

THE LATE B-TYPE STARS: REFINED MK CLASSIFICATION,
CONFRONTATION WITH STROMGREN PHOTOMETRY, AND THE EFFECTS OF ROTATION

R. F. GARRISON

David Dunlap Observatory, University of Toronto, Box 360, Richmond Hill, Ontario, Canada L4C 4Y6
Electronic mail: garrison@centaur.astro.utoronto.ca

R. O. GRAY

David Dunlap Observatory, University of Toronto, Box 360, Richmond Hill, Ontario, Canada L4C 4Y6
and Department of Physics and Astronomy, Appalachian State University, Boone, North Carolina 28608
Electronic mail: grayro@conrad.appstate.edu

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ABSTRACT

In the fourth and final of a series of papers on the late B to the early F type stars, we refine the MK spectral classification system for the late B type stars and consider the effect of rotation on both spectral classification and Strömrgren photometry of these stars. We extend the work of Morgan by establishing self-consistent sequences of narrow and broadlined standards. We reclassify a number of Bp stars, compare these classifications with Strömrgren photometry and consider the question of whether all Bp stars are main-sequence objects.

1. INTRODUCTION

This paper is the fourth and final in a series on the refinement and analysis of the MK spectral classification system for the B8–F2 stars. In this series, we have confronted our refined system of classification with Strömrgren photometry and have investigated empirically the effect of rapid rotation on spectral classification, Strömrgren photometry, and the relationships between these autonomous systems. This paper is concerned with the late B type stars (B7–B9). The first paper in the series (Gray & Garrison 1987, hereafter referred to as Paper I) dealt with the early A type stars and defined our methods and observational samples. The second paper (Gray & Garrison 1989a, hereafter referred to as Paper II) dealt with the early F type stars, and the third paper (Gray & Garrison, 1989b, hereafter referred to as Paper III) with the late A type stars. Papers I, II, and III also include a detailed discussion of the effects of rotation on classification spectra for those types.

The MK classification system for the B type stars has undergone some revision and refinement by Morgan. This refined classification system is encapsulated in the system of MK dagger standards (Morgan & Keenan 1973) and further elaborated in the spectral atlas of Morgan *et al.* (1978). This system now has been used extensively and successfully; with it, classifications of normal B type stars to within approximately one twentieth of a spectral class may be achieved with consistency (Garrison 1967). Hiltner *et al.* (1969), Garrison *et al.* (1977), and Lesh (1968) have classified a large number of B stars using this system.

The purpose of this paper is to refine further this system for the late B type stars (B7–B9) by the careful addition of more $v \sin i$ standard stars, well tied into the system represented by the work of the above authors. We also present new classifications of approximately 200 normal and peculiar late B type stars on this system, and investigate the re-

lationships between this system and Strömrgren photometry, especially with respect to rotation.

2. THE CLASSIFICATION OF THE LATE B TYPE STARS

The basic criteria used in the classification of the B type stars are well known and well explained in a number of publications (cf. Morgan *et al.* 1978), and thus we will confine ourselves to a few comments dealing either with aspects of the classification of B type stars that have not appeared in print before or with the classification of rapidly rotating stars.

One of the primary criteria for the temperature classification of B type stars involves the estimation of the strength of the neutral helium lines, especially $\lambda 4026$ and $\lambda 4471$. Both of these lines have significant forbidden components and both are subject to considerable Stark broadening. As a result, these lines show broad profiles even on classification dispersion spectrograms. Because the strength of $\lambda 4471$ is often compared to that of the nearby Mg II doublet $\lambda 4481$, which has an intrinsically narrower profile, comparison of the strengths of these two lines can lead to a systematic difference in classification between low- $v \sin i$ and high- $v \sin i$ stars. We have avoided this problem by using spectrograms of two different dispersions, 120 and 67 Å/mm (yielding resolutions of about 2.4 and 1.2 Å, respectively) and, finally, by defining both high- $v \sin i$ and low- $v \sin i$ standards (see section 3).

