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Rotational Velocities of Late-Type Stars

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ABSTRACT. A calibration based on the results of Gray has been used to determine projected rotational velocities for 133 bright stars with spectral types of F, G, or K, most of which appear in *The Bright Star Catalogue*. The vast majority have $v \sin i \leqslant 10$ km s^{-1} and, thus, are slow rotators. With the new calibration, projected rotational velocities have been determined for a sample of 111 late-type stars, most of which are chromospherically active. Some of the stars have had their rotational velocities measured for the first time.

1. INTRODUCTION

The projected rotational velocity, $v \sin i$, is a datum that is sorely lacking even for many of the 9100 or so brightest stars in the sky (Hoffleit 1982). Until the advent of solid-state detectors about two decades ago, most of the rotational velocities were determined from blue-wavelength spectrograms by measurement of one or two relatively strong lines or by visual comparison. Early studies include Elvy (1929, 1930) and the classic paper of Struve (1930), as well as a series of papers by Slettebak (e.g., Slettebak 1954, 1955, 1956). Early results for late-type stars include those of Herbig and Spalding (1955) and Kraft (1967). Slettebak et al. (1975) established a system of standard rotational-velocity stars, primarily for moderate and rapid rotators. Gray (1988, 1992) has extensively discussed stellar rotation and its analysis.

While large numbers of early-type stars are rapidly rotating (e.g., Slettebak 1954, 1955); Kraft (1967) found that in F stars the mean $v \sin i$ decreases rapidly with decreasing mass. Work over the last two decades has shown just how slowly rotating the vast majority of single late-type dwarfs (e.g., Soderblom 1982; Benz and Mayor 1984; Gray 1984) and evolved stars (e.g., Gray and Nagar 1985; Gray 1989; de Medeiros and Mayor 1989) are.

In early studies, results for slowly rotating late-type stars had considerable uncertainty because of insufficient resolution (e.g., Herbig and Spalding 1955) and because macroturbulence could not be differentiated from rotational broadening (e.g., Oke and Greenstein 1954). Carroll (1933a,b) first obtained the Fourier transform of line profiles to determine rotational velocities but was limited by the signal-to-noise ratio of his observations. Gray (1975) developed an improved Fourier-transform analysis procedure, and with the advent of solid-state detectors Smith and Gray (1976) reviewed how the Fourier-transform technique could be used to determine very low rotational velocities and to differentiate between rotational velocity and macroturbulence in high-resolution, high signal-to-noise spectrograms. The technique of matching model-atmosphere profile models to line profiles in the Fourier-transform domain has been used by Smith (1979); Vogel and Kuhi (1981); Gray (e.g., Gray 1984, 1989); Bouvier et al. (1986); and others. Soderblom (1982) and Soderblom et al. (1989) used both the Fourier transform of the profile and visual matching of profile models to the line profiles.

For late-type stars another technique, the measurement of projected rotational velocities from cross-correlation profiles, has been successfully used (Benz and Mayor 1984; Bouvier et al. 1986; de Medeiros and Mayor 1989). Unlike the visual matching of profile models or the Fourier-transform analysis, this method requires a calibration but obviously can be applied to the huge number of late-type stars in the CORAVEL data base.

Although helpful in identifying older sources of $v \sin i$ measurement, catalogs such as those of Bernacca and Perinotto (1970) and Uesugi and Fukuda (1982) have serious problems (Soderblom et al. 1989) because they attempt to combine observations that have different resolutions as well as measurements made with a variety of techniques. Soderblom et al. (1989) showed that the catalogs, particularly Uesugi and Fukuda (1982), are seriously degraded by systematic problems, due in large part to the results of Huang (1953). Thus, the user of such catalogs must exercise great caution. Because most of the old results were based on spectrograms of moderate resolution, upper limits of $v \sin i$ were determined for many late-type stars.

While most late-type stars are slowly rotating, rapid rotation in G and K stars is characteristic of very young stars and close binaries. In addition, a small group of single late-type giants has been found to be rapidly rotating (e.g., Fekel et al. 1986; Fekel and Balachandran 1993), indicating the existence of a previously unpredicted evolutionary state. Thus, rotational-velocity measurement of late-type stars is an important diagnostic for identifying interesting stars.

In the course of a program to determine the spectral types of chromospherically active stars (Strassmeier and Fekel 1990), spectra were obtained of well over 100 relatively

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bright late-type (spectral types F–K) stars for use as spectral-type standards. Projected rotational velocities have been measured for these bright stars with a calibration determined from a subset of stars that are in common with the samples of Gray (e.g., Gray 1984, 1989). This new calibration has then been used to redetermine the projected rotational velocities of a number of chromospherically active stars, many of which were listed in Fekel et al. (1986); Strassmeier et al. (1990, 1993); and Henry et al. (1995). Rotational velocities of some additional stars have been measured for the first time.

2. OBSERVATIONS

From 1989 to 1996 high-dispersion spectroscopic observations were obtained at the Kitt Peak National Observatory (KPNO) with the coudé feed telescope, coudé spectrograph, and a TI CCD. The wavelength region observed was centered at 6430 Å. The spectra have a wavelength range of 80 Å, an instrumental resolution of 0.21 Å corresponding to a velocity resolution of 9.8 km s^{-1}, and a typical signal-to-noise ratio of 200 or more.

