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THE ROTATION OF BINARY SYSTEMS WITH EVOLVED COMPONENTS

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ABSTRACT

In the present study we analyze the behavior of the rotational velocity, $v \sin i$, for a large sample of 134 spectroscopic binary systems with a giant star component of luminosity class III, along the spectral region from middle F to middle K. The distribution of $v \sin i$ as a function of color index $B-V$ seems to follow the same behavior as their single counterparts, with a sudden decline around G0 III. Blueward of this spectral type, namely, for binary systems with a giant F-type component, one sees a trend for a large spread in the rotational velocities, from a few to at least 40 km s^{-1}. Along the G and K spectral regions there are a considerable number of binary systems with moderate to moderately high rotation rates. This reflects the effects of synchronization between rotation and orbital motions. These rotators have orbital periods shorter than about 250 days and circular or nearly circular orbits. Except for these synchronized systems, the large majority of binary systems with a giant component of spectral type later than G0 III are composed of slow rotators.

Subject headings: binaries: spectroscopic — stars: fundamental parameters — stars: late-type — stars: rotation

On-line material: machine-readable table

1. INTRODUCTION

Rotation is one of the most important observable physical parameters in stellar astrophysics. Such a parameter can provide fundamental constraints for models of stellar evolution, as well as important information on the link between surface rotation and stellar atmospheric phenomena. The behavior of the rotational velocity for single evolved stars of luminosity class III is now well established (De Medeiros & Mayor 1990, 1991; Gray 1989). For this luminosity class, there is a sudden decline in the rotational velocity around the spectral type G0 III, which corresponds to $B-V \sim 0.70$. *Blueward* of this spectral type, namely, for F-type single giants, rotational velocity scatters over a wide range of values, from about 2 to 180 km s^{-1}, whereas *redward*, namely, for G- and K-type single giants, stars are essentially slow rotators, and rotation rates greater than 5 km s^{-1} are unusual. On the basis of the analysis of the kinematics-age relation, De Medeiros & Mayor (1991) have shown that the root cause for this discontinuity in rotation seems to be a mixing in ages associated with the rapid evolution of giant stars into the Hertzsprung gap. These observational results have been discovered from a large rotational and radial velocity survey of about 1100 giants (De Medeiros & Mayor 1999) accomplished with the CORAVEL high-resolution spectrometer (Baranne, Mayor, & Poncet 1979) at the Haute Provence Observatory in France and at the European Southern Observatory in Chile.

We have now examined the complete survey for the spectroscopic binary systems containing a giant component of luminosity class III. The main challenge in the study of rotation in binary systems with evolved components is to establish the extent of the synchronization between rotational and orbital motion along the giant branch. Tidal theory (e.g., Zahn 1977) predicts that, in late-type binary systems, viscous dissipation of time-dependent tidal effects should produce synchronization between rotation and stellar orbital motion, as well as circularization of the orbit of the system. The most simple way to test such effects consists of the determination of precise rotational velocities for a large sample of binary systems with giant components, presenting a wide variety of values of orbital parameters. On the basis of tidal predictions, Middelkoop & Zwaan (1981) have suggested that most late-type giants in close binary systems, with orbital periods shorter than about 80 days, rotate in synchronization with revolution, because most of these close binary systems have circular orbits. Such a tendency for synchronization in late-type binary systems was also observed by Giuricin, Mardirossian, & Mezzetti (1984). Mermilliod & Mayor (1992) have found that, in open clusters, binaries containing a giant have circularized orbits at orbital periods shorter than about 250 days. More recently, Boffin, Cerf, & Paulus (1993) have deduced a circularization cutoff period of about 70 days from an eccentricity-period diagram for a large sample of field binary systems containing late-type giants.

In the present work, we study the behavior of the rotational velocity $v \sin i$ as a function of the color index $B-V$, for a large sample of binary systems with a giant component of luminosity class III. We also analyze the link between $v \sin i$ and the orbital parameters eccentricity and orbital period.

2. THE OBSERVATIONAL DATA

The entire sample for the present work is composed of 134 single-lined spectroscopic binary systems, SB1, with spectral types between F5 III and K5 III, mostly from the Bright Star Catalogue (Hoffleit & Jaschek 1982; Hoffleit, Saladyga, & Wlasak 1983), including 73 binaries for which the orbits are known from the literature. Observations were carried out with the CORAVEL spectrometer (Baranne et al. 1979) mounted on the 1.0 m Swiss telescope at the Haute Provence Observatory, France, and on the 1.44 m Danish telescope at the European Southern Observatory, Chile, between 1986 March and 1994 January. For the determination of the projected rotational velocity $v \sin i$, we have applied a standard calibration (Duquennoy, Mayor, & Halbwachs 1991; De Medeiros & Mayor 1999) that takes into account a varying broadening mechanism, as a function of color, probably related to turbulent motions and/or magnetic fields. Nevertheless, let us recall that such calibration is an extension of the method developed by Benz & Mayor (1981, 1984), which is based on the cross-correlation technique (Griffin 1967). For the observational procedure, calibration process, and error analysis, the reader is referred to De Medeiros & Mayor (1999). A comparison of our measurements, obtained by the cross-correlation technique, with those acquired with the Fourier transform technique by Gray (1989) for a common sample of 84 single and binary giant and subgiant stars gives excellent agreement, with a typical rms of the rotational velocity differences of about 1.1 km s^{-1}, indicating a precision of 1.0 km s^{-1} for our $v \sin i$ measurements (De Medeiros & Mayor 1999). This excellent agreement between the $v \sin i$ values from CORAVEL and the Fourier transform is confirmed for the binary stars, when they are analyzed separately. By using the $v \sin i$ data given in Table 1 for 15 stars of the present sample, we have found an rms of the rotational velocity differences of 0.61 km s^{-1}.

