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Rotational Velocities of B, A, and Early-F Narrow-lined Stars

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ABSTRACT. Projected rotational velocities for 58 B, A, and early-F stars have been determined from high-resolution spectroscopic observations made at Kitt Peak National Observatory with the coudé feed telescope. All the stars are slowly rotating with $v \sin i < 60$ km s^{-1}. Because of their low rotational velocities, 15 of the stars have been observed as prospective, early-type, radial velocity standards.

1. INTRODUCTION

The projected rotational velocity of a star is a basic datum that is important in understanding the evolution of both single and binary stars. For some early-type spectral classes, rotational velocity appears to be a discriminant for stars with peculiar spectra, such as Be stars (Briot 1986) and Am and Ap stars (Abt & Morrell 1995). Rotational velocities can also be used to determine observationally close binary synchronization and compare the results with theory (Giuricin, Mardirossian, & Mezzetti 1984a, 1984b; Pan 1997). Projected rotational velocity surveys of A- and F-type stars include those of Danziger & Faber (1972), Abt & Morrell (1995), Wolff & Simon (1997), and Royer et al. (2002a, 2002b). Abt, Levato, & Grosso (2002) recently measured the projected rotational velocities of nearly 1100 bright, northern B-type stars.

Over the past decade spectroscopic observations of 58 B, A, and early F-type stars have been acquired to identify early-type constant velocity stars and to use as reference stars for spectral-type determinations. As part of the analysis, projected rotational velocities have been measured for these stars.

2. OBSERVATIONS

High-resolution spectroscopic observations were obtained with the Kitt Peak National Observatory (KPNO) coudé feed telescope, coudé spectrograph, and a TI CCD detector. Most of the spectrograms were centered in the red at 6430 Å, but additional observations were made in the blue at 4500 Å. The red spectra have a resolution of 0.21 Å, while the blue spectra have a nearly identical resolution of 0.22 Å. The spectra cover a wavelength range of about 80 Å and have typical signal-to-noise ratios of 200. Both blue and red wavelength observations were made for 20 stars, while a single observation was obtained for 13 stars.

3. $v \sin i$ MEASUREMENTS

The projected rotational velocities have been determined from the spectra of two different wavelength regions, 6430 and 4500 Å. In the 6430 Å region the measurable lines for A and early-F stars are primarily modest-strength Fe I features but also include Fe II and Ca I lines (Fig. 1). However, for B and some early-A type stars, those features are too weak for accurate determination of $v \sin i$. In the 4500 Å spectra the measured lines depend on the spectral class of the star. For early-B stars, Al III and N II lines were used, while for later spectral classes from mid-B to early-F, various Fe II and Ti II features can be measured (Fig. 2). Because they have large equivalent widths, the He I line at 4471 Å and the Mg II line at 4481 Å are useful lines to measure in the spectra of rapidly rotating B and A stars. However, the He I line has Stark-broadened wings and is blended with the forbidden [He I] component at 4470 Å (Slettebak et al. 1975), and the Mg II line is a close doublet. Because all the stars in this work are rotating relatively slowly, neither line was measured.

The procedure of Fekel (1997) has been used to determine the $v \sin i$ values. For each star, the full width at half-maximum (FWHM) of several metal lines in the 6430 Å region was determined from a Gaussian fit, and the results were 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, which resulted in the intrinsic broadening. The calibration polynomial of Fekel (1997), which is based on the results of Gray (e.g., Gray 1982, 1984, 1989), was used to convert this broadening in angstroms into a total line broadening in km s^{-1}.

Spectra centered at 4500 Å were analyzed in a manner similar to that for the red-wavelength spectra. The FWHM of several metal lines was measured, the results averaged, and an instru-

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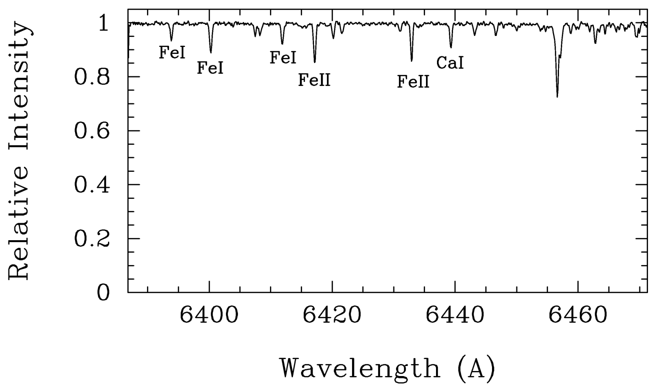

FIG. 1.—Portion of the red-wavelength spectrum of HR 1389 = 68 Tauri, spectral type A2 IV–Vs. The element and ionization stage are identified for several relatively isolated lines. In this wavelength region the Fe I lines increase rapidly in strength with later spectral class.