3. ROTATIONAL-VELOCITY ANALYSIS

The time-consuming method involving the comparison of model-atmosphere profile models to spectral lines has not been used. Instead, a procedure similar to that used by Fekel et al. (1986) and Strassmeier et al. (1990) was followed. The full width at half-maximum (FWMH) of about a half-dozen weak or moderate-strength lines, usually including 6432, 6452, 6455, 6456, 6469, 6471 Å, which have typical equivalent widths ranging from 20 to 90 mÅ, were measured and averaged. In the case of rapidly rotating late-G and K stars, those lines are often blended, and so, the least blended lines in the 6430 Å spectral region were used. The FWHM of several comparison-lamp lines was measured, and their average, typically 0.21 Å, was assumed to be the instrumental broadening. This instrumental broadening was removed from the measured broadening by taking the square root of the difference of the squares of the two measurements, resulting in the intrinsic stellar broadening.

To convert each stellar broadening to a $v \sin i$ value, Gray's results (e.g., Gray 1982a, 1984, 1989) were used. Values of the mean stellar FWHM were plotted against Gray's total broadening for the stars in common. Initially most of the stars in the sample had broadenings ≤ 10 km s^{-1}. To extend the range of the calibration, a dozen additional stars were observed that had line broadenings from 10 to 50 km s^{-1}. A second-order polynomial,

$$\mathrm{FWHM} = 0.04082 + 0.02509X + 0.00014X^2,$$

where X is the value of Gray's total broadening, was fitted to the results for 57 stars (Fig. 1) and used as the calibration curve.

Thus, for each observation the mean FWHM in Ångstroms was converted into a total line broadening in km s^{-1}, and the assumed macroturbulence then was removed by taking the square root of the difference of the squares. For those stars having more than one observation, an average rotational broadening was determined.

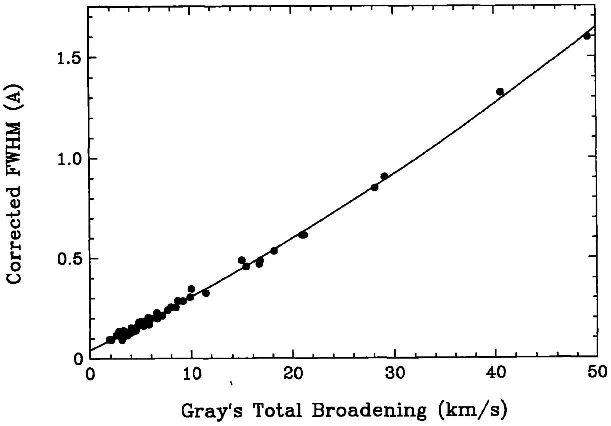

FIG. 1—For 57 stars in common, the best-fit relationship between the corrected FWHM measurements and Gray's total broadening is shown by the solid line.

The macroturbulent broadening is equal to or greater than the rotational broadening in many of the slowly rotating stars of the sample. Although 43% of the stars in Table 1 have been analyzed by Gray and so have individual macroturbulent velocities, many of the observed stars have not previously been analyzed. While some determined macroturbulent velocities have errors less than 0.5 km s^{-1}, the range of values suggests that a mean value over a spectral-type range is an adequate representation for most stars. Thus, mean macroturbulent velocities have been assumed for various ranges of spectral types. These mean values include 5 km s^{-1} for early-F dwarfs (Gray 1982a), 3 km s^{-1} for solar-type dwarfs (Soderblom 1982), and 2 km s^{-1} for K dwarfs (Marcy and Basri 1989). For giants 5 km s^{-1} has been used for early-G giants, 3 km s^{-1} for late-G and K giants (Gray 1989), and 5–3 km s^{-1} (Gray and Nagar 1985) for F–K subgiants. Macroturbulent velocities for other spectral ranges have been interpolated. For the very few bright giants and supergiants in our list, macroturbulent velocities similar to those of Gray and Toner (1986, 1987) were assumed. Note that in his papers Gray (1982b) lists most probable macroturbulent velocities, which are 1.414 times greater than the rms values given here.

Table 1 lists the computed $v \sin i$ values for 133 stars, nearly all of which are in *The Bright Star Catalogue* (Hoffleit 1982), and compares them, if possible, with other well-determined values in the literature. While the vast majority of those stars are quite inactive, showing little if any Ca II H and K emission, several single, chromospherically active G and K dwarfs and giants such as ϵ Eri, χ^1 Ori, π^1 UMa, ρ^1 Cnc, and HR 5225 have been included because their larger rotational velocities were important for the calibration or because their $v \sin i$ values had already been measured by others, providing a useful comparison. The first three columns identify the stars by HD, HR, and other name, respectively. Column 4 lists the spectral type, which has been assumed from Keenan and McNeil (1989), if available, and then from other expert classifiers. Only as a last resort has an unreferenced type been assumed from *The Bright Star*

