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ABSTRACT

We obtained high-resolution spectroscopic observations of 34 γ Doradus candidates. From the red-wavelength spectra, we determined spectral classes, radial velocities, and projected rotational velocities. The spectra of seven late A or early F stars show metallic lines that have composite profiles consisting of a narrow component near the center of a broad line, indicating that they may be shell stars or binaries. Several stars, including HD 152896, HD 173977, HD 175337, and HD 195068/9, show large line profile asymmetries. Two stars, HD 11443 (=α Trianguli) and HD 149420, are ellipsoidal variables and not γ Doradus stars. The percentage of binary systems in our sample may be as high as 74%.

Key words: binaries: general — circumstellar matter — stars: fundamental parameters — stars: variables: other

1. INTRODUCTION

The γ Doradus stars have recently been recognized as a new type of variable stars. On the basis of the properties of 13 γ Doradus variables, Kaye et al. (1999) defined this class. Objects identified so far have periods ranging from about 0.3 to 3.0 days, and most have multiple photometric periods. The photometric amplitudes range up to ~0.1 mag in Johnson *V*. The stars generally have late A or early F spectral classes and are dwarfs or subgiants. Line profile changes, resulting in radial velocity variations of 2–4 km s^{-1}, have been documented in several stars (e.g., Krisciunas et al. 1995; Balona et al. 1996; Aerts & Kaye 2001). The light and line profile variations most likely result from nonradial, *g*-mode pulsations of high-order (*n*) and low spherical degree (*l*) (Kaye et al. 1999). Guzik et al. (2000) developed the first models of a driving mechanism for these gravity-mode pulsations.

To date, only 30 stars have been confirmed as γ Doradus variables (Henry & Fekel 2002a). Thus, the full range of properties of this class and the boundaries of the region in the H-R diagram where the members reside are still being determined. While many γ Doradus stars have been discovered serendipitously (e.g., Zerbi 2000; Henry et al. 2001), several groups, including Paunzen & Maitzen (1998), Aerts, Eyer, & Kestens (1998), and Handler (1999), have systematically searched the *Hipparcos* photometry database and identified a significant number of probable and possible members. To broaden our knowledge of the basic properties of the stars that make up this class of variables, we have undertaken a spectroscopic survey of a subset of stars from several candidate lists.

2. THE SAMPLE

Our sample consists of 34 stars previously identified as probable or possible γ Doradus variables. Table 1 summarizes some of their basic information. The *V* magnitudes, $B-V$ color indices, and parallaxes are taken from the *Hipparcos* catalog (ESA 1997). Spectral types from the literature are also listed. The last column provides the source that identified the star as a possible γ Doradus variable. Most of our sample, 29 stars, come from the two lists of Handler (1999). From his analysis of *Hipparcos* photometry (ESA 1997), he identified 46 A and F stars, which he called prime γ Doradus candidates, that had multiple periods in the appropriate period range. He also presented a second group of 36 less likely candidates. In addition, we have observed five stars that were suggested by other sources as possible γ Doradus variables. Recently, using additional photometry Henry et al. (2001), Handler & Shobbrook (2002), Henry & Fekel (2002a), and G. Henry (2002, private communication) have confirmed 15 of the 34 stars in our sample as γ Doradus variables. This strongly suggests that most of our program stars will prove to be γ Doradus variables once additional ground-based photometry is obtained.

3. SPECTROSCOPY

3.1. *Observations*

From 1993 April to 2002 April, we collected high-resolution spectrograms of our 34 program stars. However,

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TABLE 1
BASIC PROPERTIES OF THE γ DORADUS CANDIDATES

HD	Other Names	V^a (mag)	$B-V^a$ (mag)	Spectral Type	*Hipparcos* Parallax[a]	Candidate Source
277	...	8.37	0.379	...	0.00973	1
2842	...	7.99	0.325	F0 V	0.00930	1
7169	...	7.30	0.380	F2 V	0.01294	1
9365	...	8.17	0.361	...	0.00830	1
11443	HR 544, α Tri	3.42	0.488	F6 IV	0.05087	2
23874	...	8.20	0.400	...	0.00697	1
86358	HR 3936	6.48	0.362	F2 V	0.01498	1
100215	...	7.99	0.323	A7 V	0.00924	1
105085	...	7.49	0.360	F2 IV–V	0.01111	3
105458	...	7.77	0.299	F0 III	0.01032	1
112429	HR 4916, IR Dra	5.23	0.303	F0 IV–V	0.03467	1, 2
113867	...	6.83	0.313	...	0.01060	1
115466	LP Vir	6.89	0.338	...	0.01261	1
122300	...	8.18	0.407	...	0.00613	4
124248	MU Vir	7.15	0.333	dA8	0.01527	1
126516	...	8.29	0.456	F3 V	0.00882	4
130173	...	6.87	0.409	F3 V	0.01119	5
149420	32 Her	6.87	0.242	A9 IV	0.00663	6
152896	V645 Her	7.55	0.314	A8 IV	0.01149	1
155154	HR 6379	6.17	0.306	A9 V	0.02226	1
160295	V2381 Oph	7.71	0.413	...	0.00799	1
167858	HR 6844, V2502 Oph	6.62	0.312	F1 V	0.01598	1, 2, 6
171244	...	7.75	0.397	F3 IV	0.00727	1
173977	HN Dra	8.12	0.354	...	0.00525	1
175337	...	7.39	0.364	...	0.01185	1
187615	...	7.95	0.300	...	0.00949	4
195068/9	HR 7828, V2121 Cyg	5.73	0.339	F2 V	0.02656	1, 3
197451	...	7.19	0.353	F2 Vp	0.00596	4
201985	...	7.95	0.319	...	0.00850	4
202444	HR 8130, τ Cyg	3.74	0.393	F2 IV	0.04780	7
206043	HR 8276, NZ Peg	5.77	0.314	F0 V	0.02557	1, 3
207651	...	7.21	0.236	...	0.00296	4
213617	HR 8586	6.43	0.350	F2 V	0.01890	4
221866	...	7.46	0.286	...	0.00845	1

[a] *Hipparcos* Catalog (ESA 1997).

REFERENCES.—(1) Table 1 of Handler 1999; (2) Aerts et al. 1998; (3) Eyer 1998; (4) Table 2 of Handler 1999; (5) Paparó et al. 1990; (6) Paunzen & Maitzen 1998; (7) Pant et al. 1968.

most of the observations were made during a single observing run in 2000 July. The spectrograms were obtained with the Kitt Peak National Observatory (KPNO) coudé feed telescope, coudé spectrograph, and a TI CCD detector. The vast majority of the KPNO spectrograms are centered in the red at 6430 Å, cover a wavelength range of about 80 Å, and have a resolution of 0.21 Å. In addition, three observations were obtained in a blue-wavelength region centered at 4500 Å. Those spectra have the same wavelength range and resolution as the ones obtained at red wavelengths. Both the blue- and red-wavelength spectra have typical signal-to-noise ratios between 150 and 200.

3.2. *Radial Velocities*

For the red-wavelength spectra, radial velocities were determined in the 6385–6444 Å region with the IRAF[2] cross-correlation program FXCOR (Fitzpatrick 1993). The IAU radial velocity standards β Vir, HR 5694, HR 7560, and ι Psc were used as reference stars. Their velocities of 4.4, 54.4, 0.0, and 5.6 km s^{-1}, respectively, were adopted from Scarfe, Batten, & Fletcher (1990). The blue-wavelength spectra were measured relative to 68 Tau, which has a radial velocity of 39.0 km s^{-1} (Fekel 1999). 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, a fit was used that gave greater weight to the points in the wings of the peak than to those in the central portion to approximate better the star's velocity. Velocities of doubled-lined binaries, observed at phases when the lines are blended, were measured by fitting two Gaussians to the asymmetric cross-correlation peak.

Our radial velocities, which are mean values if more than one observation was made, are listed in Table 2. If our observations show obvious velocity variability for a star, that result is noted instead. Individual velocities that have not previously been published are given in Table 3. Listed are the HD number, Heliocentric Julian Date of mid observation, and radial velocity. A colon indicates a velocity that is more uncertain than usual. The final column provides comments about our observations. Included in those notes are the identity of the component if the spectrum shows two

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

TABLE 2

RESULTS FOR THE γ DORADUS CANDIDATES

HD	Comp.[a]	M_v (mag)	R ($R_\odot$)	Spectral Class	Luminosity Class[b]	$v \sin i$ (km s^{-1})	Velocity (km s^{-1})	Summary Comments[c]
277	...	3.31	1.4	F2	Dwarf	38	−4.6	H01, G, Am star
2842	...	2.83	1.6	F1	Dwarf	90	8.5	...
7169	BL	2.99	1.6	F2	Dwarf	90	−9.2	CS
	NL	...	...	...	...	8	−18.8	...
9365	...	2.77	1.7	F1	Dwarf	80	−6.5	SB1[d]
11443	...	1.95	3.0	F6	Subgiant/Giant	85	−20.4	SB1,[e] E
23874	BL	2.70	1.9	F2	Dwarf	95	−25.1:	CS
	NL	...	...	...	...	8:	−18.2	...
86358	A	2.76	1.7	F0	Dwarf	25	Variable	SB2
	B	...	...	F5:	Dwarf	30:	Variable	...
100215	A	2.95	1.5	F1	Dwarf	25	Variable	SB2
	B	...	...	G0:	Dwarf	15:	Variable	...
105085	BL	2.91	1.6	F1	Dwarf	60	−1.6	CS, P
	NL	...	...	...	...	10:	1.7	...
105458	...	2.84	1.5	F2	Dwarf	40	−11.4	H01, G
112429	...	2.93	1.5	F1	Dwarf	115	8.2	...
113867	BL	2.51	1.8	A9	Dwarf	120	11.5	CS
	NL	...	...	...	...	10	8.8	...
115466	...	2.39	2.0	F1	Subgiant	44	12.5	...
122300	A	2.24	2.4	F1	Subgiant	10.4	Variable	SB2
	B	...	...	F8:	Dwarf	5:	Variable	...
124248	...	3.07	1.4	A9	Dwarf	48	−1.7	...
126516	...	3.02	1.8	F5	Dwarf/Subgiant	4.1	Variable	SB1
130173	...	2.11	2.5	F2	Subgiant	60	−18.1	V
149420	A	1.14	3.1	A9	Giant	35	Variable	SB2, E
152896	...	2.85	1.5	F1	Dwarf	49	−0.4	P
155154	...	2.91	1.5	F1:	Dwarf	180:	69.7::	H01, G, V
160295	BL	2.40	2.2	F2	Subgiant	70	−41.8	CS
	NL	...	...	...	...	7	−42.7	...
167858	...	2.64	1.7	F1	Dwarf	8.0	Variable	SB1, G
171244	...	2.06	2.5	F2	Subgiant	47	−13.5	V
173977	...	1.72	2.8	F1	Subgiant/Giant	75	Variable	SB1, P, E?
175337	...	2.76	1.7	F2	Dwarf	38	−2.2	P
187615	...	2.84	1.5	F1	Dwarf	80	8.3	...
195068/9	...	2.85	1.6	F1:	Dwarf	44	−29.6	P, V
197451	...	1.07	3.7	F2:	Giant	24	22.0	SB1,[f] Ap star
201985	...	2.60	1.8	F0	Dwarf	10	−57.9	...
202444	BL	2.23	2.3	F2	Subgiant	95	−22.5	CS
	NL	...	...	...	...	6	−19.8	...
206043	...	2.81	1.6	F2	Dwarf	140	−15.2:	H01, G
207651	BL	−0.12	5.4	A9	Giant	95	−24.4:	CS
	NL	...	...	...	...	6	−20.7	...
213617	...	2.81	1.7	F1	Dwarf	70	−12.1	V
221866	A	2.43	1.8	A8:m	Dwarf	19:	Variable	SB2,[g] G, Am star
	B	...	...	F3:	Dwarf	11:	Variable	...