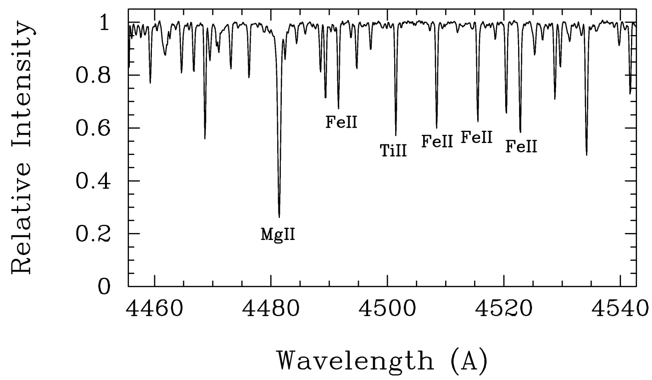

FIG. 2.—Portion of the blue-wavelength spectrum of HR 1389 = 68 Tauri, spectral type A2 IV–Vs. The element and ionization stage are identified for several relatively isolated lines.

mental broadening of 0.22 Å removed. Results from the 20 stars with both blue- and red-wavelength observations were used to convert the total intrinsic stellar broadening at 4500 Å to a $v \sin i$ value.

A second-order polynomial,

$$\mathrm{FWHM}_{4500} = 0.08016 + 0.01284X + 0.00011X^2,$$

where X is the value of the total intrinsic broadening at 6430 Å, was fitted to the data (Fig. 3) and used as a calibration curve. Since our blue-wavelength calibration is based on our red-wavelength results, it is also tied to the work of Gray.

Following Fekel (1997), for early-F stars, a macroturbulence of 5 km s^{-1} has been adopted and removed. For B and A stars, no additional broadening was removed. Uncertainties of 1 and 3 km s^{-1} were estimated for $v \sin i$ values near 20 and 50 km s^{-1}, respectively. Table 1 lists the results for 58 stars. Spectral types are from the literature, and the early-type, radial velocity standard candidates of Fekel (1999) are identified. The $v \sin i$ determinations from the blue and red spectrograms are listed separately and also averaged if there were measurements in both wavelength regions. These values *supercede* the results presented by Fekel (2003), which were based in part on a preliminary blue-wavelength calibration curve.

Two early B stars, HR 153 and HR 8768, have variable line widths, which likely result from nonradial pulsations. Their $v \sin i$ values in Table 1 are followed by a "v" to indicate that variability.

4. DISCUSSION

Recently, Royer et al. (2002a, 2002b) determined $v \sin i$ values for over 750 late-B to early-F stars. Their rotational velocities were measured from the frequency of the first zero in the Fourier transforms of several line profiles. Twenty-eight of the stars in Table 1 are in common with that sample, and in Figure 4 their individual projected rotational velocities are compared with those of this paper. Although the velocity range covered is somewhat limited, there is generally excellent agreement between our results except for the lowest and highest $v \sin i$ values, which require some explanation. The two surveys of Royer et al. (2002a, 2002b), for southern stars and northern stars, respectively, were obtained at different observatories with different spectrographs, and so the two sets of spectra have different resolutions. Royer et al. (2002b) estimated a resolution $R \approx 28{,}000$ at 4500 Å for the southern sample and $R \approx 16{,}000$ for the northern sample. The latter resolution is nearly a factor of 2 lower than that of the red-wavelength observations in this paper. Thus, at rotational velocities near 15 km s^{-1}, the departure of the northern sample $v \sin i$ values from the one-to-one relation (Fig. 4) is caused by the limiting resolution of the spectra of Royer et al. (2002b). For the seven stars with $v \sin i \geq 35$ km s^{-1}, our velocities are systematically larger than those of Royer et al. (2002b) by an average of 1.8 km s^{-1}. One reason for this difference may be that, as the rotational broad-