TABLE 1
Rotational Velocities of Bright Late-Type Stars

HD	HR	Name	Spectral type	$v \sin i$ (km s^{-1})	v_{macro} (km s^{-1})	No.	Gray[a] (km s^{-1})	Soderblom[b] (km s^{-1})	CORAVEL[c] (km s^{-1})
3651	166	54 Psc	K0 V	2.2	2.0	1	···	···	···
4128	188	β Cet	G9 III	4.0	3.0	3	3.0	···	···
6582	321	μ Cas	G5 Vb	0.4	3.0	1	···	···	···
10307	483	···	G1.5 V	2.1	3.0	2	···	2.0	2.4
10476	493	107 Psc	K1 V	0.6	2.0	1	···	···	···
10700	509	τ Cet	G8 V	0.6	2.0	2	0.9	···	···
10780	511	···	K0 V	0.6	2.0	2	···	···	···
12929	617	α Ari	K2 IIIab	1.8	3.0	3	3.1	···	···
14622	687	···	F0 III-IV	48.4	5.0	3	49.0	···	···
20630	996	κ Cet	G5 V	3.9	3.0	4	···	5.6	4.3
22049	1084	ϵ Eri	K2 V	2.0	2.0	3	2.2	···	1.5
22484	1101	10 Tau	F9 IV-V	2.8	3.0	6	···	4.5	3.3
23249	1136	δ Eri	K0 IV	0.6	2.0	2	···	···	0.0
26162	1283	ω^1 Tau	K2 III	2.2	3.0	2	···	···	···
26462	1292	45 Tau	F4 V	18.2	5.0	2	···	···	···
26965	1325	o^2 Eri	K0.5 V	1.6	2.0	1	···	···	···
30652	1543	π^3 Ori	F6 V	15.8	4.0	1	16.3	18.0	···
33021	1662	13 Ori	G1 IV	0.7	4.0	2	···	···	···
35296	1780	111 Tau	F8 V	15.4	3.0	2	16.0	···	···
37160	1907	40 Ori	K0 IIIb	0.4	3.0	1	···	···	···
39587	2047	χ^1 Ori	G0 V	8.6	3.0	2	···	9.4	9.0
40136	2085	η Lep	F1 V	16.6	5.0	1	···	···	···
48329	2473	ϵ Gem	G8 Ib	9.7	6.0	1	7.1	···	···
48843	2489	32 Gem	A9 III	9.3	5.0	8	···	···	···
61421	2943	Procyon	F5 IV-V	4.9	4.0	3	2.8	···	4.5
62345	2985	κ Gem	G8 III	2.8	3.0	3	···	···	···
62509	2990	β Gem	K0 IIIb	1.7	3.0	9	2.5	···	···
63332	3028	···	F6 V	8.6	4.0	1	···	···	···
66141	3145	···	K2 III	2.5	3.0	1	···	···	···
67228	3176	μ^2 Cnc	G1 IV	3.0	4.0	1	3.7	···	···
69267	3249	β Cnc	K4 III	4.0	3.0	2	···	···	···
69830	3259	···	G7.5 V	2.2	2.0	1	···	···	···
69897	3262	χ Cnc	F6 V	3.9	4.0	1	···	···	···
71369	3323	o UMa	G5 III	3.4	4.0	2	2.4	···	···
72905	3391	π^1 UMa	G1.5 V	9.5	3.0	1	8.5	9.5	9.7
75732	3522	ρ^1 Cnc	G8 V	2.2	2.0	2	···	···	···
79969	···	···	K3 V	2.3	2.0	1	···	···	···
82210	3771	24 UMa	G5 III-IV	5.9	4.0	1	4.9	···	···
82328	3775	θ UMa	F6 IV	6.4	5.0	4	6.4	···	···
84117	3862	···	F9 V	6.2	3.0	2	···	5.0	···
85444	3903	39 Hya	G6.5 III	2.9	4.0	1	···	···	···
88230	···	···	K7 V	3.1	2.0	1	···	···	···
90508	4098	···	F9 V	0.6	3.0	1	···	2.5	1.4
94481	4255	···	G4 III	2.4	4.0	1	3.9	···	···
95689	4301	α UMa	K0 IIIa	3.2	3.0	1	2.6	···	···
99984	4431	58 UMa	F4 V	5.5	5.0	2	···	···	···
101501	4496	61 UMa	G8 V	2.3	2.0	1	···	···	···
102574	4529	···	G0 IV	7.4	4.0	2	···	···	···
102870	4540	β Vir	F9 V	4.5	3.0	12	3.2	4.0	3.6
103095	4550	Gmb 1830	G8 Vp	2.2	2.0	1	···	···	···
104979	4608	o Vir	G8 IIIa	2.5	3.0	1	···	···	···
106516	4657	···	F7 Vm-2	6.5	4.0	1	···	···	···
107328	4695	16 Vir	K0.5 IIIb	4.0	3.0	4	···	···	···
109358	4785	β CVn	G0 V	0.4	3.0	1	2.1	1.8	2.9
109379	4786	β Crv	G5 IIb	4.4	5.0	1	···	···	···
112412	4914	α^1 CVn	F1 V	17.4	5.0	1	···	···	···
113226	4932	ϵ Vir	G8 IIIab	3.2	3.0	1	···	···	···
113337	4934	···	F5 V	8.1	4.0	1	···	···	···
113996	4954	41 Com	K5 III	3.2	3.0	1	···	···	···
114710	4983	β Com	F9.5 V	4.3	3.0	3	3.9	4.3	4.3
115383	5011	59 Vir	G0 V	9.6	3.0	1	···	7.5	7.4
115404	···	···	K2 V	3.9	2.0	1	···	···	···
115617	5019	61 Vir	G6.5 V	0.4	3.0	4	0.0	···	···
117176	5072	70 Vir	G4 V	1.2	3.0	3	···	···	···

TABLE 1
(Continued)