The entire sample for the present work, with rotational velocity and orbital parameters, when the latter are available, is listed in Table 2. For those stars with no available orbital parameters, Table 2 gives also for each star the number N of observations; the radial velocity dispersion (rms) σ; the uncertainty ϵ on the mean radial velocity, given by $\max(\epsilon_1/\sqrt{N}, \sigma/\sqrt{N})$, where ϵ_1 is the typical error for one single radial velocity measurement; the time span ΔT of the observations; and σ/σ_n, a factor indicating how many times their radial velocity dispersion (rms) exceeds the radial velocity noise expected for single stars.

For the stars with no orbital parameters listed in Table 2, one important question concerns the nature of their radial velocity variation. Is such a variability reflecting the presence of a dynamical companion, or is it intrinsic to the star, reflecting either rotational modulation by surface features or nonradial pulsations? In this context, different studies (e.g., Hatzes & Cochran 1993; Frink & Quirrenbach 2001) have revealed intrinsic radial velocity variability in K giant stars with amplitudes ranging from 0.2 to 0.4 km s^{-1}. Using the maximum likelihood approach, we have analyzed the behavior of the factor σ/σ_n defined above, to estimate if the radial velocity variability of such stars is likely indicating a dynamical companion. For this, we have estimated the expected radial velocity noise σ for single giants, from intrinsic contributions with typical amplitude of 0.4 km s^{-1}. This amplitude value was added in quadrature with 0.3 km s^{-1}, the typical precision of a single radial velocity measurement by CORAVEL (see Duquennoy et al. 1991), giving a radial velocity noise σ_n of 0.50 km s^{-1}. With this expected value of σ_n in hand, we have obtained the factor σ/σ_n listed in Table 2. Afterward, we have estimated σ/σ_n for a sample of 641 G and K single giant stars from De Medeiros & Mayor (1999). The distributions of the factor σ/σ_n for single giants and for the stars with no orbital parameters in Table 2 are displayed in Figure 1, both very well fitted by a Gaussian function. For a best presentation of the distributions, the σ/σ_n values in Figure 1 were normalized by the highest σ/σ_n for each group of stars, namely, 1.9 and 35.84 for single giants and for the stars with no orbital parameters, respectively. In addition, the frequency N for single stars was reduced by a factor of 5. From the maximum likelihood statistics we obtained a $\langle \sigma/\sigma_n \rangle$ of 0.33 ± 0.36 and 6.32 ± 4.67 for single giants and for the stars with no orbital parameters in Table 2, respectively. From this analysis we estimate that the threshold to indicate a dynamical companion is around a σ/σ_n of 0.69. Stars with no orbital parameters listed in Table 2 present a σ/σ_n higher than such a threshold value, indicating that their radial velocity variabilities reflect very probably a binarity behavior.

TABLE 1
COMPARISON BETWEEN $v \sin i$ OBTAINED BY CORAVEL AND FOURIER TRANSFORM TECHNIQUE

HR	HD	$v \sin i$ (COR) (km s^{-1})	$v \sin i$ (Gray) (km s^{-1})
373........	7672	2.9	4.5
1030......	21120	5.9	4.8
1373......	27697	1.2	2.5
3112......	65448	2.5	2.4
4301......	95689	1.6	2.6
5161......	119458	4.0	4.9
5681......	135722	1.2	1.1
6148......	148856	4.8	3.4
6239......	151627	4.1	4.7
6322......	153751	23.0	24.0
7995......	198809	4.7	5.9
8359......	208010	3.3	4.0
8442......	210220	1.8	3.4
8819......	218658	5.5	4.7
8923......	221115	1.5	3.1

NOTES.—COR = CORAVEL; Gray = Fourier transform technique.

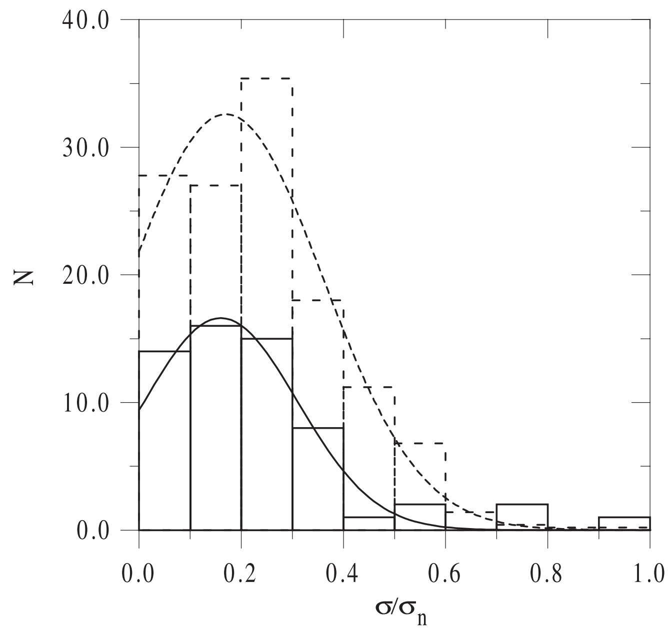

FIG. 1.—Distribution of the factor σ/σ_n for single giant stars (*dashed line*) and for the binary systems with no orbital parameters (*solid line*). For a best presentation of the distributions, σ/σ_n values and the frequency N of single giants were normalized as explained in the text.