[a] Components: (BL) broad lined, (NL) narrow lined, (A) primary, and (B) secondary.

[b] Derived from the *Hipparcos* parallax (ESA 1997) and resulting absolute visual magnitude.

[c] (H01) Henry et al. 2001; (G) confirmed γ Doradus variable; (CS) composite spectrum, possible shell star or binary; (E) ellipsoidal variable; (SB1) single-lined spectroscopic binary; (SB2) double-lined spectroscopic binary; (V) possible spectroscopic binary; (P) line profile asymmetries from pulsation or blended SB2.

[d] Liu et al. 1989.

[e] Harper 1915.

[f] Grenier et al. 1999.

[g] Kaye et al. 2003.

sets of lines and the wavelength region of the spectrum if it was not taken at 6430 Å. Spectra with significant line asymmetries are also identified.

For the more slowly rotating stars (i.e., for $v \sin i \leq 60$ km s^{-1}), the individual radial velocities generally have uncertainties of 0.5–1.0 km s^{-1}. For those stars with lines broader than 60 km s^{-1}, only one or two of the least blended 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 greater velocity uncertainties, which are estimated to be 2–3 km s^{-1}. Stellar pulsations and component line blending can produce asymmetric line profiles that will increase the velocity uncertainty. Measurement difficulties for stars with composite line profiles may also result in greater velocity uncertainty for the broad-lined component.

TABLE 3

INDIVIDUAL RADIAL VELOCITIES

HD	Date (HJD −2,400,000)	Radial Velocity[a] (km s^{-1})	Comments
2842	51,741.945	8.6	
	51,742.947	8.4	
7169	51,740.956	−11.1	Composite spectrum, broad comp.
		−17.9	Narrow comp.
	51,742.974	−7.4	Broad comp.
		−19.6	Narrow comp.
9365	51,741.977	−6.5	
11443	51,741.995	−20.3	
	51,741.996	−20.6	
23874	51,806.017	−25.1:	Composite spectrum, broad comp.
		−18.2	Narrow comp.
86358	51,734.635	41.0	SB2, primary
		3.3:	Secondary
	51,735.637	47.0	Primary
		−2.0	Secondary
	52,329.782	11.1	4500 Å, primary
		73.9	Secondary
100215	51,734.657	−22.3	SB2, single lined
	51,738.657	−32.7	Primary
		11.7	Secondary
105085	51,738.638	−2.5	Composite spectrum, broad comp.
		0.3	Narrow comp.
	52,328.936	−1.3:	Broad comp., very asymmetric
		2.2	Narrow comp.
	52,329.830	0.5	4500 Å, broad comp.
	52,392.772	−3.2	Broad comp.
		2.5	Narrow comp.
112429	51,737.634	6.3	
	51,742.662	9.5	
113867	51,737.686	6.4:	Composite spectrum, broad comp.
		9.1	Narrow comp.
	51,740.643	1.7:	Broad comp.
		9.0	Narrow comp.
	51,742.677	6.1:	Broad comp.
		8.3	Narrow comp.
	52,329.874	11.5	4500 Å, broad comp.
		3.8	Narrow comp.
115466	51,740.675	12.5	
122300	51,737.716	15.8	SB2, primary
		−25.4	Secondary
	51,738.747	−18.5	Primary
	52,014.825	0.3	Primary
	52,015.866	13.7	Primary
	52,016.862	7.7	Primary
124248	51,737.662	−1.7	
126516	51,738.711	7.4	SB1
	51,742.707	12.9	
	52,015.846	−58.8	
	52,016.910	3.3	
130173	51,737.740	−18.0	
	51,740.693	−18.2	
149420	51,736.727	9.3	SB2, primary
		−61.6	Secondary
	51,742.788	54.3	Primary
		−150.8	Secondary
152896	51,734.783	−0.9	Asymmetric lines
	51,740.725	0.1	
	51,742.743	−7.5:	Very asymmetric lines

TABLE 3—*Continued*

HD	Date (HJD −2,400,000)	Radial Velocity[a] (km s^{-1})	Comments
160295	51,734.830	−45.7	Composite spectrum, broad comp.
		−41.6	Narrow comp.
	51,735.778	−43.0	Broad comp.
		−42.2	Narrow comp.
	51,742.768	−40.6	Broad comp.
		−42.4	Narrow comp.
	52,392.966	−37.9	Broad comp.
		−44.5	Narrow comp.
171244	51,736.815	−13.8	
	51,740.832	−13.2	
173977	51,737.839	−14.6:	SB1, very asymmetric lines
	51,742.846	−105.1	
175337	51,735.802	−4.0:	Very asymmetric lines
	51,740.862	−0.4	Asymmetric lines
	51,742.821	−2.3	Asymmetric lines
187615	51,737.879	8.3	
195068/9.............	51,737.767	−30.3	Very asymmetric lines
	51,740.905	−28.9	Very asymmetric lines
197451	51,737.791	22.0	
201985	51,737.946	−57.9	
202444	51,737.811	−22.4	Composite spectrum, broad comp.
		−19.9	Narrow comp.
	51,740.910	−22.6	Broad comp.
		−19.7	Narrow comp.
207651	51,737.902	−24.4:	Composite spectrum, broad comp.
		−20.7	Narrow comp.
213617	51,737.924	−12.1	
221866	51,737.966	0.4	SB2, primary
		−29.5	Secondary
	51,740.890	0.0	Primary
		−30.9	Secondary
	51,740.933	0.5	Primary
		−30.7	Secondary
	51,741.916	2.4	Primary
		−28.5	Secondary
	51,742.880	1.6	Primary
		−27.4	Secondary

[a] A colon (:) indicates increased uncertainty.

3.3. *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 stars, as well as early and mid F stars, mostly 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 2). 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 from our spectra the luminosity classes of the program stars. Instead, these are determined from the absolute visual magnitudes computed with *Hipparcos* magnitudes and parallaxes (ESA 1997). Twenty stars in our sample have spectral classes in the literature, and our results differ on average by one subclass.

For the stars with composite spectra, spectrum addition of two reference-star spectra produced a best fit to each program star spectrum and resulted in a continuum magnitude difference with an uncertainty estimated to be 0.2–0.4 mag. If the two sets of lines represent binary components, the continuum intensity ratio gives a minimum magnitude difference when the secondary is a star of later spectral class.

3.4. *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 full width at half-maximum 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. For A-type stars, the line broadening corresponds to the $v \sin i$ value. For F-type stars, macroturbulent broadening must be taken into account. Following Fekel (1997), for early F stars a macroturbulence of 5 km s^{-1} was adopted and removed, while for mid F stars 4 km s^{-1} was used. We estimate uncertainties of 1 and 3 km s^{-1} for $v \sin i$ values near 20 and 50 km s^{-1}, respectively.

Since the calibration polynomial is based only on broadening values up to 50 km s^{-1}, a second method was used to determine the projected rotational velocities of stars with broader absorption lines. For these program stars, the spectrum of a slowly rotating reference star of similar spectral class was rotationally broadened with the program of Huenemoerder & Barden (1984) and Barden (1985). Reference-star spectra with different rotational broadenings were compared with each program star spectrum, and the best $v \sin i$ match was adopted. A similar procedure was used for stars with composite spectra. We estimate uncertainties of 5 and 10 km s^{-1} for $v \sin i$ values near 75 and 125 km s^{-1}, respectively. For stars with projected rotational velocities in the range 40–60 km s^{-1}, the two methods produced essentially identical results. Our projected rotational velocities are listed in Table 2. A colon indicates a value with greater than normal uncertainty.

4. RESULTS FOR INDIVIDUAL STARS

Our results for the individual program stars are discussed below, compared with previous results found in the literature, and summarized in Table 2. That table identifies the appropriate component, if two sets of lines are seen in the spectrum. In the case of the stars with composite spectra, the two components are identified as broad lined and narrow lined, since the components may or may not correspond to two different stars. Absolute magnitudes were determined from the *Hipparcos* parallaxes (ESA 1997). When two sets of spectral lines were seen, a magnitude difference was determined and a correction was applied to the apparent magnitude of the primary before computing its absolute magnitude. Because the stars are generally within 125 pc of the Sun, no correction for interstellar extinction has been made. The $B-V$ color index from the *Hipparcos* catalog (ESA 1997) was used in conjunction with Table 3 of Flower (1996) to obtain a bolometric correction and effective temperature, which led to the stellar radius. The absolute magnitude and radius then were compared with canonical tables of basic properties (Gray 1992; Allen 1976) to determine a luminosity class. Our spectral class, projected rotational velocity, and mean velocity for each star are also listed. In cases where our observations alone indicate that the velocity is variable, this conclusion rather than a mean velocity is given. The final column provides summary comments that include duplicity status, the identification of stars with line profile asymmetries or composite spectra, and the source of the data if it is not from the current paper. Confirmed γ Doradus variables are also noted.

In the following individual star discussions, two different possibilities often have been considered for the nature of stars. For example, some variables have line profile asymmetries that result from either pulsation or duplicity. In addition, seven stars have composite spectra with absorption components that correspond to either a binary or a metallic shell star. Thus, additional spectroscopic observations will be necessary to identify the correct alternative in such cases.

4.1. *HD 277*

Handler (1999) included HD 277 in his list of stars that are likely to be γ Doradus variables. Kaye, Gray, & Griffin (2003) classified it as a mild Am star. Follow-up observations by Henry et al. (2001) confirmed that HD 277 is indeed a γ Doradus variable. Our spectroscopic observations were presented in that paper and are given in Table 2 for the sake of completeness.

4.2. *HD 2842*

Handler (1999) identified HD 2842 as a prime γ Doradus candidate. From our red-wavelength spectra, we found a spectral class of F1; its *Hipparcos* (ESA 1997) parallax indicates that it is a dwarf. These results are similar to the F0 V spectral type of Paunzen et al. (2001). We determined $v \sin i = 90$ km s^{-1}. From two observations taken 1 day apart, the star has a constant velocity of 8.5 km s^{-1}.

4.3. *HD 7169* (=*HDS 160*)

Handler (1999) concluded that HD 7169 is a prime γ Doradus candidate. It was recently identified as a visual double star by *Hipparcos* (ESA 1997) and given the designation HDS 160. It is not surprising that its duplicity was missed by ground-based observers, since the stars have a projected separation of only 0″.2 and have a large magnitude difference of about 2.3 (ESA 1997).

Our red-wavelength spectra of HD 7169 show that each metal absorption line consists of a combination of a broad component and a narrow absorption feature near its center (Fig. 1). Although the star is a close visual binary, its large magnitude difference appears inconsistent with the relative strength of the broad and narrow components seen in our spectra, which corresponds to a continuum magnitude difference of about 1.5 mag. In addition, the broad and narrow lines have a velocity difference of about 10 km s^{-1} (Table 3), rather large if the components correspond to the visual pair,

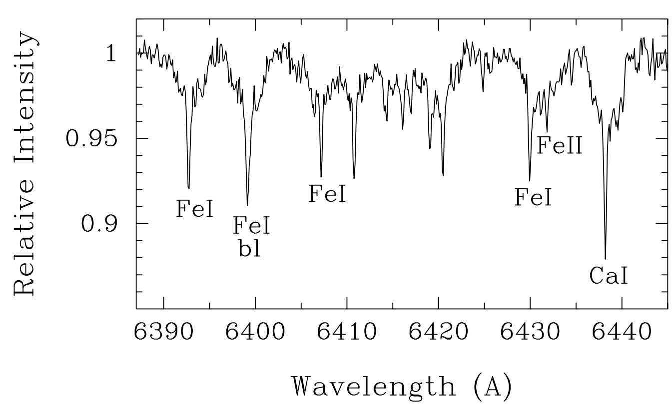

FIG. 1.—Portion of the red-wavelength spectrum of HD 7169 that shows the composite profiles of the metal lines. The broad and narrow sets of lines may be attributed to the stellar photosphere and a circumstellar shell, respectively, if the star is a metallic shell star, or alternatively, may correspond to two different stellar components. 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.

which currently have a projected separation of about 15 AU.

