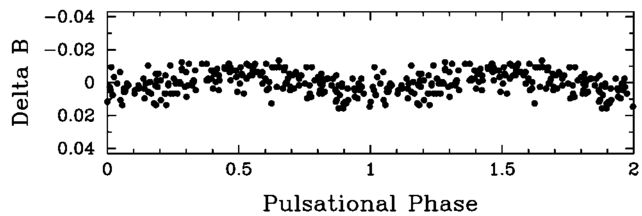

FIG. 4.—*B* photometric data for HD 10502, phased with the single frequency of 22.9470 day^{-1} and time of minimum from Table 4.

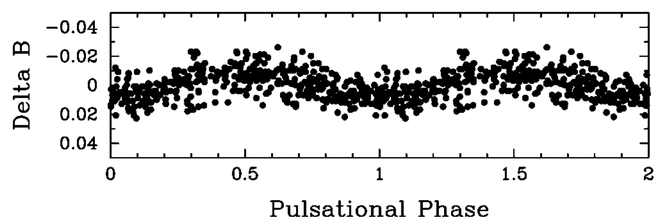

FIG. 6.—*B* photometric data for HD 63874, phased with the single frequency of 5.4235 day^{-1} and time of minimum from Table 4.

determined from three observations by Grenier et al. (1999). For HD 117589, we measured a $v \sin i$ of 70 km s^{-1}.

Our Johnson *B* photometry for the night of JD 2,452,051 is shown in Figure 1 (*third panel*). We find only a single period of 0.0623096 day in the complete *B* data set (Figs. 7 and 8, Table 4). The peak-to-peak amplitude in *B* is 4.8 mmag. Although the analysis of the *V* observations preferred the same period, the 1 day aliases are strong enough to render the identification of the true period somewhat uncertain. There is a suggestion of additional periodiodicity in the bottom panel of Figure 7, but we cannot confirm the same additional periods in both the *B* and *V* data sets and so do not list any further periods in Table 4.

3.4. HD 183364

We classified HD 183364 as an F1 star and determined a giant luminosity class from its *Hipparcos* parallax. These results are in agreement with the spectral type of F0 III found by Grenier et al. (1999). We determined a projected rotational velocity of 110 km s^{-1} and a radial velocity of 4.2 km s^{-1}. The latter value is similar to that of Grenier et al. (1999), who measured a velocity of -0.6 ± 3.6 km s^{-1} from three plates.

The Johnson *B* photometry for the night of JD 2,452,073 is shown in Figure 1 (*fourth panel*). We find the two periods 0.0640168 and 0.0677332 day in the complete data set (Figs. 9 and 10, Table 4). Both the *B* and the *V* data sets preferred these two periods, but the identification of the second one is somewhat ambiguous as a result of aliasing. The amplitudes of these two periods are 15.9 and 5.9 mmag, respectively. There is a suggestion of a third period in the bottom panel of Figure 9, but our analysis does not clearly prefer the same period in *B* and *V*, so we do not include it in Table 4.

3.5. HD 210957

We did not obtain a spectrum of HD 210957. Moore & Paddock (1950) classified the star as A9 IV and determined a radial velocity of 5 ± 8.5 km s^{-1} from two spectra. This velocity is consistent with a value of 0 ± 3.5 km s^{-1} measured by Fehrenbach & Burnage (1982) from six observations.

The Strömgren *b* photometry for the night of JD 2,451,834 is shown in the bottom panel of Figure 1. We find three periods of 0.0441427, 0.0522155, and 0.0468960 day in the complete *b* data set (Figs. 11 and 12, Table 4). The *y* data set also preferred these same three periods, but the identifications of the true periods are still somewhat ambiguous because of aliasing. The amplitudes of the three periods are 4.9, 3.2, and 2.6 mmag, respectively.