TABLE 2

STELLAR PARAMETERS FOR BINARY SYSTEMS WITH EVOLVED COMPONENTS

HR	HD	$B-V$	Spectral Type	$v \sin i$ (km s^{-1})	P (days)	e	N	σ (km s^{-1})	ϵ (km s^{-1})	ΔT (days)	σ/σ_n	Ref.
3.........	28	1.04	K1 III	1.9	72.93	0.27	...	...	...	...	...	2
40.......	895	0.65	G0 III	2.5	932.22	0.832	...	...	...	...	...	44
165.....	3627	1.28	K3 III	1.0	15000	0.34	...	...	...	...	...	2
216.....	4526	0.94	G8 III	1.7	...	...	2	9.96	7.04	309	19.92	...
360.....	7318	1.04	K0 III	3.6	7473	0.816	...	...	...	...	...	27
373.....	7672	0.90	G5 IIIe	2.9	56.8147	0.04	...	...	...	...	...	2
407.....	8634	0.43	F5 III	30.8	5.4291	0.38	...	...	...	...	...	2
469.....	10072	0.89	G8 III	2.0	7581	0.368	...	...	...	...	...	29
503.....	10588	0.94	G8 III–IV	3.3	78.0073	0.02	...	...	...	...	...	2
549.....	11559	0.94	K0 III	1.8	1672.4	0.18	...	...	...	...	...	36
645.....	13530	0.93	G8 III:v	1.0	1575.48	0.8815	...	...	...	...	...	7
731.....	15596	0.90	G5 III–IV	1.6	...	...	2	1.20	0.85	301	2.40	...
738.....	15755	1.07	K0 III	1.0	...	...	2	13.17	9.31	285	26.34	...
754.....	16161	0.87	G8 III	2.7	...	...	2	6.73	4.76	302	13.46	...
765.....	16246	0.41	F6 III	40.6	1.109526	0.062	...	...	...	...	...	42
831.....	17484	0.43	F6 III–IV	11.0	...	...	2	2.04	1.44	302	4.08	...
1023...	21018	0.86	G5 III	22.7	287.201	0.0	...	...	...	...	...	39
1030...	21120	0.89	G6 IIIFe−1	5.9	1654.9	0.263	...	...	...	...	...	38
1198...	24240	1.05	K0 III	2.3	...	...	2	3.75	2.65	419	7.50	...
1304...	26659	0.87	G8 III	4.7	...	...	5	1.58	0.71	2037	3.16	...
1313...	26755	1.09	K1 III	1.0	...	...	2	6.72	4.75	267	13.44	...
1337...	27278	0.94	K0 III	2.0	...	...	2	2.62	1.85	267	5.24	...
1360...	27497	0.92	G8 III–IV	1.4	...	...	4	3.12	1.56	3637	6.24	...
1373...	27697	0.98	K0 IIICN0.5	1.2	529.8	0.42	...	...	...	...	...	35
	28591	0.90	K1 III	27.2	21.2886	0.010	...	...	...	...	...	7
1467...	29317	1.07	K0 III	6.7	121	0.02	...	...	...	...	...	2
1514...	30138	0.93	G9 III	4.4	...	...	2	1.76	1.24	329	3.52	...
1517...	30197	1.21	K4 III	1.0	107.503	0.210	...	...	...	...	...	32
1623...	32357	1.12	K0 III	11.5	80.90	0.05	...	...	...	...	...	37
1698...	33856	1.19	K3 III	2.3	1031.40	0.098	...	...	...	...	...	4
1726...	34334	1.27	K3 III	1.0	434.8	0.1	...	...	...	...	...	6
1908...	37171	1.58	K4 III	3.9	...	...	2	5.78	4.08	367	11.56	...
1970...	38099	1.47	K4 III	5.9	143.03	0.06	...	...	...	...	...	1
2054...	39743	0.99	G8 III	9.8	...	...	3	4.87	2.81	1067	9.74	...
2077...	40035	1.00	K0 III	1.7	...	...	2	1.97	1.39	288	3.94	...
2145...	41380	1.04	G4 III	14.2	...	...	3	6.25	3.61	1079	12.50	...
2264...	43905	0.43	F5 III	13.2	6.5013	0.02	...	...	...	...	...	2
2376...	46101	1.60	K0 III:	19.8	...	...	2	13.48	9.53	282	26.96	...
2506...	49293	1.11	K0 IIIBa0.1	2.0	1760.9	0.40	...	...	...	...	...	18
2553...	50310	1.20	K0 III	2.2	1066.0	0.09	...	...	...	...	...	2
2804...	57646	1.61	K5 III	2.6	...	...	2	1.20	0.85	219	2.40	...
2973...	62044	1.12	K1 III	25.8	19.605	0	...	...	...	...	...	41
3003...	62721	1.45	K5 III	1.2	1519.7	0.325	...	...	...	...	...	13
3043...	63660	0.76	G0 III	2.9	...	...	3	5.15	2.97	1401	10.03	...
3112...	65448	0.59	G1 III	2.5	...	...	2	7.67	5.43	171	15.34	...
3149...	66216	1.12	K2 III	1.9	2437.8	0.060	...	...	...	...	...	13
3245...	69148	0.89	G8 III	3.0	89.06533	0.19	...	...	...	...	...	5
3360...	72184	1.11	K2 III	1.0	...	...	2	3.62	2.56	410	7.24	...
3385...	72688	0.95	K0 III	7.4	45.13	0	...	...	...	...	...	48
3482...	74874	0.68	G5 III	4.0	5492	0.61	...	...	...	...	...	2
3512...	75605	0.87	G5 III	2.0	...	...	3	1.89	1.09	1440	3.78	...
3531...	75958	0.86	G6 III	1.1	1898.7	0.706	...	...	...	...	...	30
3567...	76629	0.98	G8 III	4.7	...	...	3	4.96	2.86	2290	9.92	...
3627...	78515	0.97	K0 III	2.1	1700.76	0.060	...	...	...	...	...	38
3722...	80953	1.46	K2 III	1.2	...	...	2	4.43	3.13	265	8.86	...
3725...	81025	0.75	G2 III	5.0	66.717	0.0	...	...	...	...	...	2
3827...	83240	1.05	K1 IIIv	2.2	2834	0.322	...	...	...	...	...	20
3907...	85505	0.94	G9 III	3.4	...	...	4	3.01	1.50	2309	6.02	...
3994...	88284	1.01	K0 III	1.9	1585.8	0.14	...	...	...	...	...	2
4100...	90537	0.90	G9 IIIab	4.0	13833	0.66	...	...	...	...	...	2
4235...	93859	1.12	K2 III	1.0	...	...	2	1.09	0.77	419	2.18	...
4301...	95689	1.07	K0 IIIa	1.6	16060	0.35	...	...	...	...	...	2
4365...	97907	1.20	K3 III	1.9	2963	0.420	...	...	...	...	...	23
4427...	99913	0.94	K0 III	2.4	...	...	2	3.13	2.21	320	6.26	...