While duplicity remains a possible explanation for the composite spectrum of HD 7169, Mantegazza & Poretti (1996) found composite absorption line profiles in the δ Scuti variable X Caeli and concluded that the narrow lines resulted from a circumstellar shell. Thus, the broad lines of HD 7169 might correspond to the photosphere of the primary component and the relatively strong, narrow lines to a shell surrounding the primary. In such a model, the lines of the visual secondary would be too faint to be detected.

We determined a spectral class of F2 for the broad-lined component and found a dwarf luminosity class from the *Hipparcos* parallax. The spectrum of the narrow lines can be fitted with the spectrum of a star that has a similar or somewhat later spectral class. Our results agree with the F2 V classification of Fehrenbach et al. (1987), but Grenier et al. (1999) gave a rather different type of A9 IV–III. Our $v \sin i$ values for the broad- and narrow-lined components are 90 and 8 km s^{-1}, respectively. From two spectra, our radial velocity for the narrow lines is -18.8 km s^{-1}, while the velocity of the broad lines is -9.2 km s^{-1}. Previously measured radial velocities of -14.3 ± 1.6 km s^{-1} (Fehrenbach et al. 1987) and -16.9 ± 0.6 km s^{-1} (Grenier et al. 1999) are in better agreement with our velocity of the narrow rather than the broad-lined component.

4.4. *HD 9365*

HD 9365 is another star considered to be a prime γ Doradus candidate by Handler (1999). It lies in the field of the open cluster NGC 581 but is a nonmember (Steppe 1974). We classified the star as F1, and its *Hipparcos* parallax indicates that it is a dwarf. HD 9365 has a moderate projected rotational velocity of 80 km s^{-1}. Our lone spectrum has a radial velocity of -6.5 km s^{-1}. From four observations, Liu, Janes, & Bania (1989) found a mean velocity of -11.6 km s^{-1} and a velocity range of 43 km s^{-1} and called it a spectroscopic binary.

4.5. *HD 11443* (=*HR 544* = α *Trianguli*)

This bright star is a short-period, single-lined spectroscopic binary. However, its rapid rotation makes precise velocity measurement difficult. Harper (1915) determined an orbital period of 1.73652 days, which with 20 additional velocities was revised by Abt & Levy (1976) to 1.73645 days. Pike, Lloyd, & Stickland (1978) produced an orbit with a slightly longer period of 1.767 ± 0.009 days, but their 16 observations cover only a 5 day interval.

Using photometry in the *Hipparcos* database (ESA 1997), Aerts et al. (1998) identified HD 11443 as a γ Doradus candidate. They found two photometric periods, 0.8682 and 0.9494 days, but noted that in their Scargle periodograms the two frequency peaks had the smallest amplitudes of any of their γ Doradus candidates.

HD 11443 is a standard with an F6 IV spectral type (Johnson & Morgan 1953). We found that in the 6430 Å region, its spectrum is intermediate between spectral classes F5 and F8, in agreement with the standard type. Its *Hipparcos* parallax results in a subgiant/giant luminosity class. We determined a $v \sin i$ value of 85 km s^{-1}, which is in reasonable agreement with values of 90: and 100 km s^{-1} obtained by de Medeiros, do Nascimento, & Mayor (1997) and Balachandran (1990), respectively. Our radial velocity of -20.4 km s^{-1}, from two spectra taken on the same night, is in excellent agreement with the Abt & Levy (1976) center-of-mass velocity of -20.0 km s^{-1}.

HD 11443 is a rapidly rotating subgiant with a radius of 3.0 $R_\odot$ (Table 2). Because the star is a short-period binary, we assume that the primary star is synchronously rotating and also that the rotational and orbital axes are parallel. Thus, the primary has an equatorial rotational velocity of 87 km s^{-1}, very similar to our $v \sin i$ value of 85 km s^{-1}. These properties indicate that the primary should have ellipsoidal light variations. The strongest periodic signal found by Aerts et al. (1998) is exactly one-half of the spectroscopic period of Abt & Levy (1976). The power in the second frequency peak detected by Aerts et al. (1998) is extremely weak and likely not real. We conclude that the light variations seen in HD 11443 result from ellipticity rather than γ Doradus pulsations.

4.6. *HD 23874* (=*ADS 2785 AB*)

HD 23874 is a close visual binary with a current projected separation of $\sim$0."3 (Hartkopf et al. 1997). From observations obtained with the Tycho instrument of *Hipparcos*, Fabricius & Makarov (2000) determined a magnitude difference of about 1.4 mag. With the formulae in Volume 1 of the *Hipparcos* and Tycho catalogs (ESA 1997), we found $\Delta V = 1.45$ mag. Our only red-wavelength spectrum of HD 23874 shows that the metal absorption lines consist of a combination of a broad component and a narrow absorption component near its center (Fig. 2).

We classified the broad-lined component as F2, and the *Hipparcos* parallax indicates that it is a dwarf. The narrow-lined component has a somewhat later spectral class of F5:. The continuum magnitude difference is about 1.5 mag, in agreement with the result from *Hipparcos* if the broad and narrow components correspond to components A and B of the visual pair, respectively. The $B-V$ colors of the visual pair, computed from the values of Fabricius & Makarov (2000), are 0.42 for A and 0.31 for B and correspond to spectral types of F5 V and F0 V (Gray 1992), respectively. Thus, according to the colors, the fainter, narrow-lined star in our spectrum should have an *earlier* rather than a later spectral class, a puzzling situation.

Based on the available information, the correct interpretation of the composite spectrum remains uncertain. Perhaps the broad- and narrow-lined components seen in our spectrum do indeed correspond to the two components

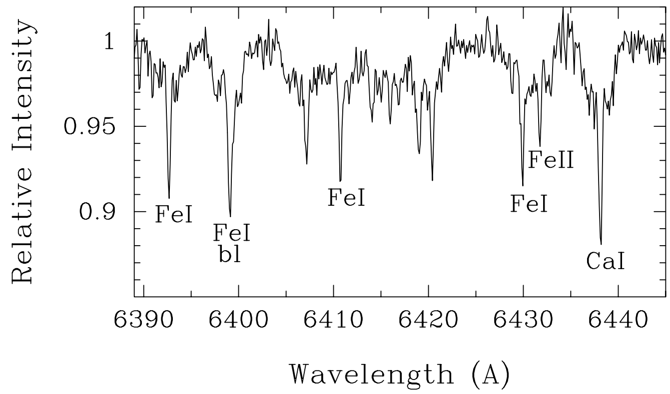

FIG. 2.—Same as Fig. 1, but for HD 23874

of the visual binary. Alternatively, given the similarity of its spectrum to other composite-spectrum stars in our sample, for which no previous evidence of duplicity has been found, it is possible that the visual components of HD 23874 both have broad lines, and the narrow component seen in our spectrum results from a shell.

Measurement of a single broad line resulted in a radial velocity of -25.1: km s^{-1}. The narrow component has a velocity of -18.2 km s^{-1}. Our projected rotational velocities are 95 and 8 km s^{-1}.

4.7. *HD 86358* (=*HR 3936*)

Handler (1999) listed HD 86358 as a prime γ Doradus candidate. Our two red-wavelength spectra obtained on consecutive nights both show relatively narrow line profiles with blueshifted asymmetries reminiscent of a double-lined spectroscopic binary with blended profiles. A blue-wavelength spectrum, taken 19 months later, shows similar line profiles but with the asymmetries redshifted (Fig. 3). Although it is perhaps possible that the line profile changes result from pulsation, we believe that the star is a binary with unresolved double lines. Support for this view comes from the remarks of Shajn & Albitzky (1932). Although they listed only a mean radial velocity of 35 km s^{-1} from four observations, they called the star a spectroscopic binary. They noted the presence of two spectra, but stated that "separation is difficult." Further support comes from Danziger & Faber (1972), who listed two values of $v \sin i$, 90 and 30 km s^{-1}. We suspect that these rotational velocities refer to two different observations rather than two components in the same spectrum. If this is correct, the very different values indicate that the star is a double-lined binary seen near quadrature and conjunction, respectively.

We were unable to adequately reproduce our red-wavelength spectra of HD 86358 with a single reference-star spectrum, lending support to our binary-star conclusion. Assuming that the star is a double-lined binary, we found spectral classes of F0 and F5: for the primary and secondary, respectively, and a continuum magnitude difference of 0.9. The *Hipparcos* parallax indicates that both stars are dwarfs. The results are in good agreement with classifications of F1 V (Cowley 1976), F3 V (Cowley & Bidelman 1979), and F2 V (Abt & Morrell 1995). For the primary and secondary, we determined projected rotational velocities of 25 and 30: km s^{-1}, respectively. In addition to the rotational velocities of Danziger & Faber (1972), Abt & Morrell (1995) estimated a value of 25 km s^{-1}, while Wolff & Simon (1997) found 38 km s^{-1}. Our radial velocities of the blended primary and secondary components are given in Table 3.

4.8. *HD 100215*

Handler (1999) identified HD 100215 as a probable γ Doradus variable. Radial velocities in the literature indicate that it is a spectroscopic binary. From three observations, Grenier et al. (1999) determined a mean velocity of -16.4 ± 14.2 km s^{-1} and concluded that HD 100215 has a variable velocity. Such variability also is indicated in the velocities of Fehrenbach et al. (1987), which have a range of 50 km s^{-1}.

We obtained two observations of this star. One red-wavelength spectrum shows single lines, while in the second a weak, partially resolved secondary component is redshifted. We classify the primary as F1, based on its metal line spectrum, and the secondary, as G0:. The *Hipparcos* parallax indicates that the components are dwarfs. The continuum magnitude difference is about 2.4. Sato & Kuji (1990) found a spectral type of A7 V, while Grenier et al. (1999) classified the star as A5mF0F2. The projected rotational velocities of the primary and secondary are 25 and 15: km s^{-1}, respectively. The individual velocities are given in Table 3.

4.9. *HD 105085*

Eyer (1998) concluded that HD 105085 is a γ Doradus candidate. Our red-wavelength observations show that its spectrum is composite. All the metal lines consist of a broad component with a narrow component near its center (Fig. 4). A blue-wavelength spectrum obtained of the 4500 Å region shows very weak, narrow features superposed on broader lines (Fig. 5).

From our red-wavelength spectra, we classified the broad component as F1, and the narrow component may have a somewhat later spectral class. If the composite spectrum results from two stars, the continuum magnitude difference is 1.9 mag. The *Hipparcos* parallax leads to a dwarf luminosity class. Grenier et al. (1999) gave it a similar classification of F2 IV–V, while Fehrenbach et al. (1987) found it to be a more luminous F2 III–IV. The broad component has a projected rotational velocity of 60 km s^{-1} and that of the narrow component is 10: km s^{-1}.