HD	HR	Name	Spectral type	$v \sin i$ (km s^{-1})	$v_{\rm macro}$ (km s^{-1})	No.	Gray[a] (km s^{-1})	Soderblom[b] (km s^{-1})	CORAVEL[c] (km s^{-1})
120136	5185	τ Boo	F7 V	14.8	4.0	6	14.8	17.0	14.5
121107	5225	7 Boo	G5 III	15.8	4.0	1	14.1	···	···
124570	5323	14 Boo	F6 IV	4.1	5.0	3	···	···	···
124897	5340	α Boo	K1.5 III	3.3	3.0	2	2.4	···	···
125111	5347	···	F2 IV	8.6	5.0	4	···	···	···
126660	5404	θ Boo A	F7 V	29.3	4.0	2	28.5	29.0	···
126868	5409	ϕ Vir	G2 IV	15.7	4.0	1	···	···	···
128167	5447	σ Boo	F2 V	7.8	5.0	9	7.5	7.5	8.1
131156	5544	ξ Boo A	G8 V	3.2	2.0	5	2.9	···	···
131977	5568	···	K4 V	1.2	2.0	2	···	···	···
134083	5634	45 Boo	F5 V	42.9	4.0	1	···	45.0	···
136202	5694	5 Ser	F8 IV-V	4.3	3.0	7	···	4.6	···
139641	5823	ϕ Boo	G7 III-IV	0.6	2.0	1	···	···	···
141004	5868	λ Ser	G0 V	2.9	3.0	2	2.3	2.4	2.8
142091	5901	κ CrB	K1 IVa	0.6	2.0	1	···	···	···
142373	5914	χ Her	F8 VFe-2	2.4	3.0	1	2.6	2.2	3.4
142860	5933	γ Ser	F6 V	9.9	4.0	4	10.8	9.3	···
142980	5940	···	K2-3 IV	2.2	2.0	1	1.1	···	···
143107	5947	ϵ CrB	K2 IIIab	1.3	3.0	2	···	···	···
144284	5986	θ Dra	F8 IV-V	27.7	3.0	2	27.8	···	···
145148	6014	···	K1.5 IV	0.6	2.0	1	···	···	···
145675	···	···	K0 V	0.6	2.0	1	···	···	···
148856	6148	β Her	G7 IIIa	3.0	4.0	1	3.4	···	···
149661	6171	12 Oph	K0 V	0.6	2.0	1	···	···	0.0
150680	6212	40 Her	G0 IV	3.9	4.0	1	2.9	···	···
156026	···	···	K5 V	2.2	2.0	1	···	···	0.0
156897	6445	ξ Oph	F2 V	19.9	5.0	2	20.6	···	···
157856	6489	···	F6 IV	15.1	5.0	1	···	···	···
157881	···	···	K7 V	3.9	2.0	1	···	···	···
161096	6603	β Oph	K2 III	2.5	3.0	5	1.6	···	···
161239	6608	84 Her	G2 IV	6.0	4.0	2	5.1	···	···
161797	6623	μ Her A	G5 IV	1.2	3.0	5	1.2	<5	···
165341	6752	70 Oph A	K0 V	3.1	2.0	3	1.6	···	···
165497	6770	71 Oph	G8 III	4.7	3.0	1	3.9	···	···
166620	6806	···	K2 V	0.6	2.0	1	···	···	0.0
167858	6844	···	F1 V	8.0	5.0	3	···	···	···
168723	6869	η Ser	K0 III-IV	2.6	2.0	2	2.8	···	···
173009	7032	ϵ Sct	G8 IIb	6.4	5.0	1	6.5	···	···
173667	7061	110 Her	F6 V	17.4	4.0	2	17.0	···	···
173920	7071	···	G5 III	8.4	4.0	1	7.7	···	···
174464	7094	···	F2 Ib	19.6	6.0	2	20.3	···	···
175225	7123	···	G9 IV	2.2	2.0	1	···	···	···
176095	7163	···	F5 IV	11.6	5.0	1	···	12.1	···
180809	7314	θ Lyr	K0 II	3.9	4.0	1	3.6	···	···
182488	7368	···	K0 V	0.6	2.0	1	···	···	···
182572	7373	31 Aql	G7 IV	2.6	2.0	2	2.3	···	···
185144	7462	σ Dra	K0 V	0.6	2.0	4	0.8	···	···
185395	7469	θ Cyg A	F4 V	3.5	5.0	3	3.4	5.3	···
185758	7479	α Sge	G1 II	6.0	5.0	2	5.8	···	···
186408	7503	16 Cyg A	G1.5 Vb	2.2	3.0	1	···	1.6	1.0
186427	7504	16 Cyg B	G3 V	0.4	3.0	1	···	2.7	2.2
187691	7560	o Aql	F8 V	3.1	3.0	6	···	<3	2.6
188376	7597	ω Sgr	G5 IV	2.2	3.0	3	···	···	···
188512	7602	β Aql	G8 IV	1.4	2.0	6	2.2	···	···
188947	7615	η Cyg	K0 III	1.8	3.0	6	···	···	···
196524	7882	β Del	F7 IV	41.2	5.0	2	40.0	···	···
196755	7896	κ Del	G2 IV	2.7	4.0	3	3.3	···	···
197964	7948	γ^2 Del A	K1 IV	2.9	2.0	3	2.8	···	···
197989	7949	ϵ Cyg	K0 III	2.0	3.0	4	3.0	···	···
198149	7957	η Cep	K0 IV	0.6	2.0	1	2.0	···	···
201091	8085	61 Cyg A	K5 V	0.6	2.0	2	···	···	0.0
201092	8086	61 Cyg B	K7 V	1.4	2.0	2	···	···	1.7
208110	8359	···	G2 III-IVm−2	5.2	5.0	1	4.0	···	···

TABLE 1
(Continued)

HD	HR	Name	Spectral type	$v \sin i$ (km s^{-1})	v_{macro} (km s^{-1})	No.	Gray[a] (km s^{-1})	Soderblom[b] (km s^{-1})	CORAVEL[c] (km s^{-1})
212698	8545	53 Aqr A	G0 V	9.9	3.0	1	⋯	9.4	⋯
212943	8551	35 Peg	K1 III-IV	1.0	3.0	3	⋯	⋯	⋯
215243	8653	⋯	F6 Vn	7.5	4.0	1	⋯	⋯	⋯
215648	8665	ξ Peg	F7 V	7.8	3.0	4	6.7	8.9	8.4
219134	8832	⋯	K3 V	2.1	2.0	2	⋯	⋯	⋯
222368	8969	ι Psc	F7 V	5.6	3.0	5	⋯	5.7	6.0

[a] Gray (1982a, 1984, 1986, 1989, 1996); Gray and Nagar (1985); Gray and Toner (1986, 1987).
[b] Soderblom (1982); Soderblom et al. (1989).
[c] Benz and Mayor (1984); Soderblom and Mayor (1993).