TABLE 2—*Continued*

HR	HD	$B-V$	Spectral Type	$v \sin i$ (km s^{-1})	P (days)	e	N	σ (km s^{-1})	ϵ (km s^{-1})	ΔT (days)	σ/σ_n	Ref.
4430 ...	99967	1.27	K2 IIICN−1	18.0	74.861	0.03	...	...	...	...	...	2
4451 ...	100418	0.60	F9 III	33.6	...	...	5	3.72	1.67	1803	7.44	...
4593 ...	104438	1.01	K0 III	1.1	...	...	2	1.77	1.25	243	3.54	...
4640 ...	105981	1.41	K4 III	3.9	461	0.17	...	...	...	...	...	2
4693 ...	107325	1.09	K2 III–IV	1.0	5792	0.55	...	...	...	...	...	24
4793 ...	109519	1.22	K1 III	2.7	110.829	0	...	...	...	...	...	34
4795 ...	109551	1.31	K2 III	1.7	561.7	0.262	...	...	...	...	...	33
4815 ...	110024	0.96	G9 III	1.4	972.4	0.590	...	...	...	...	...	11
4927 ...	113049	0.99	K0 III	1.6	...	...	4	2.88	1.44	1838	5.76	...
5053 ...	116594	1.06	K0 III	1.3	1366.8	0.193	...	...	...	...	...	21
5161 ...	119458	0.85	G5 III	4.0	149.72	0.17	...	...	...	...	...	3
5201 ...	120539	1.43	K4 III	2.0	944	0.41	...	...	...	...	...	2
5203 ...	120565	1.01	G9 III	2.6	...	...	2	1.24	0.88	341	2.48	...
5321 ...	124547	1.36	K3 III	2.2	605.8	0.137	...	...	...	...	...	45
5361 ...	125351	1.06	K0 III	1.0	212.085	0.574	...	...	...	...	...	47
5520 ...	130458	0.82	G5 III	3.6	...	...	3	2.63	1.52	2555	5.26	...
5681 ...	135722	0.95	G8 IIICN−1	1.2	...	...	11	2.98	0.90	5213	5.96	...
5692 ...	136138	0.97	G8 IIIaBa0.3	5.5	...	...	4	5.28	2.64	996	10.56	...
5769 ...	138525	0.50	F6 III	12.4	...	...	2	6.64	4.70	215	13.28	...
5802 ...	139195	0.95	K0 III:CN1B	1.0	5324	0.345	...	...	...	...	...	25
5826 ...	139669	1.58	K5 III	3.1	...	...	2	1.28	0.90	708	2.56	...
5835 ...	139906	0.83	G8 III	3.1	...	...	5	5.43	2.43	2514	10.86	...
6005 ...	144889	1.37	K4 III	1.0	2230	0.14	...	...	...	...	...	22
6018 ...	145328	1.01	K0 III–IV	1.0	...	...	31	4.49	0.81	6925	8.98	...
6046 ...	145849	1.34	K3 III	3.2	2150	0.6	6	...	...	...	...	...
6148 ...	148856	0.94	G7 IIIa	4.8	410.575	0.55	...	...	...	...	...	2
6239 ...	151627	0.87	G5 III	4.1	...	...	2	6.39	4.52	333	12.78	...
6322 ...	153751	0.89	G5 III	23.0	39.4816	0.007	...	...	...	...	...	7
6363 ...	154732	1.09	K1 III	1.7	790.6	0.217	...	...	...	...	...	26
6388 ...	155410	1.28	K3 III	1.0	876.25	0.609	...	...	...	...	...	10
6577 ...	160365	0.56	F6 III	30.0	...	...	3	17.92	10.35	1829	35.84	...
	160538	1.05	K2 III	7.2	903.8	0.072	...	...	...	...	...	8
6790 ...	166207	1.04	K0 III	1.6	...	...	2	1.66	1.17	276	3.32	...
6791 ...	166208	0.91	G8 IIICN−0.3CH	3.2	2017	0.378	...	...	...	...	...	28
6853 ...	168322	0.99	G9 III	1.8	...	...	22	2.76	0.59	5542	5.52	...
6860 ...	168532	1.53	K3 III:Ba0.	3.9	485.45	0.359	...	...	...	...	...	46