Radial velocities previously have been determined by three different groups. Hill et al. (1976) measured -1.6 ± 2.6 km

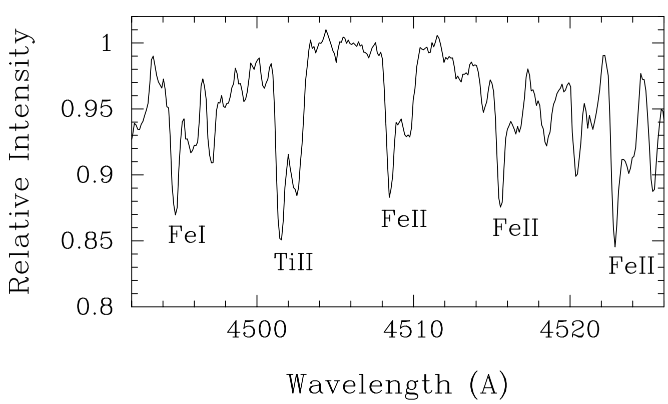

FIG. 3.—Portion of the blue-wavelength spectrum of HD 86358. The stronger lines of component A are blended with the weaker lines of component B. The element and ionization stage are indicated for some of the lines.

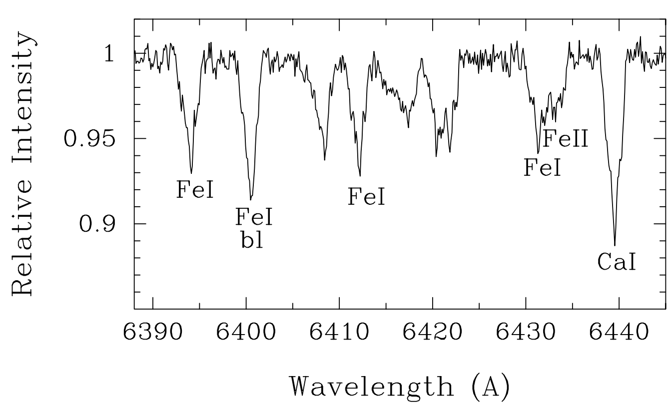

FIG. 4.—Same as Fig. 1, but for HD 105085

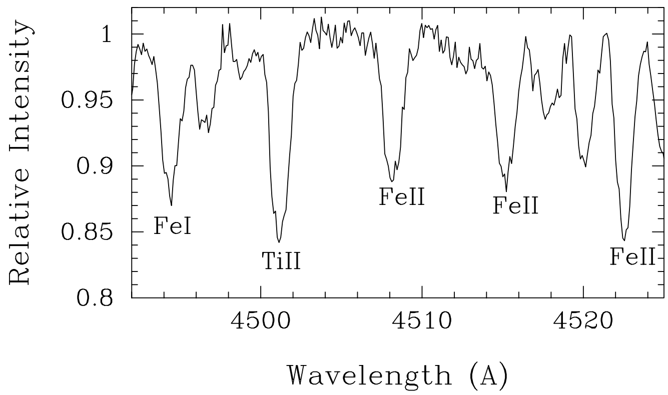

FIG. 5.—Portion of the blue-wavelength spectrum of HD 105085 that shows the composite profiles of the metal lines. The broad lines dominate the spectrum, while the narrow features are less apparent than those seen in Fig. 4. See Fig. 1 for additional information.

s^{-1} from four observations, Fehrenbach et al. (1987) got -2.2 ± 4.5 km s^{-1} from four plates, and Grenier et al. (1999) determined -6.4 ± 4.4 km s^{-1} from three observations. Our results require some discussion. The spectrum taken on HJD 2,452,328.936 shows the broad features to have significant asymmetries. Individual velocities of the three most isolated lines range from -14.0 to -1.3 km s^{-1}. The latter velocity comes from the most symmetric line, and so we adopt the velocity of -1.3 km s^{-1} for the broad component. Thus, our mean velocity from four observations is -1.6 km s^{-1}. For the narrow component, our three red-wavelength observations give a mean velocity of 1.7 km s^{-1}.

The four sets of velocities have similar means for the broad-lined component, suggesting that it is not a short-period binary. The *Hipparcos* observations give no indication that HD 105085 is a visual binary. Although HD 105085 may be a newly discovered double star, the observations to date are also consistent with it being an early F shell star.

Bounatiro (1993) listed HD 105085 as a possible member of the open cluster Melotte 111 in Coma. The radial velocity and parallax of the star appear to be consistent with cluster membership.

4.10. *HD 105458*

Handler (1999) listed HD 105458 as a prime γ Doradus candidate. Follow-up observations by Henry et al. (2001) confirmed it as a γ Doradus variable. Our spectroscopic observations were discussed in that paper but are summarized in Table 2 for the sake of completeness.

4.11. *HD 112429 (=HR 4916 = IR Draconis)*

Aerts et al. (1998) identified HD 112429 as a γ Doradus candidate, and the star was included in the Handler (1999) list of prime candidates. Kazarovets, Samus, & Durlevich (2000) assigned it the variable star name IR Dra. We determined a spectral class of F1, and its *Hipparcos* parallax indicates that it is a dwarf. These results are in good accord with spectral types of A9 V (Cowley 1976), F0 V (Cowley & Bidelman 1979), F0 IV–V (Gray & Garrison 1989), and F2 Vwl (Abt & Morrell 1995). Our $v \sin i$ of 115 km s^{-1} is somewhat less than the value of 130 km s^{-1} determined by Abt & Morrell (1995). From two spectra, we measured a mean radial velocity of 8.2 km s^{-1}, which is in agreement with the value of 9.0 km s^{-1} from Campbell (1928). Thus, the limited evidence indicates that this star is single.

4.12. *HD 113867*

Handler (1999) listed HD 113867 as a likely γ Doradus variable. Our red-wavelength spectra show that each line consists of a broad component with a narrow component near its center (Fig. 6). However, unlike the other composite-spectrum stars that we have found in our sample, the narrow lines appear to dominate the spectrum. We recently obtained a blue-wavelength spectrum of HD 113867, which shows a similar situation.

Despite the relatively weak appearance of the broad lines in our red-wavelength spectra, their equivalent widths are greater than those of the narrow features. The broad-lined spectrum has an A9 spectral class. The narrow-lined component has a similar or perhaps somewhat later spectral class. If the composite spectrum results from two stars, the continuum magnitude difference is 0.44 mag. The *Hipparcos* parallax leads to a dwarf luminosity classification. We found $v \sin i$ values of 120 and 10 km s^{-1} for the broad- and narrow-lined components, respectively. The mean velocity of the broad component in the three red-wavelength spectra is 4.7: km s^{-1}. The same component in the single blue-wavelength spectrum has a velocity of 11.5 km s^{-1}. Given that the uncertainty of the velocities measured from the red-wavelength spectra is on the order of 5 km s^{-1}, and that the star is a probable pulsator, such a velocity difference does not necessarily reflect binary motion. The mean velocity of the narrow component is 8.8 km s^{-1} in the three red-wavelength spectra and 3.8 km s^{-1} in the lone blue spectrum. The latter spectrum was taken 19 months after the red-wavelength spectra, so the velocity difference may indicate binary motion. On the other hand, if HD 113867 is a shell star, temporal variations may have occurred in the shell. Shell lines of A-type shell stars are known to vary with time in both strength and velocity (e.g., Abt & Moyd 1973; Jaschek, Jaschek, & Andrillat 1988; Jaschek & Andrillat 1998). From three observations, Hill et al. (1976) determined a mean velocity of 12.1 ± 0.9 km s^{-1}.

The similar line strengths of the two components suggest that perhaps HD 113867 is a binary and not a shell star. However, *Hipparcos* results (ESA 1997) provide no evidence for such a conclusion. If HD 113867 is an early F shell star,

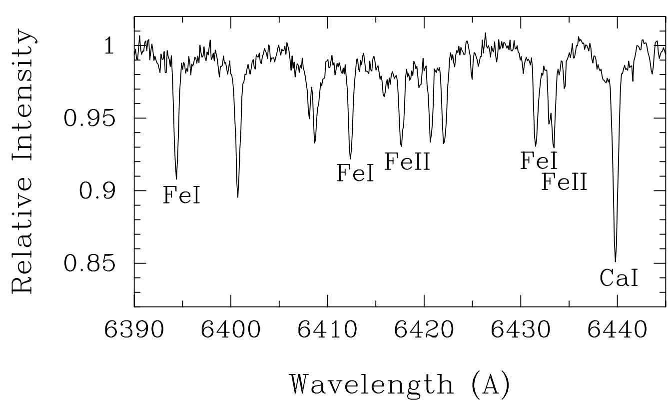

FIG. 6.—Same as Fig. 1, but for HD 113867. Of the seven composite-spectrum stars in our sample, HD 113867 has the strongest narrow features.

it is by far the most extreme example of the shell-star phenomenon that we have found in our sample.

4.13. *HD 115466* (=*58 Vir* = *LP Virginis*)

The light variability of HD 115466 was discovered by the *Hipparcos* mission team (ESA 1997), and it was assigned the variable star name LP Vir by Kazarovets et al. (1999). From additional analysis of the *Hipparcos* photometry, Handler (1999) concluded that HD 115466 is a prime γ Doradus candidate.

We classified its red-wavelength spectrum as F1, while the *Hipparcos* parallax leads to a subgiant luminosity class. Our $v \sin i$ value is 44 km s^{-1}. Our lone spectrum has a radial velocity of 12.5 km s^{-1}. From three observations, Christie & Wilson (1938) computed a mean velocity of 6 ± 1.8 km s^{-1}. The difference between the two velocities may result from a zero-point difference between observatories, duplicity, or perhaps line profile variations.

4.14. *HD 122300*

Handler (1999) identified HD 122300 as a possible γ Doradus variable. The three observations of Nordström et al. (1997) have a velocity range of 45 km s^{-1}, indicating that it is a spectroscopic binary. They also found the star to have rather narrow lines with $v \sin i = 13.2$ km s^{-1}.

Of our five red-wavelength spectra, only the first one shows double lines. From an analysis of that spectrum, we classify the primary as F1 and the secondary as F8:. The continuum magnitude difference is about 2.4 mag. The *Hipparcos* parallax indicates that the primary is a subgiant. For the primary and secondary, $v \sin i = 10.4$ and 5: km s^{-1}, respectively. Our velocities are listed in Table 3 and show a velocity range of 34 km s^{-1} for the primary. The velocity of that component on HJD 2,452,015.866 is quite similar to its velocity in the spectrum with double lines, yet no secondary was seen.

4.15. *HD 124248* (=*97 Vir* = *MU Virginis*)

The light variability of HD 124248 was found by the *Hipparcos* mission team (ESA 1997), and the star was given the variable name MU Vir (Kazarovets et al. 1999). Analysis of photometry from the *Hipparcos* database by Handler (1999) resulted in its designation as a prime γ Doradus candidate. We classified the star as A9, while its *Hipparcos* parallax indicates that it is a dwarf. Its projected rotational velocity is 48 km s^{-1}. The radial velocity of our lone observation is -1.7 km s^{-1}, which is consistent with the result of Wilson & Joy (1950), who found a mean velocity of 0.0 ± 4.0 km s^{-1} from four spectra, suggesting that this star is single.

4.16. *HD 126516*

Handler (1999) included HD 126516 in his list of possible γ Doradus variables since his analysis of its *Hipparcos* photometry resulted in only a single, weak periodicity of 0.493 days. Our red-wavelength spectra of HD 126516 show absorption lines that are much narrower than the vast majority of stars in our sample, and we determined $v \sin i = 4.1$ km s^{-1}. The spectrum of Procyon is an excellent match to our spectra, and so we classified HD 126516 as F5 IV–V. The *Hipparcos* parallax places the star in a similar intermediate luminosity position. Moore & Paddock (1950) classified it as F3 V, in reasonable agreement with our result. Our four observations have a radial velocity range of 72 km s^{-1} and a mean velocity of -8.8 km s^{-1}. From three observations, Moore & Paddock (1950) found a mean velocity of -37 ± 6 km s^{-1}. This star is clearly a short-period binary, but there is no evidence of secondary lines in our spectra.