Another problem connected with the use of the He I lines in the temperature classification of the B type stars is their sensitivity to gravity. Generally, the strength of the He I lines diminishes with lower gravities (higher luminosities); thus a B8 III star will generally have weaker He I lines than a B8 V star, and this must be taken into account in the temperature classification or the giant stars will tend to be classified too late. Thus the classification of the B type stars should be an

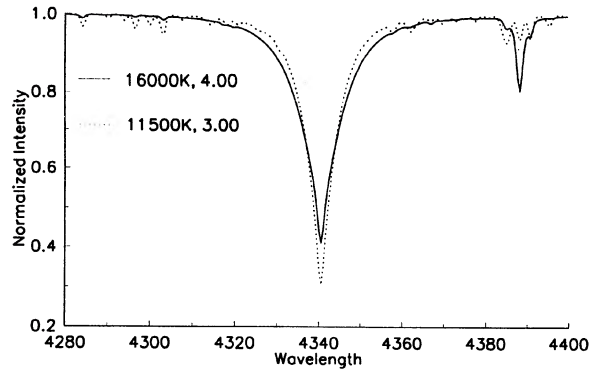


FIG. 1. Synthetic spectra for a B5 V star and a B8 III star, computed from Kurucz models (Gray 1991). Note the differences in the hydrogen-line profiles.

iterative process. An approximate luminosity class should be found before the final temperature classification is made.

The hydrogen lines may also be used in the temperature classification of B type stars. Since the hydrogen lines are sensitive to both temperature and luminosity, one must be concerned not only with the strength of the hydrogen lines, but with their profiles. On classification spectrograms the hydrogen line strengths in a B5 V and a B8 III star are similar, but close inspection reveals that the profiles are different (see Fig. 1). The B5 V profile is broader and more shallow than the B8 III profile. The ability to make this distinction is critical to the discovery of helium-weak stars. Unfortunately, rotation, low resolution, or low S/N spectra can blur this distinction.

Finally, the C II $\lambda 4267$ doublet may be used in the temperature classification in the sense that it is usually not visible in classification spectra of the late B type stars. This feature usually disappears from classification spectra at a spectral type of B5 or B6. However, there are a few late B type stars that show this doublet. Close inspection of these stars usually reveals some other peculiarities, such as a hydrogen line type that is earlier than the He I type, which characterize the so called helium-weak stars. Our sample contains a number of stars that show such discrepancies (Sec. 4).

The luminosity classification of the late B type stars is based on the sensitivity of the Stark wings of hydrogen (and to a much lesser extent those of He I) to gravity. In supergiant B9 stars, weak lines of Ti II and Fe II (especially $\lambda\lambda 4172-9$ and $\lambda 4233$) appear. Occasionally, stars with giant or bright giant luminosities show these lines as well and are possibly related to the “proto-shell” stars defined in Paper I (see, also, Sec. 5 below).

3. PROPOSED STANDARD STARS

The framework or set of standard stars used in this study is based on the system of standard stars defined by Morgan and Keenan (1973) and Morgan *et al.* (1978). We have added a few standards to complete our system of high- $v \sin i$ and low- $v \sin i$ standards established in papers I, II, and III. We

TABLE 1. Proposed Late B-type Standard Stars.

Spectral type	Low- $v \sin i$ standards	High- $v \sin i$ standards
B8 V	HR 9050	18 Tau ¹
B8 III		27 Tau ¹
B8 II	HR 3571	
B9 Va	ω For A	HR 2328
B9 IV	134 Tau	α Del ¹
B9 III	HR 4712	ϵ Tuc
B9 II	HR 7245	
	HR 5898 ²	

¹Dagger standard star: Morgan and Keenan 1973

²Suitable secondary standard

have used the techniques established in those papers for the selection of these new standards. In particular, we have used spectra of two different dispersions (120 and 67 Å/mm) for each star and classification criteria insensitive to rapid rotation to establish the high- $v \sin i$ grid. All new standards have been established by careful interpolation in the existing grid of MK standards. The proposed standard stars for B8–B9.5 stars are listed in Table 1. The classifications for 200 late B type stars on this system are presented in Table 2. (This table is presented in its complete form in the ApJ/AJ CD-ROM Series, Vol. 2, 1994.) Observations were made at the 60 cm Helen Sawyer Hogg Telescope of the University of Toronto Southern Observatory on Las Campanas, Chile, with the Garrison classification spectrograph and with an identical spectrograph on the 84 cm telescope of the Universidad Nacional Autonoma de Mexico at San Pedro Martir in Baja California.