6886 ...	169221	1.07	K1 III	2.0	...	...	2	2.82	1.99	339	5.64	...
7010 ...	172424	0.96	G8 III	1.5	...	...	3	1.03	0.59	372	2.06	...
7024 ...	172831	1.00	K1 III	1.3	485.3	0.209	...	...	...	...	...	14
7125 ...	175306	1.19	G9 IIIbCN−0.5	14.7	138.420	0.11	...	...	...	...	...	2
7135 ...	175515	1.04	K0 III	1.2	2994	0.24	...	...	...	...	...	12
7137 ...	175535	0.90	G8 III	2.3	...	...	6	3.69	1.51	2579	7.38	...
7176 ...	176411	1.08	K1 IIICN0.5	2.1	1270.6	0.27	...	...	...	...	...	15
7180 ...	176524	1.15	K0 III	2.1	258.48	0.21	...	...	...	...	...	16
7208 ...	176981	1.67	K2 III	1.8	...	...	2	3.91	2.77	295	7.82	...
7252 ...	178208	1.27	K3 III	1.4	...	...	2	10.31	7.29	338	20.62	...
7333 ...	181391	0.92	G8 III–IV	2.8	266.544	0.833	...	...	...	...	...	9
7413 ...	183611	1.39	K5 III	2.1	...	...	2	1.71	1.21	331	3.42	...
7636 ...	189322	1.13	G8 III	1.0	...	...	2	3.30	2.34	312	6.60	...
7798 ...	194152	1.08	K0 IIIv	2.1	1124.06	0.759	...	...	...	...	...	31
7884 ...	196574	0.95	G8 III	3.7	205.2	0.138	...	...	...	...	...	40
7897 ...	196758	1.06	K1 III	1.8	...	...	2	2.74	1.94	377	5.48	...
7901 ...	196787	1.02	G9 III	2.9	...	...	12	3.02	0.87	3637	6.04	...
7939 ...	197752	1.18	K2 III	1.5	2506	0.383	...	...	...	...	...	17
7995 ...	198809	0.83	G7 IIICN−1	4.7	...	...	2	3.86	2.73	358	7.72	...
	199547	1.13	K0 III	1.0	2871	0.632	...	...	...	...	...	19
8035 ...	199870	0.97	K0 IIIbCN−0.5	1.2	635.1	0.44	...	...	...	...	...	43
8078 ...	200817	0.99	K0 III	2.2	...	...	2	3.98	2.81	366	7.96	...
8149 ...	202951	1.65	K5 III	4.4	...	...	2	5.12	3.62	370	10.24	...
8359 ...	208110	0.80	G0 IIIs	3.3	...	...	6	3.81	1.56	1844	7.62	...
	209813	1.08	K0 III	21.1	24.4284	0.01	...	...	...	...	...	2
8442 ...	210220	0.88	G6 III	1.8	...	...	2	7.03	4.97	381	14.06	...
8445 ...	210289	1.62	K5 III	2.0	...	...	2	1.67	1.18	374	3.34	...
8575 ...	213389	1.15	K2 III	34.4	17.755	0.02	...	...	...	...	...	2
	217188	1.10	K0 III	3.0	47.1162	0.463	...	...	...	...	...	7

TABLE 2—*Continued*

HR	HD	$B-V$	Spectral Type	$v \sin i$ (km s^{-1})	P (days)	e	N	σ (km s^{-1})	ϵ (km s^{-1})	ΔT (days)	σ/σ_n	Ref.
8748 ...	217382	1.43	K4 III	1.0	...	...	2	1.04	0.73	334	2.08	...
8819 ...	218658	0.80	G2 III	5.5	556.72	0.297	...	...	...	...	...	46
8923 ...	221115	0.94	G7 III	1.5	...	...	2	2.38	1.68	241	4.76	...
8961 ...	222107	1.01	G8 III–IV	6.9	20.5212	0.04	...	...	...	...	...	2
8990 ...	222682	1.24	K2 III	1.0	...	...	2	1.18	0.83	287	2.36	...

NOTE.—Table 2 is also available in machine-readable form in the electronic edition of the *Astrophysical Journal*.