4. DISCUSSION

Table 5 lists some of the physical properties of the five new δ Scuti stars. The mean unreddened $(B-V)_0$ color indices, ab-

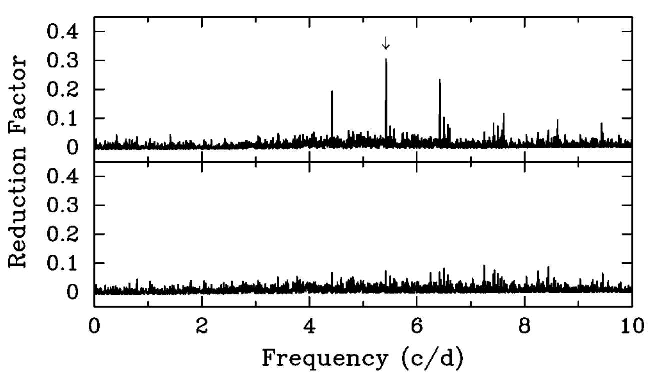

FIG. 5.—Least-squares spectra of the HD 63874 *B* data set. The arrow in the top panel indicates the single detected frequency at 5.4235 day^{-1}. The same frequency was confirmed in the *V* data set.

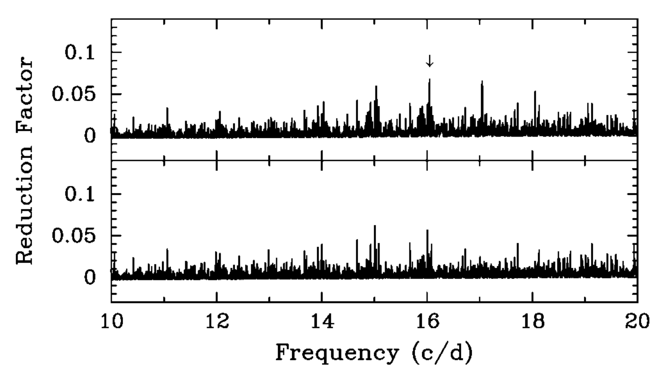

FIG. 7.—Least-squares spectra of the HD 117589 *B* data set. The arrow in the top panel indicates the single detected frequency at 16.0489 day^{-1}. The same frequency was confirmed in the *V* data set.

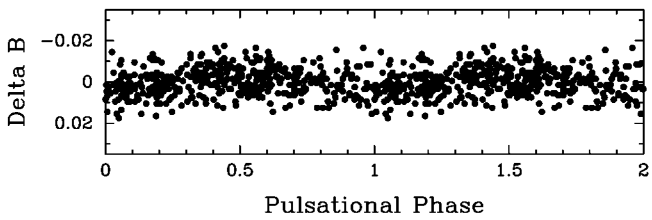

FIG. 8.—*B* photometric data for HD 117589, phased with the single frequency of 16.0489 day^{-1} and time of minimum from Table 4.

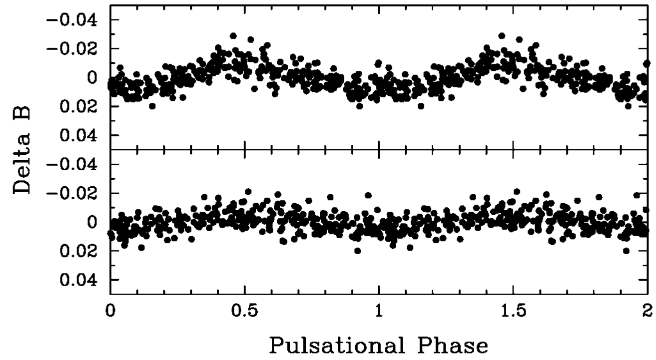

FIG. 10.—*B* photometric data for HD 183364, phased with the two frequencies and times of minimum from Table 4. The two frequencies are 15.6209 day^{-1} (*top*) and 14.7638 day^{-1} (*bottom*). For each panel, the data set has been prewhitened to remove the other known frequency.

solute magnitudes, luminosities, and radii in columns (2)–(5) were computed from the *Hipparcos* mean magnitudes, mean apparent color indices, and parallaxes (ESA 1997) with the procedure outlined in Henry et al. (2001). The five stars are also plotted in the H-R diagram in Figure 13. They cover a 1.5 mag range in absolute magnitude, but all lie comfortably within the δ Scuti instability strip.