With its mid F spectral type, it will be important to determine whether HD 126516 is truly a γ Doradus variable. If it is, the red edge of the γ Doradus instability strip will be shifted to significantly cooler temperatures.

4.17. *HD 130173* (=*ADS 9371 A*)

HD 130173 is the brightest star of a visual multiple system, ADS 9371, and has two somewhat fainter companions, each about 10″ distant (Paparó et al. 1990). It has been observed primarily as a photometric comparison star for HR 5492. Paparó et al. (1990) summarized the results of previous photometric studies and presented new observations. On one night Paparó et al. (1990) obtained differential photometry of HD 130173 that showed a brightening trend. As a result, they suggested that the period of 1.29 days attributed to HR 5492 by Bossi et al. (1981) belongs instead to its comparison star, HD 130173. With such a period, HD 130173 may be a γ Doradus variable.

We found an F2 spectral class for HD 130173, and its *Hipparcos* parallax indicates that it is a subgiant. Abt (1981) classified it as F3 V. We determined a moderate projected rotational velocity of 60 km s^{-1}. From three objective prism plates, Fehrenbach et al. (1997) computed a mean radial velocity of -5 ± 13.8 km s^{-1}, suggesting that the velocity of HD 130173 is variable. Our two observations taken 3 days apart produce a constant velocity of -18.1 km s^{-1} that is rather different from the mean velocity of Fehrenbach et al. (1997), so the star may be a binary.

4.18. *HD 149420* (=*32 Herculis* = *ADS 10116 A*)

HD 149420 is the brighter member of the visual binary ADS 10116 AB and is also a short-period, single-lined binary. Its visual companion is about 4″ distant and 7 mag fainter (Batten, Fletcher, & MacCarthy 1989). For the short-period binary, McKellar (1935) determined a period of 3.3943 days. Analyzing photometry in the *Hipparcos* database, Paunzen & Maitzen (1998) identified HD 149420 as a possible γ Doradus variable.

Our spectral class of A9 and giant luminosity class from its *Hipparcos* parallax are in good agreement with previous spectral types of A9 IV (Abt & Bidelman 1969), F0 III (Floquet 1975), and A9 IV (Abt 1985). We determined $v \sin i = 35$ km s^{-1}, somewhat larger than the value of 24 km s^{-1} found by Abt & Hudson (1971). In our red-wavelength spectra, we detected weak lines of the secondary of the short-period binary. From those spectra, we estimated a magnitude difference of 2 mag and determined a preliminary mass ratio of 0.51. A more extensive analysis and discussion of the system is in preparation.

The primary of HD 149420 is an evolved star with moderate rotation and an orbital period of 3.3943 days. Paunzen & Maitzen (1998) found light variations with a period of 1.6972 days. Thus, the orbital period is twice as long as the period of light variability, and we conclude that HD 149420 is an ellipsoidal variable and not a γ Doradus star.

4.19. *HD 152896* (=*V645 Herculis*)

Handler (1999) identified HD 152896 as a prime γ Doradus candidate. Our three spectra show that the line profiles

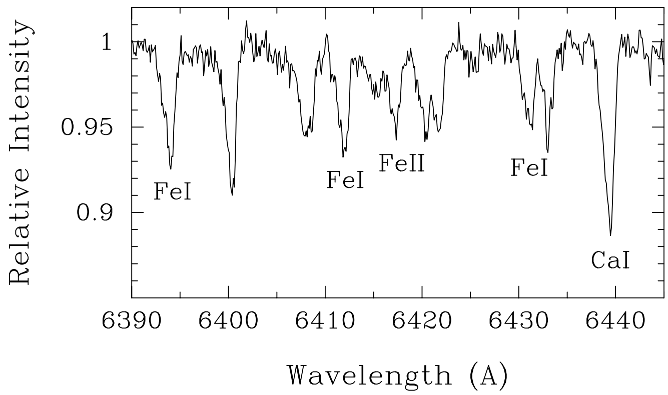

FIG. 7.—Same as Fig. 1, but for HD 152896. The element and ionization stage are indicated for some of the lines. The asymmetries likely result from the nonradial pulsation ongoing in the star although duplicity is a possibility.

vary in shape. The spectrum obtained on HJD 2,451,742 (Fig. 7) has quite asymmetric lines. Such asymmetries may result from pulsation, star spots, or because the star is a double-lined binary observed at a phase when the lines of the two components are only partially resolved. Indeed, the line asymmetries of HD 152896 are similar to those found by Henry & Fekel (2002a) for HD 221866, a star that Kaye et al. (2003) have recently shown to be a double-lined binary.

For the spectrum taken on HJD 2,451,742, the radial velocity was determined assuming that HD 152896 is a double-lined binary. The cross-correlation peak of the two least blended lines is well fitted by a double Gaussian, which results in radial velocities of 8.3 and -26.3 km s^{-1} for the putative primary and secondary. If the star is indeed double, we estimate spectral classes of A9: and F5: and projected rotational velocities of 30: and 25: km s^{-1} for the primary and secondary, respectively.

In a double-lined binary with unequal strength absorption lines, the blended line profiles should have increased symmetry, greater depths, and narrower widths as the two stars approach their center-of-mass velocity. Our other two spectra have much more symmetric line profiles than the spectrum of HJD 2,451,742. However, the line widths in those two spectra are quite similar to the widths of the asymmetric lines in the spectrum of HJD 2,451,742, and the depths of the corresponding lines are less than the line depths in the asymmetric-lined spectrum. This suggests that the star is not a double-lined binary.

From the spectrum with the most symmetric lines, we have determined a spectral class of F1. The *Hipparcos* parallax leads to a dwarf luminosity class. Grenier et al. (1999) classified HD 152896 as A8 IV. We found $v \sin i = 49$ km s^{-1}, in excellent agreement with Solano & Fernley (1997), who determined a value of 50.2 km s^{-1}. The two spectra with the more symmetric lines produced a mean radial velocity of -0.4 km s^{-1}, while the spectrum with the very asymmetric absorption profiles gave -7.5 km s^{-1}. Our mean from the two spectra is in good agreement with the results of both Grenier et al. (1999), who determined -1.9 ± 0.2 km s^{-1} from two observations, and Young (1939), who listed 1.1 ± 1.5 km s^{-1} from four spectra. We conclude that HD 152896 is probably single.

4.20. *HD 155154* (=*HR 6379*)

HD 155154 is another prime γ Doradus candidate from Handler (1999). Follow-up observations by Henry et al. (2001) resulted in its identification as a γ Doradus variable. Our spectroscopic observations were discussed by Henry et al. (2001), and we list the results in Table 2 for the sake of completeness.

4.21. *HD 160295* (=*V2381 Ophiuchi*)

Kazarovets et al. (1999) gave HD 160295 the variable star name V2381 Oph after it was found to be a periodic variable by the *Hipparcos* mission team (ESA 1997). Handler (1999) included it in his list of stars likely to be γ Doradus variables. Our red-wavelength spectra show that all the lines have composite line profiles consisting of a broad-lined component with a narrow-lined component near its center (Fig. 8). We determined a spectral class of F2 for the broad component and a subgiant luminosity class from its *Hipparcos* parallax. The spectrum of the narrow lines can be fitted with the spectrum of a star that has a similar or somewhat later spectral class. If the composite spectrum results from two stars, the continuum magnitude difference is about 1.9 mag. The narrow lines have a projected rotational velocity of 7 km s^{-1}, while for the broad-lined component the projected rotational velocity is 70 km s^{-1}, somewhat larger than the value of 60.7 km s^{-1} found by Nordström et al. (1997). Their mean radial velocity of -41.9 ± 0.9 km s^{-1} from three observations is essentially identical to our value of -41.8 km s^{-1} for the broad lines. The narrow lines have a similar velocity of -42.7 km s^{-1}. *Hipparcos* results (ESA 1997) provide no evidence that HD 160295 is a close visual binary. HD 160295 is either a newly discovered double star or another early F shell star.

4.22. *HD 167858* (=*HR 6844* = *V2502 Ophiuchi*)

The *Hipparcos* mission team (ESA 1997) showed HD 167858 to have light variability with a period of 1.307 days. Additional analysis of the *Hipparcos* data by Aerts et al. (1998) and Paunzen & Maitzen (1998) led to the identification of HD 167858 as a γ Doradus candidate. Handler (1999) included the star in his list of prime candidates. From recent ground-based photometry, Handler & Shobbrook (2002) concluded that the star is indeed a γ Doradus variable. Fekel (1997) found HD 167858 to be a slow rotator

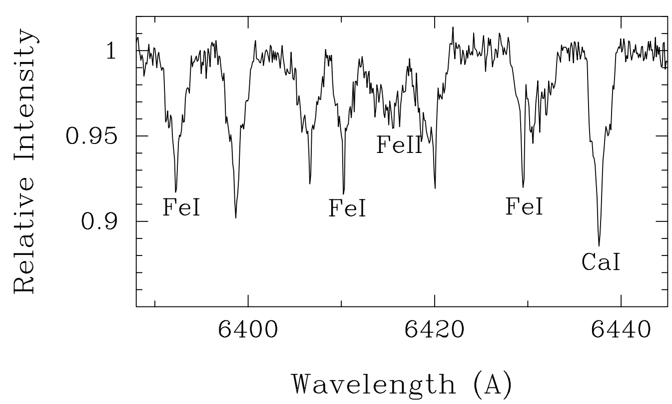

FIG. 8.—Same as Fig. 1, but for HD 160295

with $v \sin i = 8.0$ km s^{-1}. Both Gray & Garrison (1989) and Abt & Morrell (1995) classified the star as F1 V.

We determined a spectral class of F1, and the *Hipparcos* parallax indicates that it is a dwarf. Our first spectroscopic observation was obtained in 1993 April, and we now have over 40 spectrograms. From our radial velocities, we have determined an orbital period of 4.485 days. However, velocity residuals to the orbit are significantly larger than expected. On several nights, we obtained more than one observation and found velocity variations consistent with the *Hipparcos* photometric period. Fekel & Henry (2003) present a more extensive analysis and discussion of the data.

4.23. *HD 171244*

HD 171244 is another star identified by Handler (1999) as a probable γ Doradus variable. We found a spectral class of F2, and the *Hipparcos* parallax indicates that the star is a subgiant. The F3 IV spectral type of Grenier et al. (1999) is nearly identical. Our $v \sin i$ value of 47 km s^{-1} is in excellent agreement with a value of 49 km s^{-1} from Nordström et al. (1997). From two spectra, we determined an average radial velocity of -13.5 km s^{-1}. Nordström et al. (1997) found a mean velocity of -14.0 ± 0.7 km s^{-1} from three spectra, while Grenier et al. (1999) obtained -22.0 ± 2.6 km s^{-1} also from three observations. Comparison of the three average velocities suggests that the star's velocity is possibly variable.

4.24. *HD 173977* (=*HN Draconis*)

HD 173977 was discovered to be a variable star by the *Hipparcos* mission team (ESA 1997) and given the variable star name HN Dra (Kazarovets et al. 1999). Handler (1999) included it in his list of prime γ Doradus candidates. We classified the star as F1, and the *Hipparcos* parallax results in a subgiant/giant luminosity class. We determined a projected rotational velocity of 75 km s^{-1}. Two observations taken 5 days apart have a velocity difference of 90 km s^{-1}. Although the lines in the first spectrum are quite asymmetric, the large velocity difference between the two spectra indicates that this star is likely a short-period spectroscopic binary. The star also has a high luminosity, large radius of 2.7 $R_\odot$, and moderate rotation. Such properties suggest that HD 173977 is an ellipsoidal variable, while the line asymmetries may be an indication of pulsation.