4. CONFRONTATION OF THE REFINED CLASSIFICATIONS WITH STRÖMGREN PHOTOMETRY

4.1 Mean ($b-y$) Indices

Inspection of the ($b-y$) indices for the late B type field stars in our sample show that many of these stars are affected by interstellar reddening. Hence, we have applied the dereddening method of Crawford (1978) to derive the intrinsic colors of these stars. Mean colors for the different $v \sin i$ groups were calculated as in Papers I, II, and III, and are presented in Table 3. In the late B type stars there appears to be no really significant systematic difference in ($b-y$) between low- and high- $v \sin i$ stars, such as those we find in the early A type stars (cf. Paper I), although the B9 dwarfs do show a slight, but not statistically significant, difference in ($b-y$) between the different $v \sin i$ groups in the same sense as the early A type dwarfs (i.e., rapidly rotating stars tend to be slightly redder than low- $v \sin i$ stars).

4.2 The Effect of Rotation on the $H\beta$ Index

In Paper I it was shown that rotation had a measurable effect on the β index of the early A0 type stars in the sense that β was systematically weakened in the rapidly rotating stars. This became evident when either β or $\delta\beta(b-y)$ —that is the β index corrected for the effects of temperature—was plotted versus $v \sin i$: the upper envelope of the distribution was horizontal out to $v \sin i=200$ km/s and then began to

TABLE 2. Spectral types of late B type stars.*

HD	HR/ID	Spectral Type	b-y	m ₁	c ₁	β	N
141		B9 Vbn	-0.026	0.143	0.947	2.873	
358	α And	kB9hB8HeB9 III (MnHg)..	-0.046	0.120	0.520	2.743	*
560	34 Psc	B8.5 Vnn	-0.028	0.126	0.826	2.810	
1279	62	B7 II'	-0.020	0.092	0.588	2.675	
2772	λ Cas	B8 Vnn	-0.043	0.118	0.716	2.754	
2884	β ¹ Tuc	B9 IV	-0.029	0.140	0.856	2.853	*
3240	144	B7 IV	-0.043	0.109	0.675	2.750	
4622	220	B9 Va	-0.030	0.130	0.976	2.850	
4636	v Cas	B8 IV-v	-0.040	0.112	0.578	2.739	
5737	α Scl	B7 II' C II..	-0.063	0.095	0.506	2.660	*
6457	ψ ¹ Psc B	B9 IVn	-0.021	0.145	0.869	2.851	*
7374	87 Psc	B8 IV-v HgMn..	-0.038	0.117	0.610	2.745	*
10205	τ And	B8 III-IV	-0.032	0.098	0.638		
11529	ω Cas	B7 III	-0.033	0.099	0.628	2.698	
12534	γ ² And	B9 Va					*
12767	v For	kB8hB8HeB9 III (Si)..	-0.077	0.119	0.508	2.715	*
13294	59 And A	B9 IVn					*
14228	φ Eri	B8 IV	-0.046	0.102	0.631	2.761	
16046A	ω For A	B9 Va	-0.016	0.126	0.963	2.847	*
16978	ε Hyi	B9 Va	-0.027	0.132	0.926	2.869	
17036	o Ari	B8 IV	0.012	0.107	0.814	2.788	
17081	π Cet	B7 IV	-0.052	0.105	0.599	2.700	
17573	41 Ari	B8 Vn	-0.052	0.125	0.671		
19356	β Per	B8 Vs	-0.007	0.104	0.625	2.748	
20863	HL 581	B9 Va'	0.024	0.115	0.821	2.813	*
20961	HL 625	B9 Va'	0.086	0.128	0.940	2.875	*
21071	1029	B7 V	-0.028	0.102	0.444	2.727	*
21291	1035	B9 Ia	0.364	-0.064	0.490	2.554	
21364	ξ Tau	B9 IVn	-0.036	0.132	0.649	2.782	
21455	1047	B7 Vne	0.120	0.073	0.587	2.731	*
21551	1051	B8 III-IVn	0.002	0.101	0.683	2.746	*
21641	HL 955	B8 Ve	0.014	0.109	0.718	2.743	*
21661	1059	B9 III	0.103	0.059	0.903	2.712	*
21699	1063	kB8hB7HeB9.5 III..	-0.040	0.110	0.369	2.697	*
21790	17 Eri	B9 III	-0.036	0.107	0.832	2.761	*
21931	HL 1082	B9 Va	0.034	0.126	0.847	2.829	*
21933	6 Tau	kB8HeB9.5 V (HgMn)..	-0.030	0.115	0.743	2.788	*
22203	τ ³ Eri	B8 IV	-0.036	0.112	0.702	2.763	*
23288	16 Tau	B7 IVn	0.007	0.093	0.651	2.750	*
23324	18 Tau	B8 Vn	-0.016	0.097	0.643	2.749	*
23363	24 Eri	B7 V	-0.029	0.100	0.648	2.735	*
23408	20 Tau	B7 III	-0.009	0.088	0.622	2.692	*
23432	21 Tau	B8 Vn	-0.003	0.114	0.768	2.793	*
23441	22 Tau	B9 Van	-0.004	0.132	0.860	2.823	*
23480	23 Tau	B7 III-IVn	0.003	0.076	0.602	2.642	*
23630	η Tau	B7 III	-0.021	0.088	0.739	2.653	*
23850	27 Tau	B8 III	-0.019	0.092	0.708	2.697	*
23923	1183	B9 Vann	-0.014	0.120	0.896	2.794	*
24388	30 Eri	B7.5 IV	-0.042	0.111	0.608	2.737	*
26793	1315	B8 Vn	-0.033	0.101	0.732	2.735	