The majority of all δ Scuti variables are Population I objects pulsating in nonradial *p* modes with low amplitudes (Breger 2000). The catalog of Rodríguez et al. (2000) shows that nearly 30% of known δ Scuti stars have amplitudes smaller than 0.02 mag, implying that many more low-amplitude variables are yet to be discovered. The five new δ Scuti stars in this paper all have amplitudes below this limit. We obtained spectra of four of the five stars, and the best fits to these spectra occurred with comparison stars having solar or greater than solar iron abundances. We computed Galactic space-velocity components for all five stars, and none of the stars is a high-velocity object. Clearly, these five new variables belong to the most common group of low-amplitude variables and not to the high-amplitude δ Scuti stars (HADS) or the Population II SX Phe subgroups (Breger 2000). As seen in Figure 5 of Rodríguez et al. (2000), the high-amplitude stars have low rotational velocities ($v \sin i < 20$ km s^{-1}), while the low-amplitude stars rotate much more rapidly. The four low-amplitude stars in this paper for which we have spectra all have $v \sin i$ values of 70 km s^{-1} or greater and so support this trend.

We thank Lou Boyd and Don Epand for their support of the

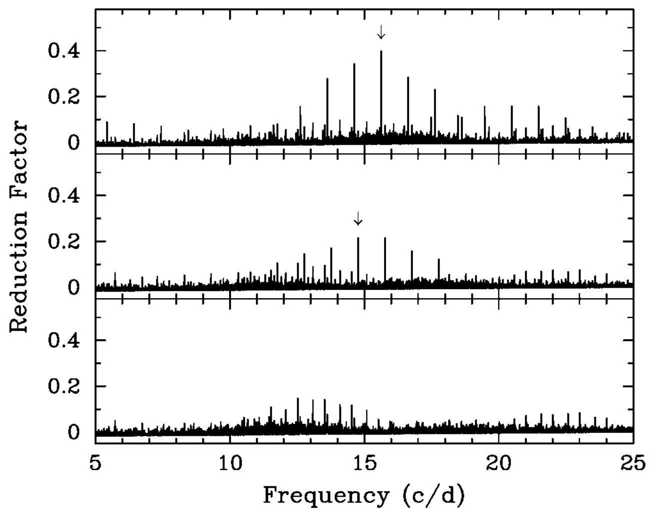

FIG. 9.—Least-squares spectra of the HD 183364 *B* data set, showing the results of progressively fixing the two detected frequencies. The arrows indicate the two frequencies at 15.6209 day^{-1} (*top*) and 14.7638 day^{-1} (*middle*). Both frequencies were confirmed in the *V* data set.

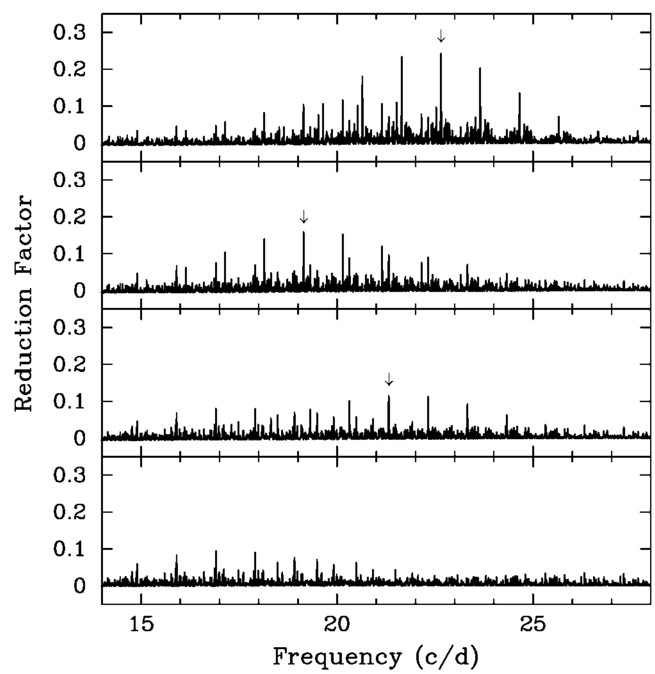

FIG. 11.—Least-squares spectra of the HD 210957 *b* data set, showing the results of progressively fixing the three detected frequencies. The arrows indicate the three frequencies (*top to bottom*): 22.6538, 19.1514, and 21.3238 day^{-1}. All three frequencies were confirmed in the *y* data set.