4.25. *HD 175337*

Handler (1999) identified HD 175337 as a prime γ Doradus candidate. Our three spectra show that the line profiles vary in shape. Our first spectrum, taken on HJD 2,451,735 has line asymmetries that are quite similar to those of HD 152896 (Fig. 7). The cross-correlation peak for that spectrum of HD 175337 was fitted with two Gaussians and resulted in radial velocities of 12.0 and -12.5 km s^{-1} for the putative primary and secondary, respectively. The cross-correlation peaks for the other two spectra of HD 175337 are more symmetric but can be fitted reasonably well with two Gaussians. If the star is indeed double, we estimate spectral classes of F1: and F8: and projected rotational velocities of 25: and 18: km s^{-1} for the primary and secondary, respectively.

Like HD 152896, however, other properties of the spectral lines suggest that the star is likely single. The sets of lines of the three spectra show little difference in residual line depth and line width. Solved as a double-lined binary, the most symmetric cross-correlation peak has a larger velocity difference for the two supposed components than the velocity difference of the two components of the very asymmetric cross-correlation peak. This suggests that the star is not a double-lined binary.

Assuming that the star is single, from the spectrum with the most symmetric lines, we have determined a spectral class of F2, while the *Hipparcos* parallax leads to a dwarf luminosity class. The projected rotational velocity of HD 175337 is relatively low, 38 km s^{-1}. The radial velocity appears to be constant, and its mean from three observations is -2.2 km s^{-1}.

4.26. *HD 187615*

Handler (1999) included HD 187615 in his list of possible γ Doradus variables. We obtained a single spectrum from which we classified the star F1. The *Hipparcos* parallax indicates that it is a dwarf. We determined a $v \sin i$ value of 80 km s^{-1} and a radial velocity of 8.3 km s^{-1}.

4.27. *HD 195068/9* (=*HR 7828* = *43 Cyg* = *V2121 Cygni*)

This star has two HD numbers and is listed as HD 195068 in the Bright Star Catalogue (Hoffleit 1982) but under HD 195069 in SIMBAD. The light variability of HD 195068/9 was found by the *Hipparcos* mission team (ESA 1997), and they suggested that this star is an RR Lyrae variable. Kazarovets et al. (1999) gave it the variable star name V2121 Cyg. Eyer (1998) first identified it as a possible γ Doradus variable, and Handler (1999) listed it as a prime candidate.

Our red-wavelength spectra show that its lines are quite asymmetric (Fig. 9). As noted previously, such line asymmetries may be the result of pulsation, duplicity, or perhaps star spots. Like HD 152896 and HD 175337, we first analyzed the star assuming that it is a double-lined spectroscopic binary. Radial velocities of the putative primary and secondary components are -11.8 and -47.0 km s^{-1}, respectively, on HJD 2,451,737 and -11.0 and -44.7 km s^{-1}, respectively, 3 days later on HJD 2,451,740. We estimate spectral classes of A9: and F5: and projected rotational velocities of 30: and 20: for the primary and secondary, respectively.

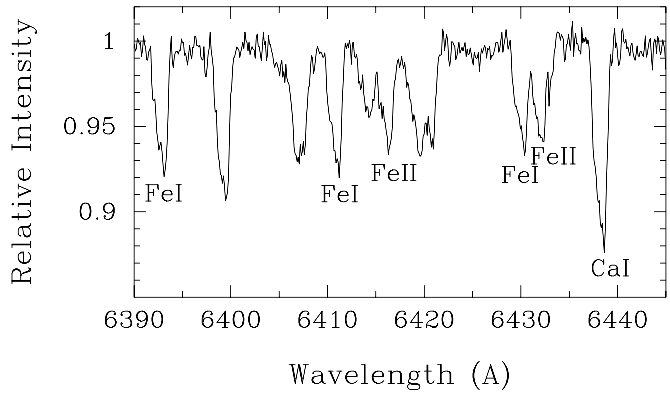

FIG. 9.—Same as Fig. 1, but for HD 195068/9. The element and ionization stage are indicated for some of the lines. Similar to HD 152896 (Fig. 7), the asymmetries likely result from the nonradial pulsation of the star although duplicity is a possibility.

We have also analyzed the star's properties assuming that it is single. Because of the obvious line asymmetries, such determinations are more difficult than usual. We estimate a spectral class of F1: for HD 195068/9, while its *Hipparcos* parallax indicates that it is a dwarf. Our results are in good accord with the F2 V spectral type of Abt & Morrell (1995). Our $v \sin i$ of 44 km s^{-1} is in excellent agreement with the value of 43 km s^{-1} from Abt & Morrell (1995). Our mean velocity from two observations is -29.6 km s^{-1}. From four observations, Fehrenbach et al. (1997) measured a velocity of -29 ± 3.6 km s^{-1}, in close agreement with our result, while from three spectra Harper (1937) got -20.6 km s^{-1}. The difference seen between the three mean velocities may result from line profile variations, similar to the velocity differences found in our results for HD 152896, but duplicity cannot be ruled out. Nevertheless, we list our analysis for the single-star results in the various tables.

4.28. *HD 197451*

Handler (1999) analyzed the *Hipparcos* photometry of HD 197451 and found a period of 1.803 days. He identified HD 197451 as a possible γ Doradus variable but commented that it might be an Am or Ap star. Although we assigned it a spectral type of F2:, we were unable to find a good match to its spectrum because several Fe II and Ca I lines in the 6430 Å region are not well fitted by our reference-star spectra. The *Hipparcos* parallax results in a giant luminosity class, making it one of the most luminous stars in our sample. Grenier et al. (1999) classified it as F0 II–III. In retrospect, our classification difficulties are not surprising. From Strömgren four-color photometry, Olsen (1979) predicted that HD 197451 is an Am or Ap star. This conclusion was confirmed by Abt, Brodzik, & Schaefer (1979), who identified it as an extreme Ap star and classified it as F2 Vp(Sr,Eu,Cr)s.

We measured a modest projected rotational velocity of 24 km s^{-1}. Our lone radial velocity of 22.0 km s^{-1} is quite different from the mean value of Grenier et al. (1999), -42.9 ± 7.3 km s^{-1}. Thus, it supports their conclusion that the velocity is variable, and so the star is a spectroscopic binary. We find no evidence of a secondary component in our spectrum. The period of 1.8 days found by Handler (1999) is similar to the periods found for other Ap stars (Catalano & Renson 1998) and suggests that the light variations likely result from stellar rotation rather than nonradial pulsations.

4.29. *HD 201985*

Handler (1999) identified HD 201985 as a possible γ Doradus variable. Handler & Shobbrook (2002) obtained additional photometry of the star but were unable to reach a firm conclusion concerning its status. Although they detected little nightly variability, on one night they found the star to be 0.15 mag fainter than on the rest of their nights, and so they suggested that HD 201985 might be an eclipsing binary.

We classified the star as F0, and the *Hipparcos* parallax results in a dwarf luminosity class. HD 201985 has quite narrow lines, and we determined $v \sin i = 10.0$ km s^{-1}. Our lone radial velocity is -57.9 km s^{-1}.

4.30. *HD 202444* (*=HR 8130 = τ Cygni = ADS 14787 AB*)

Abt (1961) summarized the claims for rapid velocity variability that were made in the early 1900s. From 16 new spectrograms, he found a mean velocity of -21.6 ± 3.0 km s^{-1} and concluded that the velocities showed " no significant changes between nights or during single nights." Pant, Gaur, & Pande (1968) reported that rapid light variations with periods of about 2 or 3 hr were sometimes present in HD 202444.

Our red-wavelength spectra of HD 202444 show that all its metal lines have composite line profiles, each consisting of a broad-lined component with a narrow-lined component near its center (Fig. 10). We classified the broad-lined component as F2. The spectrum of the narrow lines can be fitted with the spectrum of a star that has a somewhat later spectral class. If the composite spectrum results from two stars, the continuum magnitude difference is about 2.2 mag. The *Hipparcos* parallax of HD 202444 results in an absolute magnitude that indicates a subgiant luminosity class. Our results are in accord with the spectral types of F2 V and F2 IV of Cowley & Fraquelli (1974) and Abt & Morrell (1995), respectively. For the broad component, we found $v \sin i =$ 95 km s^{-1} in excellent agreement with Abt & Morrell (1995), who determined 98 km s^{-1}. The projected rotational velocity of the narrow-lined component is 6 km s^{-1}. From two spectra, our radial velocities are -22.5 and -19.8 km s^{-1} for the broad- and narrow-lined components, respectively. The former is in excellent agreement with the mean velocity determined by Abt (1961).

HD 202444 is also a close visual binary with a current separation of about 0.″8 and a V magnitude difference of 2.74 (ten Brummelaar et al. 2000). That ground-based difference is identical to the one we computed using the separate magnitudes of the visual components from the Tycho instrument on *Hipparcos* (Fabricius & Makarov 2000). The magnitude difference plus the $B-V$ color index of the visual secondary indicate that it is a mid G dwarf. Stockton & Fekel (1992) reported that components with a magnitude difference of $\lesssim 2.5$ mag can be detected at wavelengths near 6430 Å. Thus, the broad and narrow features that we see in our spectrum just might correspond to the visual-binary components, or alternatively, the primary of HD 202444 may be another early F shell star. Additional spectra from a previous observing campaign are being analyzed by one of us (A. B. K.).

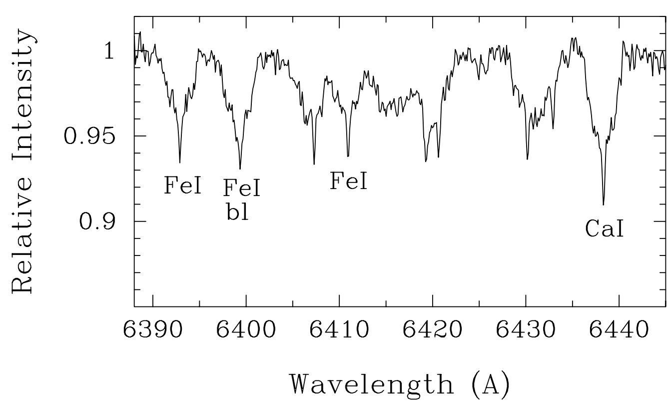

FIG. 10.—Same as Fig. 1, but for HD 202444 (=τ Cyg)

4.31. *HD 206043* (=*HR 8276* = *NZ Pegasi*)

Eyer (1998) first identified HD 206043 as a possible γ Doradus variable, and Handler (1999) listed it as a prime candidate. Follow-up observations by Henry et al. (2001) confirmed it as a γ Doradus variable. Our spectroscopic observations were presented in Henry et al. (2001), and we list our results in Table 2 for the sake of completeness.

4.32. *HD 207651*

Handler (1999) noted HD 207651 as a possible γ Doradus candidate. Handler & Shobbrook (2002) obtained ground-based photometry that indicated both short-term δ Scuti–type variability and additional longer term modulations. They concluded that more observations were needed to fully characterize the variability.

We obtained a single spectrum that shows composite line profiles consisting of a narrow component situated near the center of a broad-lined component (Fig. 11). We classified the broad component as A9, while the *Hipparcos* parallax indicates that the star is a giant and the most luminous star in our sample. The spectrum of the narrow component has a similar or somewhat later spectral type. We determined a projected rotational velocity of 95 km s^{-1} for the broad component and 6 km s^{-1} for the narrow component. The radial velocity of the latter is -20.7 km s^{-1}, while measurement of a single line produced a velocity of -24.4: km s^{-1} for the broad component. Fehrenbach et al. (1997) found a rather different mean velocity of 2 ± 6.5 from five objective-prism spectra. Thus, the star may have a variable velocity.