REFERENCES.—(1) Basset 1978; (2) Batten, Fletcher, & MacCarthy 1989; (3) Beavers & Griffin 1979; (4) Bertiau 1957; (5) Carquillat et al. 1983; (6) Christie 1936; (7) De Medeiros & Udry 1999; (8) Fekel et al. 1993; (9) Franklin 1952; (10) Griffin 1978; (11) Griffin 1981a; (12) Griffin 1981b; (13) Griffin 1982a; (14) Griffin 1982b; (15) Griffin 1982c; (16) Griffin, Harris, & McClure 1983; (17) Griffin 1983; (18) Griffin 1984a; (19) Griffin 1984b; (20) Griffin 1985; (21) Griffin 1986; (22) Griffin 1988; (23) Griffin 1990; (24) Griffin 1991a; (25) Griffin 1991b; (26) Griffin 1991c; (27) Griffin 1991d; (28) Griffin 1992; (29) Griffin 1998; (30) Griffin & Eitter 1999; (31) Griffin & Eitter 2000; (32) Griffin et al. 1985; (33) Griffin, Eitter, & Reimers 1990; (34) Griffin & Eitter 1992; (35) Griffin & Gunn 1977; (36) Griffin & Herbig 1981; (37) Hall et al. 1995; (38) Jackson, Shane, & Lynds 1957; (39) Lucke & Mayor 1982; (40) Lucy & Sweeney 1971; (41) Luyten 1936; (42) Morbey & Brosterhus 1974; (43) Radford & Griffin 1975; (44) Scardia et al. 2000; (45) Scarfe 1971; (46) Scarfe et al. 1983; (47) Scarfe & Alers 1975; (48) Strassmeier et al. 1988.

It is important to underline that in this paper we are analyzing only the binary systems presenting an SB1 behavior on the basis of our CORAVEL observations. Double-lined systems, SB2, and binaries presenting a composite spectrum will be discussed in a forthcoming work. We have excluded from the sample all those systems classified in the literature with a composite spectrum, in spite of the fact that, for some systems, the CORAVEL observations have shown an SB1 behavior.

3. RESULTS AND DISCUSSION

The main results of the present work are displayed in Figures 2 and 3, where we show the distribution of the rotational velocities as a function of the color index $B-V$ and orbital parameters. Several important features are well marked.

Figure 2*a* shows the general trend of the distribution of the rotational velocity $v \sin i$ as a function of the color index $B-V$ for spectroscopic binary systems with an evolved component, with a tendency for a sudden decline around $B-V \sim 0.70$, corresponding to the spectral type G0 III. This behavior seems to follow that of the rotational velocity presented by their single counterparts. Blueward of the spectral type G0 III there is a spread in the values of rotational velocity, ranging from a few to at least 40 km s^{-1}, whereas redward of this spectral type, namely, along the G and K spectral regions, the great majority of binary systems rotate very slowly, following the same trend observed for single giants. Let us recall that the mean rotational velocity $v \sin i$ for single G- and K-type giants ranges typically from about 6 km s^{-1} at G1 III to about 3 km s^{-1} at G5 III and to about 2 km s^{-1} along the spectral region from G8 III to K7 III (De Medeiros, Da Rocha, & Mayor 1996). Nevertheless, 12 out of 124 binary systems located redward of G0 III show moderate to moderately high rotation rates, typically stars with $v \sin i$ higher than 6 km s^{-1}. For a more consistent analysis on the extent of the decline in $v \sin i$ shown in Figure 2*a*,

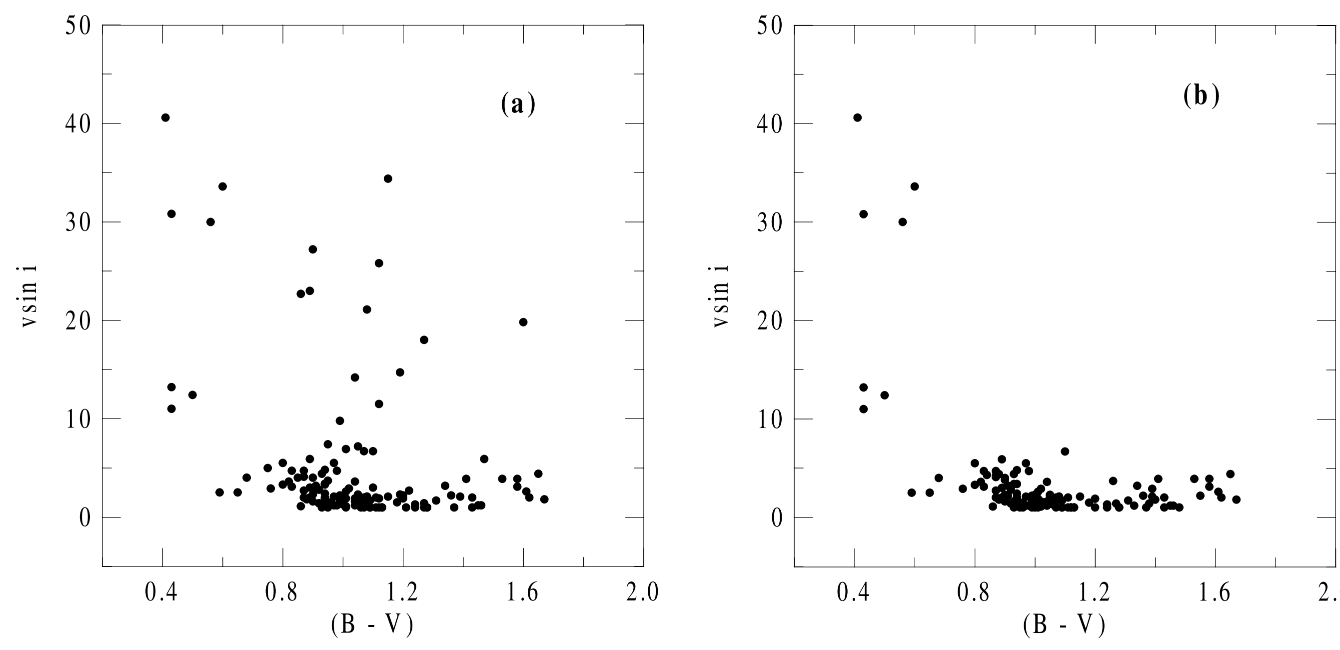

FIG. 2.—Distribution of the rotational velocity $v \sin i$ for binary systems with evolved component. (*a*) For all the stars listed in Table 2. (*b*) For systems with G- or K-type component but with orbital period longer than 250 days and all the systems with F-component.