Catalogue (Hoffleit 1982). This is because the spectral type plays a critical role in assigning a macroturbulent velocity. Columns 5–7 list for each star the $v \sin i$ value, assumed macroturbulence, and number of spectrograms. For comparison, the literature was searched for rotational velocities from the work of Gray and Soderblom as well as results obtained with CORAVEL. Those values are listed in columns 8–10, respectively.

Table 2 lists the projected rotational velocities of an additional 97 systems, which are identified as chromospherically active because the stars show significant Ca II H and K emission or have photometric variations attributed to spots or have significant ultraviolet emission. Given in columns 1–7 are the HD number, variable star name, other name, duplicity, $v \sin i$, assumed macroturbulent velocity, number of spectrograms, and minimum radius, respectively. The minimum radius has been computed from the measured $v \sin i$ value and a photometrically determined rotational period taken from the literature (e.g., Strassmeier et al. 1989, Hooten and Hall 1990, Strassmeier et al. 1993, Henry et al. 1995).

In Table 2 the same relationship between macroturbulence and spectral type has been assumed that was used for the stars in Tables 1 and 3. While it is possible that active stars by their very nature may have significantly larger macroturbulent velocities compared to inactive stars of the same spectral type, no study to search for such an effect has so far been done. The vast majority of active late-type stars are rapid rotators, usually due to synchronization or pseudosynchronization of rotational and orbital periods if the stars are in binary systems or due to their youthfulness if the stars are single. Thus, the $v \sin i$ values of most of the stars are large enough so that the assumed macroturbulence is relatively unimportant.

A few of the stars in Table 2 have a colon after the $v \sin i$ value indicating greater uncertainty. These stars are typically the secondaries in double-lined binaries. Their lines are quite weak when compared to those of the primaries and hence, more likely to be affected by blending. In such cases the true projected rotational velocities are likely to be *smaller* than the listed values.

Table 3 lists 14 stars, many previously appearing in Henry et al. (1995), that are not identifiable with the groups in Tables 1 or 2. The columns in Table 3 are the same as those in Table 2 except that there is no minimum radius column.

The rotational velocities and minimum radii in the tables supersede previous results, determined with a different calibration, that have appeared in the literature in several papers including Fekel et al. (1986); Strassmeier et al. (1990); Fekel and Balachandran (1993), and Henry et al. (1995); as well as the compilation of chromospherically active binaries (Strassmeier et al. 1993). In many cases the velocities on the old scale have been revised upward by about 15%–20%. Some of the stars listed in Tables 1–3, however, have had their projected rotational velocities determined for the first time.

4. DISCUSSION

The projected rotational velocities of the stars in Table 1 that are in common with Gray's sample are *not* independent values. Nevertheless, since mean macroturbulent velocities were assumed, the results for the low $v \sin i$ stars do not solely depend on the calibration. The calibration appears to be robust enough so that removing many of the stars from it would do little to change it except at the upper end.

As shown in Table 1, our sample has a significant overlap, 27 stars, with the combined sample of Soderblom (1982) and Soderblom et al. (1989). Figure 2 compares the individual rotational velocities with a line corresponding to a one-to-one correlation shown for reference. The best-fit slope is 0.97 so a slope of 1.0 represents the data quite well. The rms scatter of points is 1.1 km s^{-1}, which is slightly greater than the typical error for Soderblom's $v \sin i$ measures (Soderblom et al. 1989). This indicates the good agreement between the two samples and suggests that our errors are in the range of 0.5–1.0 km s^{-1}. Figure 3 compares the 28 stars in common with published CORAVEL results (Benz and Mayor 1984; Soderblom and Mayor 1993). Once again, a one-to-one line is shown for reference and indicates that there is good general agreement between the two systems. The rms scatter of points about the one-to-one correlation line is 0.8 km s^{-1}, similar to that for the Soderblom sample.

While rotational velocities less than 30 km s^{-1} have estimated errors of 0.5–1.0 km s^{-1}, larger velocities have greater uncertainties for several reasons. First, above 30 km s^{-1} there are only two calibration points (Fig. 1). Second, the line depth decreases with broadening, making the effects of blends and continuum placement more important. Third, in chromospherically active stars, many of which are rapidly rotating, the effect of spots on the line shapes be-