Hipparcos results (ESA 1997) provide no evidence that HD 207651 is a visual binary. However, Handler & Shobbrook (2002) noted that Strömgren photometry yields an absolute magnitude that is 1.2 mag fainter than the *Hipparcos* parallax result and mentioned that this difference might indicate that the star is a binary. Although we see two sets of lines in our red spectrum, the continuum magnitude difference is 1.2 mag and so cannot account for the absolute magnitude discrepancy. The nature of the composite spectrum of HD 207651 is quite similar to that of other stars in our sample. Thus, it is uncertain whether the composite profiles correspond to a shell star or a binary.

Handler et al. (2002) recently found HD 209295 to be the first star that has light-variability periods typical of both δ Scuti and γ Doradus variables. As noted above, for HD 207651 Handler & Shobbrook (2002) detected δ Scuti pulsations, as well as longer term variations. However, recently, G. Handler (2002, private communication) reported that analysis of additional data indicates that the long-term variations come from duplicity.

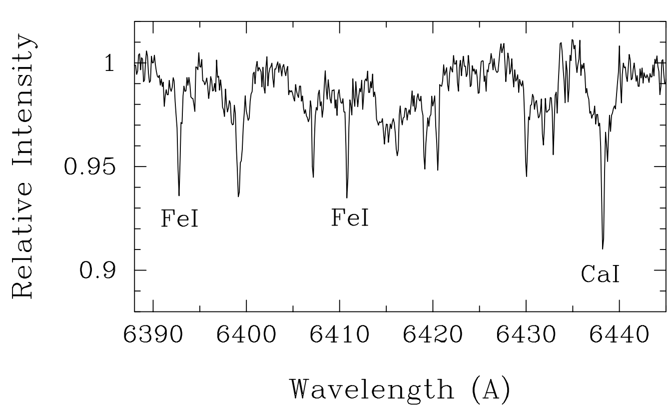

Fig. 11.—Same as Fig. 1, but for HD 207651

4.33. *HD 213617* (=*HR 8586* = *39 Pegasi*)

Handler (1999) considered HD 213617 a possible γ Doradus candidate. We found a spectral class of F1, and the *Hipparcos* parallax indicates that it is a dwarf. These results are in good agreement with the classifications of Cowley & Fraquelli (1974) and Abt & Morrell (1995), who found F1 V and F2 V, respectively. Our $v \sin i$ value of 70 km s^{-1} is smaller than that of Abt & Morrell (1995), who determined 83 km s^{-1}. Our single velocity of -12.1 km s^{-1} differs somewhat from the mean velocity of Shajn & Albitzky (1932), who measured -19.9 ± 2.7 km s^{-1} from five observations. This difference suggests that HD 213617 may be a binary.

4.34. *HD 221866*

HD 221866 is a prime γ Doradus candidate from Handler (1999). Henry & Fekel (2002a) obtained follow-up photometric observations that confirmed it as a γ Doradus variable. They also obtained spectroscopic observations and argued that the line profile asymmetries seen in the spectrum of the star resulted from pulsation rather than duplicity or star spots. Recently, however, Kaye et al. (2003) showed that HD 221866 is in fact a double-lined binary with a period of 134.92 days and an eccentricity of 0.678.

Radial velocities for our five spectroscopic observations are listed in Table 3. According to the orbital ephemeris of Kaye et al. (2003), our observations have phases ranging from 0.26 to 0.30. At such phases, the orbit predicts a velocity difference of about 31 km s^{-1} for the components, which is in agreement with our radial velocity results. This velocity difference is not large enough to fully resolve the lines of the two components in our spectra, and so the lines appear as single, asymmetric features.

Since the lines of the two stars are blended in all of our spectra, the properties we determined from the spectra are somewhat more uncertain than usual. Spectral classes of the primary and secondary are A8:m and F3:, respectively. Kaye et al. (2003) have reported that HD 221866 is an Am star, and our spectra show that the Ca I lines of the primary are much weaker than those in the reference star, identifying the primary as the Am star. The continuum magnitude difference from our red-wavelength spectra is about 1.1 mag, in approximate agreement with the estimate of Kaye et al. (2003), who reported that in the blue the ratio of the luminosities may approach 1 mag. The *Hipparcos* parallax indicates that the stars are dwarfs. For components A and B, our projected rotational velocities are 19: and 11: km s^{-1}, respectively, compared with values of 19 and 14 km s^{-1} found by Kaye et al. (2003). These basic properties are listed in Table 2.

Turcotte (2002) briefly discussed the relationship between diffusion and pulsation and showed that more massive, evolved Am stars are expected to pulsate. In his meeting summary at IAU Symposium 185, Kurtz (2002) referred to a question posed by G. Michaud and queried whether there are γ Doradus variables that show Am star characteristics. HD 221866 may to be such a star. As noted above, it is a confirmed γ Doradus variable, and the primary of this binary system is an Am star. The tentative spectral type of the secondary places that component just outside the currently defined γ Doradus region, while the Am star is perhaps within the region, and so it may be the Am star that is the pulsator. However, we note that the models of Turcotte (2002) indicate that pulsating Am stars should be significantly evolved, but the primary of HD 221866 is a main-sequence star.

5. DUPLICITY

If a star is a binary, its duplicity can affect some of the basic properties that are determined for the system. For example, line blending problems can complicate measurement of a star's radial velocity and projected rotational velocity. In addition, the combined magnitudes and colors of the system may need revision in order to represent the individual components. The presence of a close companion also produces tidal effects that can induce pulsation in a star (Kumar, Ao, & Quataert 1995; Willems & Aerts 2002). Thus, it is of interest to identify the binaries in our sample.

In our spectroscopic survey, several factors make the identification of binaries difficult. The very limited number of spectra obtained for most of the stars means that to assess the possibility of duplicity, it is often necessary to compare our results with those of other surveys. Velocity zero-point differences can contribute to differences in the mean velocities for observations obtained at different observatories. Since the stars have late A or early F spectral classes, many of the stars have broad lines, resulting in velocities with increased uncertainty. Another complication is that some of the spectra show line profile asymmetries that may result from pulsation rather than duplicity.

In addition to the above difficulties, there are seven stars in our sample that have composite spectra. Each absorption line consists of a broad component with a narrow component near its center. As mentioned in the discussions of the individual stars, the composite profiles are the signature of either binaries or shell stars. Three of the seven are known close visual binaries and have visual magnitude differences that may be consistent with our spectroscopic results. If the binary interpretation is correct, these systems consist of a rapidly rotating late A or early F type primary and a slowly rotating F or G type secondary. The very different rotational velocities make the two components easily identifiable.

To examine the incidence of duplicity in our sample, we eliminate the two ellipsoidal variables, HD 11443 and HD 149420, as well as the Ap star, HD 197451, from further discussion, so that all the stars under consideration are confirmed, probable, or possible pulsators. Thus, our remaining sample of late A to mid F stars contains 31 stars. We note that each of the three eliminated stars is a short-period binary.

From our spectroscopic observations alone, we have identified six short-period binaries, and two more have been found by other observers. Thus, at least 26% of the stars are binaries. When compared with mean velocities in the literature, our mean velocities of another six systems differ by 8 km s^{-1} or more. If all of these are binaries, this increases the percentage of binaries to 45%. None of the composite-spectrum stars have so far been included. If it is assumed that all seven of the composite-spectrum stars are binaries, the binary fraction rises to 68%. Finally, two additional stars show very asymmetric line profiles that might result from duplicity, making a total of 23 stars or 74% of our sample. Considering only the subsample of 22 prime γ Doradus candidates of Handler (1999), the percentage of binaries is almost identical for each of the binary groups considered above. Given the limited number of observations obtained so far for our 31 stars, the maximum total of 23 binaries results in an extremely high binary percentage. For comparison, the extensive CORAVEL survey of 164 late F and G dwarfs produced 80 binaries, 49% (Mayor et al. 1992) of their sample. However, this observed binary total includes not just spectroscopic and visual binaries, but also a large number, 29 systems, of common proper motion pairs. Thus, either the binary fraction is quite different in our sample of slightly more massive stars, or many of the stars are not really binaries.

6. METALLIC SHELL STARS?

Struve (1932) and Morgan (1932) described the first examples of A- and F-type shell stars, 17 Lep and 14 Com, respectively. Additional bright members of this class of stars were identified by Abt & Moyd (1973), Andersen & Nordström (1977) and others, but the total number remains quite small, less than 100 members (Jaschek & Andrillat 1998). Jaschek et al. (1988) determined that only 1.5% of the A stars in the Bright Star Catalogue (Hoffleit 1982) are known to be Ae- and A-type shell stars. The number of F-type shell stars, the most prominent of which are 14 Com and π Peg, is even more meager. Such A- and F-type stars are generally thought to be an extension of the Be star phenomenon (e.g., Slettebak 1982, 1986; Jaschek et al. 1988). In the cooler A- and F-type stars, however, the signature of the shell is a set of narrow absorption components superposed on a broad-lined spectrum attributed to the photosphere of the star. Dominy & Smith (1977) obtained high-resolution spectra of the F0 III shell star 14 Com and identified about 250 shell features, most of which are lines of ionized metals at near-ultraviolet and blue wavelengths. From their examination of six late A- or F-type shell stars, they concluded that for a given spectral type the more evolved the star, the stronger its shell spectrum tends to be.

For the δ Scuti variable X Caeli, Mantegazza & Poretti (1996) made high-resolution spectroscopic observations of the 4500 Å region and discovered narrow cores superposed on broad absorption features of Ti II and Fe II. 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. Following that detection, two more δ Scuti variables, HD 173471 (Henry et al. 2001) and HD 10502 (Henry & Fekel 2002b), as well as the γ Doradus variable HD 108100 (Henry & Fekel 2002a) were found to have composite spectra.

Like the four stars noted above, seven stars in this survey have composite absorption line profiles. All are A9–F2 dwarfs or subgiants except for HD 207651, which is a giant. Figures 5 and 6 show that the visibility of the narrow lines is significantly enhanced in the neutral lines seen in our red-wavelength spectra compared with the lines from singly ionized elements at blue wavelengths. Thus, stars with similar features would have been easily missed in earlier surveys done at blue wavelengths with photographic plates. While the seven may be binaries, it seems somewhat surprising that such a significant percentage of the stars in our sample should show similar composite profiles. There is enough uncertainty in our results to suggest that even the composite spectra of the three close visual binaries may represent shell stars. Of course, both the binary and shell-star possibilities may be correct, some of the seven stars may be binaries and others, shell stars.

In the following paragraphs, we explore the ramifications of the *assumption* that all seven of the composite-spectrum stars are shell stars. Although this assumption may be incorrect, it leads to some interesting results. We again consider only the sample of 31 confirmed, probable, or possible pulsators.

For our seven composite-spectrum stars, called shell stars in the rest of this section, the absolute value of the velocity difference between the stellar and shell velocities is 4.0 ± 1.2 km s^{-1}. Three of the shell velocities are more positive than the corresponding stellar velocity, indicating a contracting shell, while four shell velocities are more negative, indicating an expanding shell. The shell lines are quite narrow, having $v \sin i$ values between 6 and 10 km s^{-1}.

The average and minimum $v \sin i$ values for the eight mid to late A shell stars discovered by Abt & Moyd (1973) are 202 and 175 km s^{-1}, respectively. For a similar spectral type range, Jaschek et al. (1988) found mean and minimum values of 187 and 80 km s^{-1}. Our seven shell stars, which have a somewhat later average spectral class of F1, have a mean $v \sin i$ of 90 and a lower limit of 60 km s^{-1}. From Table B1 of Gray (1992), the average $v \sin i$ for A9 to F2 dwarfs is 108 km s^{-1}. Thus, the mean value for our shell stars appears to be typical of or slightly lower than the average field star of those spectral classes. Figure 12 is a plot of the $B-V$ color index versus $v \sin i$ value for our sample. It shows that while our metallic shell stars may have projected rotational velocities similar to typical field stars, the rotational velocities of our shell stars are in the upper envelope of the distribution of our sample of pulsating stars.