Notes to Table 2

Notes on Columns:

Col. (1). - HD or DM number. A letter following the number indicates a component of a double or multiple star.

Col. (2). - Other identification: open cluster identification number, Bayer designation, Flamsteed designation, or BSC number, in that order of preference. The following notation and numbering systems are used in the open cluster identifications: HL: α Persei cluster; Heckmann *et al.* 1958. HZ: Pleiades; Hertzsprung 1947. Bincol: Blanco 1 cluster; Epstein 1968. N2516: NGC 2516; Cox 1955. I2602: IC 2602; Braes 1962. K: NGC 3532; Koelbloed 1959. N6475: NGC 6475; Koelblood 1959. N6633: NGC 6633; Kopff 1943.

Col. (3). - Spectral type. An asterisk appended to the end of the spectral type means that the full spectral type is too long to be included in the table and is printed in full in the individual remarks below.

Col. (4). - *b-y* color index on the Strömgen system. A "D" implies that the photometry is of the star and its close companion.

Col. (5). - *m*₁

Col. (6). - *c*₁

Col. (7). - β

TABLE 2. (continued)

Col. (8). - An asterisk in this column refers to a supplementary note on the star in the individual remarks below.

Note. - The Strömrgren photometry has been taken from Olsen (1987). When not available in that source, the photometry has been taken from Simbad.

Remarks on Notation in Spectral Classification

Normal Stars. - The traditional notation for MK classifications is used in this table with two exceptions for normal stars. We have found it possible, because of the quality of our spectral material to assign temperature types of B7, B7.5, B8, B8.5, and B9. B9.5 stars can be found in Table 3 of paper I. Similarly, we have found it possible, in certain cases, to assign luminosity classes intermediate to the full luminosity class boxes (Vb, Va, IV-V, IV, III-IV, III, etc.). These intermediate types have been designated using superscript plus or minus signs. Thus, IV⁺ lies between the IV-V and IV boxes, and IV⁻ between the IV and III-IV boxes. These intermediate types have been used as sparingly as possible, and only when the star seemed truly intermediate.

Bp stars. - Bp stars have not been designated by a "p" in this table, but they may be easily distinguished on the basis of the notation used in their spectral classes. We have assigned "temperature" types to the Ca II K-line, the hydrogen line and the helium lines, and have then appended a list of elements, or simply "metallic lines" to give some indication of the type of peculiarity. Parentheses are used to indicate the strength of the peculiarity. For instance, the notation "Si" indicates a peculiarly strong $\lambda\lambda 4128-30$ doublet of singly ionized silicon, whereas (Si) and ((Si)) indicate successively weaker forms of the same peculiarity.