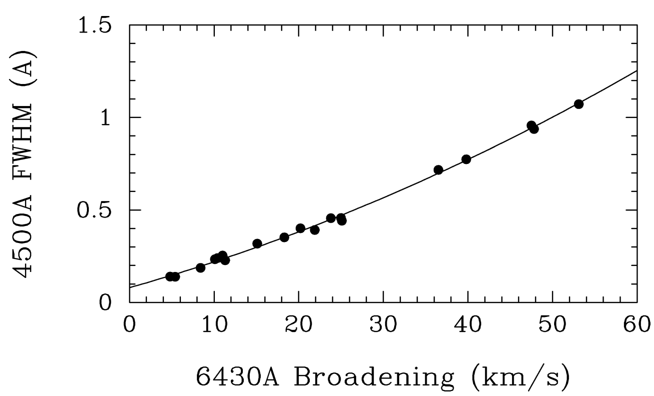

FIG. 3.—Best-fit relationship for 20 stars with both blue and red spectra. Plotted on the abscissa is the total stellar line broadening measured at 6430 Å. The ordinate is the stellar FWHM measurement at 4500 Å.

TABLE 1
v sin *i* Values of B, A, and F Stars

HR	HD	Spectral Type	*v* sin *i*[a] 6430 Å	4500 Å	Final
153[b]	3360	B2 IV	...	20.6v	21v
675[b]	14252	A2 IVs	25.0	24.3	25
811	17081	B7 V	...	21.2	21
895	18557	A2/A6:/F0	18.7	...	19
1174	23793	B3 V	...	48.4	48
1296	26553	A3/A7/A5	6.1	...	6
1389[b]	27962	A2 IV–Vs	10.1	11.0	11
1397	28114	B6 IV	...	20.4	20
1458Aa[c]	29140	A4/A6/A7	...	39.7	40
1613	32115	A9 V	11.0	12.2	12
1637	32537	F1 Vp	17.0	...	17
1664	33054	A2/F2/F3	39.5	39.9	40
1810[b]	35708	B2.5 IV	...	29.4	29
2010[b]	38899	B9 IV	...	29.9	30
2085	40136	F2 IV	16.6	...	17
2124Aa	40932	A4/A5/A7	9.7	...	10
2154[b]	41692	B5 IV	...	35.2	35
2238	43378	A1 Va	47.5	48.3	48
2421	47105	A2 IV	11.3	10.6	11
2489[b]	48843	A8 II	10.4	11.4	11
2818[b]	58142	A0mA1 IV	18.3	18.3	18
3136[b]	65900	A1 IV	36.5	37.5	37
3354	72037	A3/A5/A7	11.1	11.2	11
3383[b]	72660	A1 II	4.8	4.5	5
3526	75811	A4/A6/A7	11.1	...	11
4033	89021	A1 IV	...	53.4	53
4187	92728	A0 Vs	21.9	20.6	21
4237A[c]	93903	A3/A7 V/A9	20.2	21.1	21
4295[b]	95418	A1 IV	47.8	47.5	48
4359[b]	97633	A2 IV	25.1	23.5	24
4378	98280	A2 Vs	...	10.7	11
4454	100518	A2/A5 III/A6	6.6	...	7
4689Aa[c]	107259	A2 IV	5.8	...	6
4717	107966	A3 V	55.3	53.1	54
4750A[c]	108642	A2/A7/A7	6.9	...	7
4780	109367	A5/A7/A7	15.1	16.3	16
5017	115604	F3 IV	4.1	...	4
5075	117201	F2 V	10.1	...	10
5445	128093	F5 V	...	8.1	8
5447[b]	128167	F2 V	7.7	...	8
6035	145647	A1 III	...	46.9	47
6041	145788	A1 IIIs	8.4	7.8	8
6455	157087	A3 IVs	11.3	...	11
6787	166182	B2 IV	...	44.1	44
6844	167858	F1 V	7.9	...	8
7287	179761	B8 II–III	...	16.6	17
7431	184552	A2/A7 V/F0	11.0	...	11
7502	186377	A6 III	11.6	...	12
7512[b]	186568	B8 III	...	18.2	18
7773[b]	193432	B9.5 Va	23.8	24.2	24
7878	196426	B8 IIIp	...	4.0	4
7891	196724	A0 IV	...	54.0	54
7903	196821	A0 IIIps	...	22.9	23
8404[b]	209459	B9.5 V	4.0	...	4
8641	214994	A1 IV	5.4	4.4	5
8704A[c]	216494	B9 III	...	1.5	2
8768	217811	B2 V	...	12.0v	12v
8822	218753	A5/A7/F0	4.7	...	5