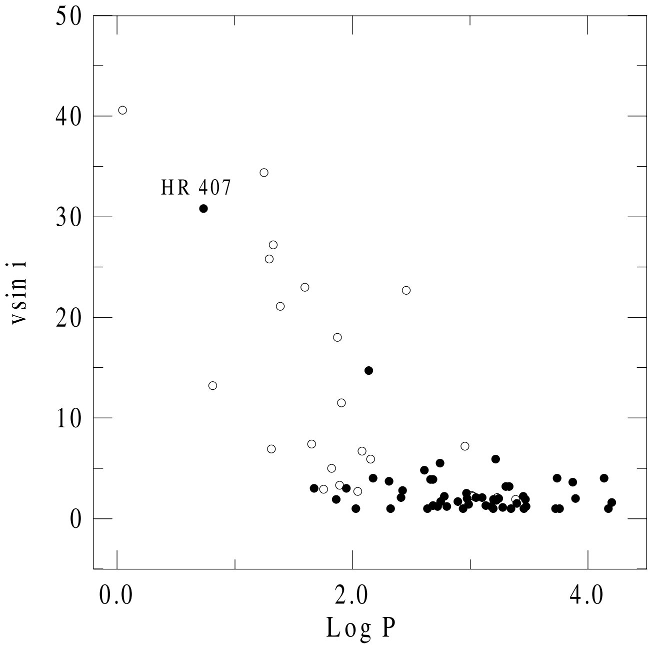

FIG. 3.—Distribution of the rotational velocity $v \sin i$ as a function of the orbital period, for the binary systems listed in Table 2 with available orbital parameters. Binary systems with a circular or nearly circular orbit ($e \leq 0.10$) are represented by open circles, whereas the systems with eccentric orbits ($e > 0.10$) are represented by filled circles. The deviating behavior of the star HR 407 is discussed in the text.

one should inquire about the root cause of the enhanced rotation presented by such binary systems. By analyzing the orbital parameters given in Table 2, we find that the G and K binary systems with enhanced rotation have an orbital period shorter than about 250 days and a circular or nearly circular orbit, such a value pointing to the critical period of synchronization between axial rotational motion and orbital revolution due to tidal effects. The critical period of synchronization around 250 days found on the basis of a large sample of field binary systems sounds like an interesting result because it follows that found by Mermilliod & Mayor (1992) from a sample of 88 binary systems with an evolved component in open clusters. In this context, one can conclude that the enhanced rotation of binary systems along the G and K spectral regions results from the synchronization between rotation and orbital motions. Hence, the moderate to moderately high rotation shown by these synchronized binary systems reflects angular momentum that has been drawn from the orbital motion. The orbit acts as a source of angular momentum to replace that lost via stellar wind, during the evolution along the giant branch. It is clear that for some systems the synchronization may increase their observed rotational velocity by more than about 15 times the mean rotational velocity observed for single giant stars at a given spectral type. Following Zahn (1966, 1977), in binary stars possessing a convective envelope, tidal effects become important if the convective region occupies a substantial fraction of the star and if convection transports most of the energy flux. According the tidal theory, in the components of a late-type binary system, the tidal wave, which is due to the gravitational interaction, is slightly lagging because a small fraction of its kinetic energy is converted into heat, as required by the second principle of thermodynamics. The system evolves toward its state of minimum kinetic energy, in which the orbit is circular, the spin axes are aligned and perpendicular to the orbital plane, and the rotation of both stars of the system is synchronized with the orbital motion. Such synchronism is predicted to be completed before orbits become circular (Zahn 1977), unless the spin angular momentum is comparable to the orbital angular momentum (Zahn 1977; Hut 1980). Since evolutionary models predict that the rapid increase of the thickness of the convective envelope coincides with the late-F spectral region (e.g., Maeder & Meynet 1994), our finding presents strong evidence that the synchronization is achieved once stars arrive in the late-F to early-G spectral regions.