Shell stars. - Shell and "proto-shell" stars have been designated in Table 3 with "shell", "(shell)", and "((shell))." Shell stars generally show deep, narrow cores in the Balmer lines as well as enhanced lines of ionized iron and titanium arising from metastable levels, and usually weak Mg II $\lambda 4481$ lines. We have coined the term "proto-shell" to describe stars which show only enhanced lines of ionized iron and titanium (and usually a weak $\lambda 4481$ line) inappropriate to their luminosity class based on the hydrogen-line wings. These stars are designated by "(shell)" and "((shell))", the number of pairs of parentheses indicating successively weaker manifestations of the shell features.

Visual Binaries. - Visual binaries are indicated in the following notes. When spectra were available, and both components have a spectral type within the range of the late-B type stars, then both spectral types are found in the table. Otherwise, the spectral type is found in the notes below.

Notes on Individual Stars

HD 358: Full spectral type: kB9 hB8 HeB9 III (MnHgSi) (metallic lines). A faint metallic-line spectrum is visible. $\lambda 4030$ (Mn I) is slightly too strong and $\lambda 4481$ is very slightly weak. Abt (1984) classified this star as λ Boo, but we do not agree with this classification.

HD 2884: HD 2884 (HR 126) is a visual binary with HR 127, classified as A2 Va in paper I.

HD 5737: Full spectral type: B7 II* C II ((metallic lines)).

HD 6457: HD 6457 (HR 311) is a visual binary with HR 310, classified as A0 IV-Vnn in paper I.

HD 7374: Full spectral type: B8 IV-V HgMn metallic lines.

HD 12534: Close visual double. Spectral type is for the composite spectrum.

HD 12767: Full spectral type: kB8 hB8 HeB9 III (Si) ((metallic lines)). This star also shows a weak $\lambda 4481$ line.

HD 13294: HD 13294 (HR 628) is a visual binary with HR 629, classified as A1 IIIIn in paper I.

HD 16046A: HD 16046A (HR 749A) is a visual binary with HR 749B, classified as A5 V in paper III.

HD 20863, 20961, 21071, 21455, 21551, 21641, 21699, and 21931: Members of α Per cluster.

HD 21455 is an emission-line star; clear emission in H β and H γ , H δ looks filled in.

HD 21641 is also an emission-line star. The emission is detectable as a slight filling of the H β line.

HD 21661: Non-member of the α Per cluster. The Ca II K-line looks slightly weak for the spectral type.

TABLE 2. (continued)