TABLE 2
Rotational Velocities of Chromospherically Active Stars

HD	Variable name	Other name	Duplicity[a]	$v \sin i$ (km s^{-1})	$v_{\rm macro}$ (km s^{-1})	No.	R$_{\rm min}$ ($R_\odot$)
1405	PW And	···	C	23.4	3.0	1	0.8
1833	BD Cet	···	SB1	18.2	3.0	2	12.4
6286	BE Psc	···	SB1	17.5	3.0	3	12.3
7205	···	···	SB1	2.6	3.0	4	1.1
8357A	AR Psc	···	SB2	7.6	3.0	6	1.8
B	···	···	···	4.2	3.0	6	···
9746	OP And	HR 454	C	9.0	3.0	1	13.5
10909	UV For	···	SB1	3.0	3.0	4	1.9
11150	···	···	C	16.2	3.0	4	···
12545	XX Tri	···	SB1	18.2	3.0	1	9.0
13480Aa	TZ Tri	HR 642	SB2	37.3	3.0	6	10.8
Ab	···	···	···	8.3	4.0	4	···
17144	UY For	···	C	21.3	3.0	2	6.8
17433	VY Ari	···	SB1	10.2	2.0	1	3.3
17925	···	HR 857	C:	var	2.0	8	···
18632	···	···	C:	1.8	2.0	2	0.4
18645	···	···	C	9.8	4.0	2	4.2
19485A	WZ Ari	···	SB2	10.9	3.0	4	1.4
B	···	···	···	9.4	3.0	4	···
19942	V510 Per	···	SB1	13.5	3.0	4	5.9
22694A	···	···	SB2	8.4	3.0	1	1.2
B	···	···	···	8.4	3.0	1	1.2
25893	V491 Per	···	C	5.2	3.0	1	0.8
28591	V492 Per	···	SB1	28.8	3.0	1	4.1
29697	V834 Tau	···	C	9.5	2.0	3	0.7
31738A	V1198 Ori	···	SB2	21.7	3.0	1	···
B	···	···	···	8.9:	3.0	1	···
31993	V1192 Ori	···	C	33.4	3.0	1	18.9
32357	BM Cam	HR 1623	SB1	13.1	3.0	5	22.0
33363	···	···	SB1	10.7	3.0	7	8.8
37824	V1149 Ori	···	SB1	14.9	3.0	6	16.0
33798	V390 Aur	···	C	33.1	3.0	1	6.4
37847A	TW Lep	···	SB2	23.4	3.0	4	13.1
B	···	···	···	4.0	4.0	1	···
39743	···	HR 2054	SB1	9.5	3.0	3	13.7
51066	···	···	SB1	45.6	3.0	3	14.6
62668	···	···	SB1	16.3	3.0	5	22.5
65626A	AE Lyn	HR 3119	SB2	12.9	3.0	2	···
B	···	···	···	17.0	3.0	2	3.4
70573	···	···	C	13.6	3.0	2	0.9
72146	···	···	C	17.4	3.0	4	9.8
72429	···	···	C	19.6	4.0	2	3.6
80492	···	···	SB1	26.3	3.0	1	···
80953	···	HR 3722	C:	4.0	3.0	1	7.7
81410	IL Hya	···	SB1	27.1	3.0	4	6.9
82286A	···	···	SB2	38.8	3.0	5	2.5
B	···	···	···	39.7	3.0	3	···
82443	···	···	C	6.2	2.0	3	0.7
85091A	···	···	SB2	8.5	3.0	7	0.6
B	···	···	···	7.1:	2.0	2	···
89546	···	···	SB1	18.0	3.0	6	7.6
95559A	···	···	SB2	32.9	3.0	2	···
B	···	···	···	33.8	3.0	2	···
106225	HU Vir	···	SB1	31.3	3.0	1	6.4
106677A	DK Dra	HR 4665	SB2	12.7	3.0	1	16.0
B	···	···	···	13.5	3.0	1	17.0
112859A	···	···	SB2	20.2	3.0	6	7.4
B	···	···	···	7.5	3.0	5	···
113816	···	···	SB1	5.9	3.0	3	2.7
118234	···	···	SB1	6.5	3.0	1	8.2
118981A	···	···	SB2	7.6	3.0	5	0.9
B	···	···	···	8.8:	2.0	2	···
122767	···	···	SB1	9.2	3.0	1	17.5
131511	···	HR 5553	SB1	3.9	2.0	2	0.8
141690Aa	···	···	SB1	20.6	3.0	1	1.0

Table 2
(Continued)

HD	Variable name	Other name	Duplicity[a]	$v \sin i$ (km s^{-1})	$v_{\rm macro}$ (km s^{-1})	No.	R$_{\rm min}$ ($R_\odot$)
Ac	···	···	···	7.0:	3.0	1	···
144110A	···	···	SB2	31.3	3.0	3	1.0
B	···	···	···	27.0	3.0	3	···
144515Aa	···	···	SB1	12.1	3.0	1	1.2
Ba	···	···	SB1	7.0	3.0	1	···
148405	···	···	SB1	8.7	3.0	1	9.8
152178	V2253 Oph	···	SB1	28.8	3.0	2	12.7
160538	DR Dra	29 Dra	SB1	6.7	3.0	2	4.2
160934	···	···	C	16.4	2.0	3	0.6
161570	···	···	SB1	7.0	3.0	4	···
163621A	···	···	SB2	7.6	3.0	1	0.5
B	···	···	···	9.9:	3.0	1	···
165141	V832 Ara	···	SB1	16.7	3.0	5	11.4
165590Aa	V772 Her	···	SB1	69.3	3.0	3	1.2
B	···	···	···	14.6	3.0	3	···
166181	V815 Her	···	SB1	31.2	3.0	4	1.1
171488	···	···	C	38.0	3.0	3	1.0
178450	V478 Lyr	···	SB1	24.7	3.0	1	1.0
179094	V1762 Cyg	HR 7275	SB1	17.5	3.0	1	9.9
181809	V4138 Sgr	···	SB1	4.2	3.0	6	5.0
181943	···	···	C	6.2	2.0	4	···
185510	V1379 Aql	···	SB1	19.6	3.0	1	9.9
193891	V1971 Cyg	···	SB1	11.4	3.0	5	9.2
199178	···	···	C	65.4	5.0	1	4.3
203251	AU Cap	···	C	46.5	3.0	1	···
203387	ι Cap	HR 8167	C	5.0	4.0	3	6.7
205249	AS Cep	···	SB1	7.4	3.0	3	8.5
206301A	···	HR 8283	SB2	5.2	4.0	3	1.2
B	···	···	···	4.4	3.0	3	···
208472	···	···	SB1	19.7	3.0	4	8.8
213389	V350 Lac	HR 8575	SB1	35.7	3.0	1	12.5
216489	IM Peg	HR 8703	SB1	28.2	3.0	1	13.6
217188	AZ Psc	···	SB1	4.2	3.0	3	7.6
217411	···	···	C	3.4	3.0	3	···
218153	KU Peg	···	SB1	28.9	3.0	3	12.6
220140	V368 Cep	···	C	16.1	3.0	2	0.9
223971A	···	···	SB2	6.1	4.0	2	6.4
B	···	···	···	30.1:	5.0	3	···
224085	II Peg	···	SB1	23.1	3.0	4	3.1
245059	···	···	C:	23.0	3.0	1	···
337518A	···	···	SB2	14.2	2.0	2	0.8
B	···	···	···	13.5	2.0	1	···
···	···	BD −00°4234A	SB2	8.4	2.0	1	0.7
···	···	B	···	6.9	2.0	1	···
···	···	BD +05°3080A	SB2	5.6	3.0	4	···
···	···	B	···	6.2:	3.0	2	···
···	···	BD +13°13A	SB2	23.7	3.0	5	0.9
···	···	B	···	22.5:	2.0	4	···
···	···	BD +17°4799	SB1	11.4	3.0	1	···
···	···	BD +30°2130	SB1	8.6	3.0	2	···
···	···	BD +36°2193	SB1	4.7	3.0	1	···
···	···	BD +48°3686	C	19.8	2.0	2	0.9
···	DM UMa	BD +61°1211	SB1	27.4	3.0	2	4.0
···	ET Dra	BD +70°959	C	23.5	3.0	2	6.6
···	···	1E2349.8−0112[b]	C	47.3	3.0	4	1.1
···	···	Tau 1A	SB2	18.8	3.0	3	0.5
···	···	B	···	19.5	3.0	3	···