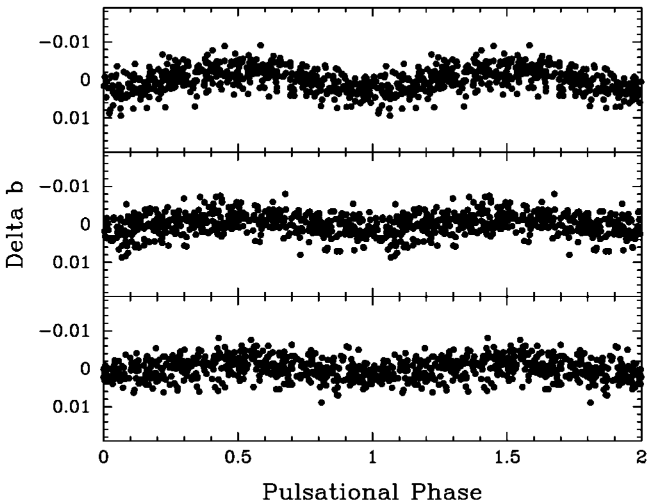

FIG. 12.—*b* photometric data for HD 210957, phased with the three frequencies and times of minimum from Table 4. *Top to bottom:* Frequencies are 22.6538, 19.1514, and 21.3238 day^{-1}. For each panel, the data set has been prewhitened to remove the other two known frequencies.

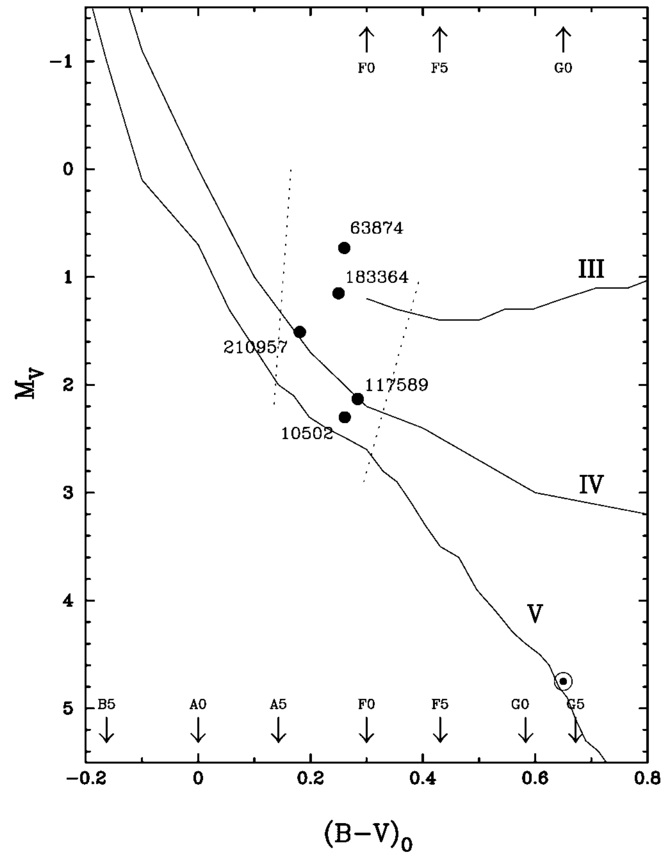

FIG. 13.—Five new δ Scuti variables from this paper plotted in the H-R diagram. The dotted lines indicate the boundaries of the δ Scuti instability strip. The Sun's position is shown at lower right.

TABLE 5
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)
10502	0.261	2.30	9.2	1.8
63874	0.260	0.73	39.2	3.8
117589	0.284	2.13	10.8	2.1
183364	0.250	1.15	26.6	3.1
210957	0.181	1.51	19.3	2.4

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