[a] In units of km s^{-1}. v = variable line broadening.
[b] Early-type radial velocity standard candidate (Fekel 1999).
[c] Primary of a double-lined spectroscopic binary.

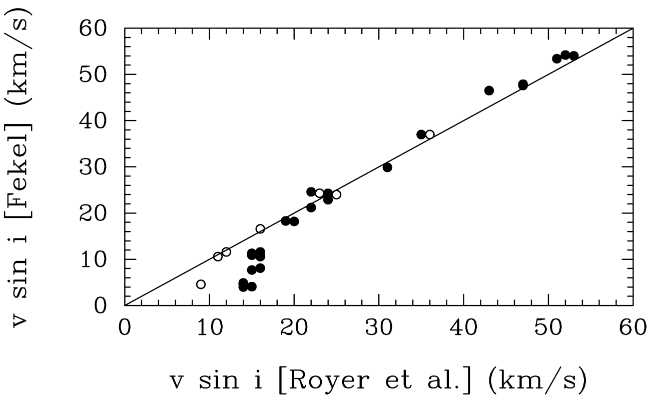

Fig. 4.—Comparison of the present data with the *v* sin *i* data of Royer et al. (2002a, 2002b). Their southern data are open circles, and their northern data are filled circles. The line showing a one-to-one correlation is plotted as a guide and is not a fit to the data.

ening of the stellar lines increases, a Gaussian curve becomes a poorer fit to the profiles. However, such a modest mean difference between our results and those of Royer et al. (2002b) is within the uncertainty estimates of our individual *v* sin *i* values.

Forty of the stars in Table 1 are in common with those measured by Abt & Morrell (1995). Their results are based on the *v* sin *i* standard-star system of Slettebak et al. (1975), and they estimated that they could not resolve rotational velocities $\lesssim 10$ km s^{-1}. As seen in Figure 5, their *v* sin *i* values between 10 and 20 km s^{-1} appear to scatter substantially about our values, and some of the individual values differ from ours by 10 km s^{-1} or more. This suggests that the lower limit to their *v* sin *i* values is closer to 20 rather than 10 km s^{-1}. Above the threshold value of ~20 km s^{-1}, their values are systematically too small, a result already noted by Royer et al. (2002b).

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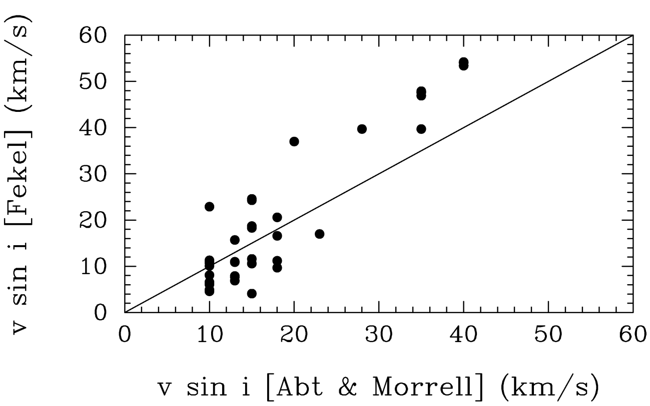

Fig. 5.—Comparison of the present data with the *v* sin *i* data of Abt & Morrell (1995). The line showing a one-to-one correlation is plotted as a guide and is not a fit to the data.

version of this work. I thank H. Abt for his suggestions and comments. The research at Tennessee State University is supported in part by NASA grant NCC5-511 and NSF grant HRD-9706268.

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