[a] C=constant velocity, SB1=single-lined binary, SB2=double-lined binary, :=a more uncertain quantity, var =variable.

[b] $\alpha=23^{\rm h}52^{\rm m}24\overset{\rm s}{.}5$, $\delta=-00°56'15''$(2000).

TABLE 3
Rotational Velocities of Other Stars

HD	Variable name	Other name	Duplicity[a]	v sin i (km s^{-1})	$v_{\rm macro}$ (km s^{-1})	No.
3266A	...	...	SB2	2.9	3.0	3
9939A	...	...	SB2	2.2	2.0	5
99267	...	...	C	88.7:	5.0	1
100440	...	...	C	3.9	3.0	3
105020	...	...	SB1	3.2	3.0	1
113449	...	...	C:	5.3	3.0	1
141207	...	...	C:	1.4	3.0	2
144432	...	...	C:	72.6	5.0	1
148127	...	...	C:	4.2	3.0	3
181475	...	...	C:	8.2	6.0	2
195987A	...	...	SB2	2.1	3.0	3
200077A	...	...	SB2	6.5	3.0	1
202951	...	HR 8149	C:	4.0	3.0	2
...	...	BD +72°245	SB1	2.9	3.0	2

[a] C=constant velocity, SB1=single-lined binary, SB2=double-lined binary, :=a more uncertain quantity.

comes more noticeable. Fourth, a Gaussian slowly becomes a poorer fit to the observed profile although manual measurement of the FWHM of lines in such rapidly rotating stars indicates that a Gaussian representation remains adaquate for stars with rotational velocities up to 50 km s^{-1}. At 50 km s^{-1} the estimated errors are 2–3 km s^{-1}. Above 50 km s^{-1} the values are extrapolated, and values near 70 km s^{-1} have estimated errors of 5 km s^{-1}. Additional rapidly rotating stars are needed to confirm and extend the upper end of the calibration.

Fifty-four or 41% of the stars listed in Table 1 do not have published v sin i values by Gray, Soderblom, or the CORAVEL group. Only nine stars are common to all four systems.

5. NOTES ON INDIVIDUAL STARS

The following notes provide a brief status report or update on some of the systems. Unreferenced results come from the material used in the present study.

5.1 Table 1

32 Gem (HD 48843): This star is being observed as an early-type radial-velocity standard.

κ Gem (HD 62345): κ Gem has been followed on a yearly basis since 1989. Those observations indicate that it is a low-amplitude, long-period, single-line spectroscopic binary with a period of over 7 years.

σ Boo (HD 128167): σ Boo is being observed as an early-type radial-velocity standard.

HR 6844 (HD 167858): *The Bright Star Catalogue* (Hoffleit 1982) does not list a radial velocity for HR 6844. A half-dozen observations show the star to be a low-amplitude binary, and spectroscopic observations are continuing.

HR 8653 (HD 215243): The fundamental properties of HR 8653 given in the literature are contradictory. Its spectrum was classified as G8 IV by Harlan and Taylor (1970), and that type is listed in *The Bright Star Catalogue* (Hoffleit 1982). However, Cowley's (1976) classification of F6 Vn, where n means that the lines are rotationally broadened, is quite different. In contrast, Kraft (1967) determined a

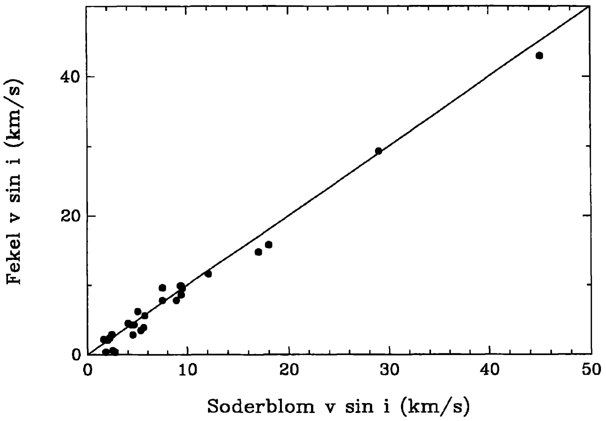

FIG. 2—Comparison of the present data with published v sin i data of Soderblom. The line showing a one-to-one correlation is plotted as a guide and is not a fit to the data.