At this point one should ask about the nature and the extent of the decline in rotation around G0 III, suggested by Figure 2*a*. Is it *really* paralleling the rotational discontinuity at G0 III observed in single giant stars? In fact, we see two possible regimes. First, the synchronization is achieved only for stars along the G to K spectral regions (let us recall that the extent of the convective envelope and the effectiveness of convection in transporting energy flux become important only when the star evolves up the giant branch). In this context we can consider that binary systems in the F spectral region, in particular, those with an early to middle F-type component, are not synchronized, their rotation reflecting only the normal evolution of the star with no effects from binarity. Following this scenario, in Figure 2*b* we represent the rotational velocity $v \sin i$ as a function of the color index $B-V$ for binary systems with a G- or K-type component but with orbital periods longer than 250 days and all systems with an F-type component. We have also excluded from this figure the G and K binary systems with significant enhanced rotation with respect to the mean, HR 2054, HR 2145, and HR 2376, for which no orbital parameters are available in the literature, but their large radial velocity ranges, 9.58, 10.59, and 19.19 km s^{-1}, respectively, indicate short or moderately short orbital periods. The sudden decline in $v \sin i$ around $B-V = 0.70$ is now quite clear. Of course, low-rotator binary systems situated along the G and K spectral regions should be mostly nonsynchronized systems. Consequently, they should have orbital periods longer than the cutoff period of about 250 days and rather noncircular orbits. Nevertheless, a few systems in Table 2, such as HR 373 and HR 503, have nearly circular orbits with periods shorter than 250 days and low rotation. Perhaps their true rotation rates are high but $v \sin i$ is suppressed by low inclination of their rotation axis. Second, the F-type stars with short orbital periods, such as HR 765 and HR 2264, would have also reached a stage where the convective envelope is sufficiently developed for synchronization, in spite of their middle-F spectral types. Following such a scenario, we can also ask about the nature of the additional F-type stars represented in Figure 2*b* but with no orbital parameters available in the literature. If these stars are also in synchronization, there is no supporting evidence for a rotational discontinuity in binary systems following that observed for single giants, as proposed in the first scenario discussed above. To decide between these two scenarios it is necessary, first, to determine orbital parameters for all the F-type stars composing the present sample and, second, to determine the rotational velocity for a larger number of F-type stars.

In Figure 3 we show the behavior of the rotational velocity as a function of the orbital period. Stars are separated into two groups: those with circular or nearly circular orbits, namely, an eccentricity e lower than about 0.10, and those with noncircular orbits, namely, an eccentricity e higher than 0.10. This figure shows clearly that the binary systems with enhanced rotation, typically $v \sin i$ greater than about 6 km s^{-1}, have an orbital period shorter than about 250 days and a circular or nearly circular orbit. Two additional trends are clearly observed in this figure: first, high rotators with orbital an period longer than 250 days seem to be unusual and, second, there is an absence of slow rotators with very short orbital periods. These results are consistent with the expected features for the synchronization process in binary systems with evolved components. While the great majority of binary systems with enhanced rotation present a circular or nearly circular orbit, one star represented in Figure 3, HR 407, appears to violate the general rule. This star, in spite of the very short orbital period of 5.4291 days, has an F5 III spectral type that may indicate that at this evolutionary stage the extent of its convective envelope and the effectiveness of convection in transporting energy flux are not yet well developed, indicating that tidal effects are not yet enough to produce a circular or nearly circular orbit. On the basis of this reasoning, the deviating behavior of HR 407 in the $v \sin i$ period-eccentricity plane is easily understood. Naturally, enhanced rotation is not a general property among binary systems with circularized orbits. As shown in Figure 3, binary systems with circular or nearly circular orbits present a wide range of $v \sin i$ values, from a few to about 40 km s^{-1}.

We have also analyzed the behavior of the rotational velocity $v \sin i$ versus the mass function, $f(m)$, searching for particular features between rotation and stellar mass. Clearly, the mass function per se is not a very useful parameter because of its rather complex dependence on the inclination angle i of the orbital plane with respect to the plane of the sky. The relevance of such analysis rests on the fact that the mass function $f(m)$ has a direct dependence on the orbital period, P, and eccentricity, e, namely, on P and $1 - e^2$, respectively. Nevertheless, no significant feature resulted from this analysis.

4. CONCLUSIONS

Precise rotational velocities, $v \sin i$, are given for a large sample of 134 single-lined binary systems with an evolved component of luminosity class III. For these binary systems the distribution of rotation rates as a function of color index $B-V$ presents a behavior that seems to parallel the one found for their single counterparts. Namely, there is a sudden decline in rotation around the spectral type G0 III, as is the case for single giants. Binary systems located blueward of the spectral type G0 III, typically, those systems with a color index $B-V$ lower than about 0.70, present a large spread in the values of rotational velocity, from a few to at least 40 km s^{-1}. In addition, we have found that along the G and K spectral regions there are a considerable number of moderate to moderately high rotators, reflecting clearly the effects of synchronization between rotation and orbital motions. These stars have orbital periods shorter than about 250 days as well as circularized or nearly circularized orbits. For a given spectral type, the process of synchronization increases the observed rotational velocity of the binary systems up to about 15 times the mean rotational velocity of single giants. Except for these synchronized systems, the majority of binary stars later than spectral type G0 III are essentially composed of slow rotators, following the same behavior as single giants. A few binary systems present synchronization characteristics and low rotation, but probably their $v \sin i$ is suppressed by low inclination of their rotation axis. We have also observed that enhanced rotation is not a general property among binary systems with circularized orbit. Admittedly, in the present study the number of binary systems with an F-type component is very scarce, and one should be cautious with the proposed rotational discontinuity around the spectral type G0 III. In addition, the extent of tidal effects along the F spectral region is not yet established. In this context only the determination of rotational velocity and orbital parameters for a larger sample of binary systems with an F-type component could confirm such a discontinuity on a more solid basis. Finally, we would like to point out that for the large majority of stars discussed in this work the duplicity is established on very solid grounds. However, for 58 stars additional measurements of radial velocity are undoubtedly necessary to establish their orbital parameters. Nevertheless, it is important to underline that the discussion of the rotational velocity for binary systems with an evolved component carried out in the present work is not hampered by this fact because, in particular, the large majority of stars with no available orbital parameters are slow rotators.

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