The stellar projected rotational velocities of our seven shell stars range from 60 to 120 km s^{-1}. In our sample, 14 stars are within that range, and so 50% of the pulsating variables are shell stars. This percentage decreases to 44% when all stars having $v \sin i \geq 60$ km s^{-1} are included. For Be stars, Hanuschik (1996) found a shell star fraction of 23%. From this percentage, he concluded that the circumstellar disk occults the star if the inclination to the observer's line of sight is $\geq 77°$. Our larger fraction of 44% suggests that the disks of our F stars have a wider opening angle. The four other recently found composite-spectrum stars mentioned above have $v \sin i$ values ranging from 65 to 160 km s^{-1}.

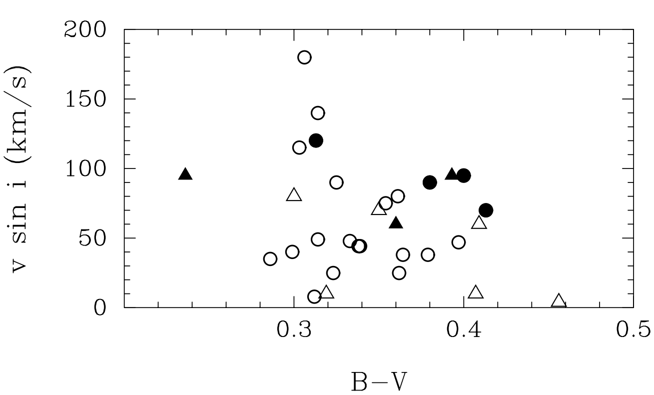

FIG. 12.—Plot of $B-V$ vs. $v \sin i$ for the 31 confirmed or suspected pulsating variables. Circles are the prime γ Doradus candidates of Handler (1999). Triangles are the less likely candidates of Handler (1999), as well as possible γ Doradus variables from other sources. If the circle or triangle is filled, the star has a composite spectrum.

As summarized by Slettebak (1988), optical spectroscopy and polarization, as well as infrared and radio observations provide support for a rotating flattened disk of material that is cooler than the photospheres of Be stars. As one example, the study of Briot (1986) examined the correlation of the rotational velocities of Be stars with their emission characteristics. She argued that the shell of metallic elements is a flattened thick disk of material and concluded that the metallic shell "may only be detectable when the star is seen very near the equatorial plane." If our field stars make up a random sample, they have randomly oriented axes of rotation. In such a sample, half of the stars should have inclinations greater than 60° (Russell, Dugan, & Stewart 1938). Thus, one possible interpretation of the above statistics is that all the stars in our sample having projected rotational velocities ≥ 60 km s^{-1} are shell stars, but they are only detectable if their inclinations are greater than about 60°.

Our minimum rotational velocity of 60 km s^{-1} for the presumed shell stars is the lowest yet found, and all but one of the seven stars is a dwarf or subgiant. This begs the question, how does a star with a strong gravitational pull and such a low rotational velocity produce a shell?

In Be stars, rapidly varying line profiles were first detected in ζ Oph (Walker, Yang, & Fahlman 1979) and μ Cen (Baade 1984). A number of Be stars have light and line profile variations with periods of 0.5–2.0 days, and many of them are monoperiodic (Balona 1995). Rapid rotation is a necessary but insufficient condition for the Be star phenomenon. Nonradial pulsation and corotating material trapped in localized magnetic loops have been suggested as the additional cause, and the subject remains hotly contested (e.g., Gies 1994; Balona 1995; Balona & Kaye 1999; Smith 2001). Balona (1995) has argued that nonradial pulsation is not viable, but advocacy of nonradial modes continues. For the star μ Cen, which has multiple modes, Rivinius et al. (1998) claimed that period beating determines the times of its circumstellar outbursts. Rivinius et al. (2001) successfully modeled its line profile variations with a combination of nonradial pulsation modes.

Clearly, nonradial pulsation has not been proven to be a cause of the Be star phenomenon nor of the presumably related metallic-lined A and F shell stars. Nevertheless, since all the stars in our sample are confirmed, probable, or possible pulsators, perhaps pulsation is intimately involved in the shell formation of these stars. One way to test this possibility would be to observe photometrically a random sample of late A and early F stars and identify those that are pulsators. G. Henry (2002, private communication) has recently carried out such a survey. Follow-up spectroscopy of the variable and constant stars could be used to determine the percentage of metallic shell stars in each group.

7. DISCUSSION

We examine the general properties of our entire sample of 31 confirmed or likely pulsators and in particular the

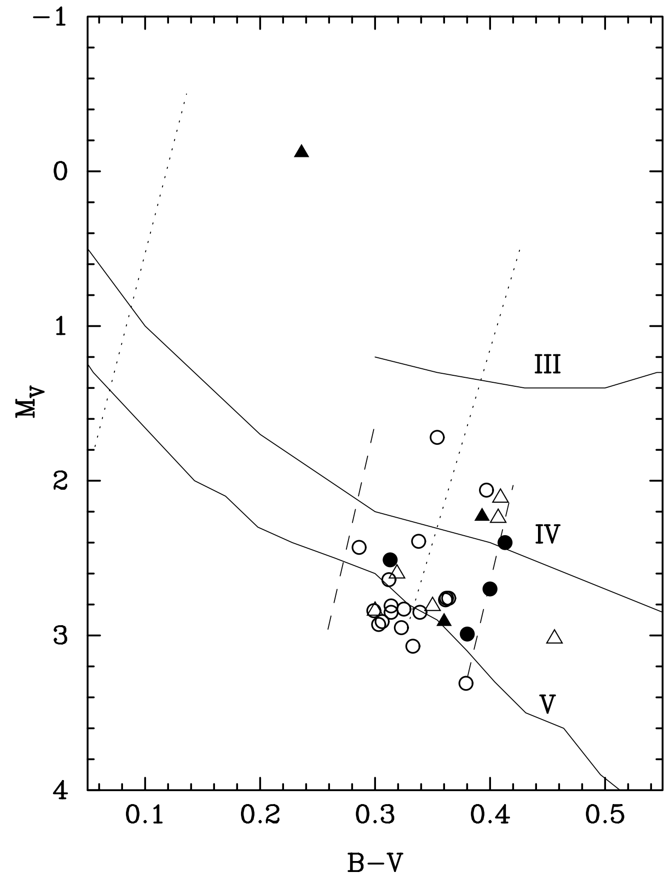

FIG. 13.—Position in the H-R diagram of the 31 confirmed or suspected pulsating variables. Symbols for the stars are the same as in Fig. 12. The dotted lines indicate the boundaries of the δ Scuti instability strip converted from those of Breger (2000). The dashed lines show the latest estimate of the domain of the γ Doradus pulsators. Solid lines indicate the dwarf and giant sequences of Gray (1992) and the subgiant sequence of Allen (1976), which are identified by the corresponding luminosity class symbol. The solid triangle in the top left of the diagram represents the position of HD 207651 (see § 4.32), while the open triangle redward of the γ Doradus domain is HD 126516 (see § 4.16).

properties of the 22 prime γ Doradus candidates from Table 1 of Handler (1999). Figure 13 is a plot of the $B-V$ color index (ESA 1997) versus absolute visual magnitude for the sample of 31 variables. Also shown are the current boundaries of the region in the H-R diagram where the γ Doradus variables are found, determined from 30 confirmed γ Doradus stars (Henry & Fekel 2002a). However, following Handler & Shobbrook (2002), we have excluded HD 209295 from consideration because its γ Doradus–type pulsations may result from tidal interactions. Since the δ Scuti and γ Doradus regions overlap in the H-R diagram, the boundaries of the δ Scuti instability strip, derived from Breger (2000), have been plotted as well. We converted his $b-y$ values for the boundaries to $B-V$ values with Table B1 of Gray (1992). These boundaries were then compared with a sample of 146 δ Scuti stars, taken from the catalog of Rodríguez, López-González, & López de Coca (2000), that had *Hipparcos* parallaxes with uncertainties $\leq$10%. We found 97% of those stars to be within the boundaries.

As noted in § 2, we believe that most of the stars in our sample of candidates will be confirmed as γ Doradus variables. Because they were preselected as γ Doradus candidates, the stars in our sample are usually close to the red edge of the δ Scuti instability strip (Fig. 13), with nearly equal numbers on either side of that boundary. Figure 13 also shows that nearly all of our 31 pulsators are contained within the boundaries defined by the confirmed γ Doradus variables. The two anomalous stars are the giant star HD 207651, positioned in the top left area of the H-R diagram, and HD 126516, the coolest star in our sample. As noted in § 4.32, Handler & Shobbrook (2002) recently found HD 207651 to be a δ Scuti variable, but it also has longer term variations, which G. Handler (2002, private communication) now concludes do not result from γ Doradus–type pulsations. Except for HD 207651, all the other stars are subgiants or dwarfs, and so have luminosities consistent with the current definition of γ Doradus variables (Kaye et al. 1999).

Handler et al. (2002) found that HD 209295 has both γ Doradus– and δ Scuti–type pulsations. Thus, it is the first variable star to be identified as a member of two pulsating variable star classes. In addition, Handler et al. (2002) discovered that the star is a binary with a period of 3.106 days, suggested that it has a white dwarf or neutron star companion and noted that there is evidence that its γ Doradus pulsations are tidally excited. This result raises questions about the relationship between tidal forcing and pulsation modes. Some theoretical work in this area has already been done. Investigations of tidally induced luminosity variations and radial velocity variations in close binaries have been made by Kumar et al. (1995) and Willems & Aerts (2002), respectively.

Besides HD 209295, a search of the literature identifies only three other γ Doradus variables, HD 49015, HD 62454, and HD 86371, as members of short-period binaries. To the modest total, we have added a fifth, HD 167858. Of the 22 prime γ Doradus candidates in our survey, 10 have constant velocities, six are short-period binaries, and the other six are possibly variable or have only a single observation. Of the remaining nine possible γ Doradus variables, two are short-period binaries. Thus, we have a total of 14 confirmed or possible short-period binaries in our sample. In light of the results of Handler et al. (2002), determining which γ Doradus variables are members of short-period binaries, as well as the overall fraction of γ Doradus stars in close binary systems, will be important future projects.

Is there any evidence of a connection between rotational velocity and γ Doradus pulsators? The 22 prime γ Doradus candidates of Handler (1999) have a mean projected rotational velocity of 68 km s^{-1}. This value is substantially less than the mean value of 108 km s^{-1} (Gray 1992) for similar field stars. However, the projected rotational velocities of the prime candidates range from 8 to 180 km s^{-1}, so pulsation occurs in stars having a wide range of rotational velocities.

Although our spectroscopic survey does not shed extensive light on the γ Doradus nature of most of the stars in our sample, we have provided a significant amount of basic information on the stars including radial velocities, rotational velocities, and spectral classes. In addition, we have identified two stars as ellipsoidal variables, eliminating them from the list of γ Doradus candidates. We also have discovered a potential additional complication, seven stars in our sample may be shell stars. Slettebak (1986) presented spectra of the Hα region for five A–F shell stars. The spectra have broad Hα absorption features with sharp absorption cores. Since binary components would be expected to have similarly broadened Hα features, observations of this line may enable us to choose between the binary and shell star possibilities for the seven composite-spectrum stars.

Spectroscopy is an important complement to multicolor photometry. Time series spectroscopic observations, obtained to determine binary orbits and analyze line profile variations, will be required to understand the modes of variability of γ Doradus stars.

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