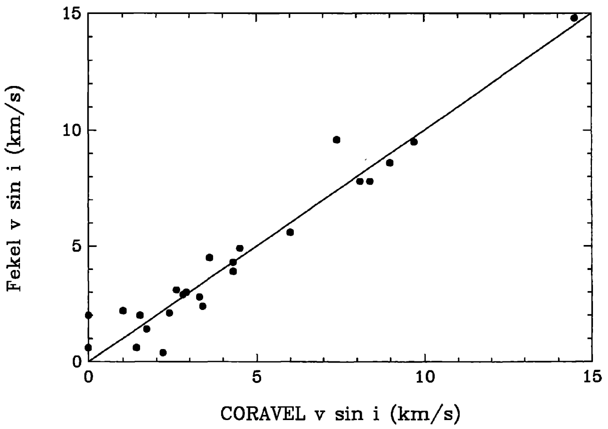

FIG. 3—Comparison of the present data with published v sin i values determined with CORAVEL. The line showing a one-to-one correlation is plotted as a guide and is not a fit to the data.

$v \sin i$ value of $\leq 6\ \mathrm{km\ s^{-1}}$, indicating that the lines have no large rotational broadening. To clear up these conflicting results, one spectrogram centered on 6430 Å was obtained. The spectrum is clearly that of a mid-F star, suggesting that the spectral type given by Harlan and Taylor (1970) belongs to another star. Our $v \sin i$ value of $7.5\ \mathrm{km\ s^{-1}}$ is consistent with Kraft's (1967) result. One possible explanation for Cowley's (1976) detection of line broadening is that the star is actually a double-lined binary whose components have not yet been resolved.

5.2 Table 2

HD 6286: Pasquini and Lindgren (1994) identified this star as a chromospherically active, Population II binary and conclude that it is a giant. While the star is indeed a chromospherically active giant binary, it is *not* metal poor. Instead, the weakened lines occur because the continuum of a hot secondary dilutes the strength of the absorption features.

HD 7205: This single-lined binary (Fouts 1987) has an orbital period of 18.0 days.

HD 11150: Fekel and Balachandran (1994) found this star to be a rapidly rotating, single, chromospherically active giant, but no search for photometric variablility has been made. Thus, its rotation period is unknown.

HR 857 (HD 17925): Henry et al. (1995) discussed the possibility that HR 857 is an unresolved double star. Well-determined $v \sin i$ values in the literature range from 3 to 8 $\mathrm{km\ s^{-1}}$. Two revised values from different observing seasons are 2.9 and $6.6\ \mathrm{km\ s^{-1}}$, in agreement with the range found in the literature.

HD 31738: Fekel et al. (1986) first identified this star as a double-lined binary. Although numerous additional spectra have been obtained, the system is quite difficult to analyze because the line broadening of both components is significant, and the velocity variations are small, resulting in lines that are always blended. The orbital period has not yet been determined.

HD 106225: This single-lined binary is actually part of a triple system whose long period is about 2100 days.

HD 161570: This star is a single-lined G giant with an orbital period of about 46 days.

HD 217411: Pounds et al. (1993) identified this object as an EUV source. Mulliss and Bopp (1994) found its Hα line partly filled and concluded that it is a chromospherically active star. Barstow et al. (1994) obtained ultraviolet spectra and discovered a white dwarf companion. The star is more extensively discussed in Henry et al. (1995).

HDE 245059: Skinner et al. (1991) identified this star as a naked T Tauri star.

BD +05°3080: Latham et al. (1988) discovered this metal-poor star to be a binary with a period of 9.94 days. Pasquini et al. (1991) found Ca II H and K emission from both components. Red-wavelength spectra show double absorption features.

BD +17°4799: Jeffries (1995) identified this star as an active single K V/IV star with a strong lithium line. A single radial velocity of $-20.2\ \mathrm{km\ s^{-1}}$ compared with Jeffries (1995) average of $-2.6\ \mathrm{km\ s^{-1}}$ indicates that the star is a binary.

Tau 1: This object appears in a survey of possible post-T Tauri stars by Walter (1986), who gave the star the designation listed in Table 2. Although Walter (1986) showed that the object has no significant lithium line and is, thus, not a post-T Tauri star, it is listed as a T Tau-type star in the SIMBAD data base. The star is more extensively discussed by Henry et al. (1995).

5.3 Table 3

HD 100440: Houk and Smith-Moore (1988) classified the star as K1-2V(p) with Ca II H and K cores possibly in emission but noted that the spectrum is underexposed. From a spectrum obtained at 6430 Å the star is classified as a K3 III but appears to be somewhat metal weak. The mean of three radial velocities is $58.3\ \mathrm{km\ s^{-1}}$.

HD 105020: Tan et al. (1993) found this giant to be a single-lined binary and estimated a period of about 20 days.

HD 195987: Latham et al. (1988) confirmed an orbital period of 57.3 days for this metal-poor binary. Spectra obtained at red wavelengths show weak secondary features.

HD 200077: Latham et al. (1988) discovered this metal-poor star to be a binary with an orbital period of 112.55 days.

BD +72°245: Latham et al. (1992) discovered this metal-poor star to be a binary with an orbital period of 7.54 days. No secondary features are seen at red wavelengths.

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