- HD 21699*: Full spectral type: kB8 hB7 HeB9.5 III Si (C II) (metallic lines). Prototype of helium-weak star.
- HD 21790*: Ca II K-line looks slightly weak for the spectral type.
- HD 21933*: Full spectral type: kB8 HeB9.5 V (HgMn) ((metallic lines)).
- HD 22203*: SB2
- HD 23288, 23324, 23363, 23408, 23432, 23441, 23480, 23630, 23850, 23923*: Members of the Pleiades. *HD 23324* (HR 1144) is a dagger and high-vsini standard. *HD 23630* (HR 1165) is a dagger standard, *HD 23850* (HR 1178) is a dagger and high-vsini standard.
- HD 24388*: He I 4384 has an unusually broad profile. He I 3820 is slightly strong for the spectral type.
- HD 27376 = HR 1347*: A close double with $\Delta m = 1.0$. Probably a composite spectrum.
- HD 29305*: Full spectral type: kB8 hB7 HeA0 V Si ((metallic lines)).
- HD 32039, 32040*: Components of a visual double. Both stars have very broad lines. *HD 32040* (HR 1610) has very broad, but shallow hydrogen-line wings.
- HD 32273A*: *HD 32273A* (HR 1619A) is a visual binary with HR 1619B, classified as A3Va in paper III.
- HD 32549*: Full spectral type: kB8 hB9 HeA0 II-III Si metallic lines.
- HD 33904*: Full spectral type: kB9 hB8 HeB9 IV HgMn (C II) ((metallic lines)).
- HD 34085*: Dagger standard.
- HD 35281A*: *HD 35281A* (HR 1778A) is a visual binary with HR 1778B, classified as F0 V in paper II.
- HD 35497*: B7 III standard (Morgan et. al. 1978).
- HD 38899 = HR 2010*: Low-vsini B9 IV standard.
- HD 40312*: Full spectral type: kB8 hB9 HeA0 II Si (metallic lines).
- HD 45380*: High-vsini B9 V standard.
- HD 49023*: Hydrogen lines show deep, narrow cores, $\lambda 4233$ is slightly enhanced, and H β shows faint emission wings.
- HD 49028*: Cores of the hydrogen lines look narrow and may be shell-like. Presence of $\lambda 4233$ supports the classification of this star as proto-shell.
- HD 49151*: H β , H γ look slightly filled in.
- HD 49606*: Full spectral type: kB8 hB7 HeB9.5 IV-V ((C II)) ((MnHg:)).
- HD 51250B*: *HD 51250B* (HR 2593B) is a visual binary with HR 2593A which we classify as K2 III. Component B has peculiar line profiles and may be an SB2.
- HD 56022*: Full spectral type: kB8 hB9 HeA0 V (Sr) ((Si)).
- HD 65663*: H β in emission.
- HD 66066*: Non-member of NGC 2516.
- HD 66137*: Line profiles indicate that this star may be an SB2.
- HD 66684A*: *HD 66684A* (HR 3164A) is a visual binary with HR 3164B, classified as A1 IVn in paper I.
- HD 71487*: *HD 71487* (HR 3327) is a visual binary with HR 3328, classified as A2 Va in paper I. HR 3327 is an eclipsing binary and has hydrogen lines with slightly peculiar narrow cores.
- HD 76728*: Full spectral type: B8 II Mn metallic lines.
- HD 79931*: Shows an extremely weak metallic-line spectrum.
- HD 87901*: Broad but shallow hydrogen-line wings.
- N3532-157*: Not a member of NGC 3532, but perhaps a member of a background association or cluster. #25, 191 (an O7 I star), 229 and 251 (B3 stars) may be additional members of this background association.
- HD 103192*: Full spectral type: kB8 hB8 HeA0 V Si (metallic lines). Hydrogen lines have curious rounded profiles.
- HD 106625*: Full spectral type: B8 III-IV ((metallic lines)). Classified as a HgMn star in the BSC, but the usual lines of Hg and Mn are not visible in our spectrum. However, a faint, but rich metallic-line spectrum is visible.
- HD 107832*: Low-vsini B9 III standard.
- HD 110073*: Full spectral type: B8 III Mn (metallic lines).
- HD 112413*: Full spectral type: kB8 hB8 HeA0 II Si (Eu). *HD 112413* (HR 4915) is a visual binary with HR 4914, classified as F1 V in paper II. The magnitude difference ($\Delta V = 2.70$) suggests that the primary, *HD 112413* is subluminescent for its spectral type.
- HD 114911A*: *HD 114911A* (HR 4993A) makes a wide double with HR 4993B, classified as kB8hF0: SrSi. Probably not a physical pair.
- HD 118991A*: *HD 118991A* (HR 5141A) is a visual binary with HR 5141B, classified as A2.5 Va in paper I.
- HD 120642A*: *HD 120642A* (HR 5207A) is a visual binary with HR 5207B, classified as A7 V in paper III.
- HD 129174*: Full spectral type: B9 III HgMn metallic lines.
- HD 134759*: Full spectral type: B9 II Si (metallic lines).
- HD 144206*: Full spectral type: kB8 hB8 HeB9.5 IV HgMn ((metallic lines)). He I 4026 shows an unusually broad profile.

TABLE 2. (continued)

- HD 144334*: Full spectral type: kB8 hB4 HeB9 V (Si-4200)
HD 145389: Full spectral type: B9 III (MnHg:) ((metallic lines)).
HD 145501A: Full spectral type: kB8 hB4 HeB9 III (Si) (metallic lines).
HD 145964: Very high $v \sin i$. The K-line and the He I lines look weak for the spectral types. Mg II $\lambda 4481$ is weak. Spectrum appears almost featureless except for the hydrogen lines.
HD 146416: SB? Both Ca II K and He I lines look weak for spectral type. Very broad-lined star.
HD 147010: Full spectral type: kB8 hB8II HeA0 mA2Ib Si (Cr:). Member of the Upper Scorpius Association. Very peculiar spectrum. Hydrogen lines indicate a luminous, late B-type star, but the metallic-line spectrum is rich. The metallic-line spectrum is composed mostly of ionized iron and titanium lines and looks very much like the metallic-line spectrum of an A2 Ib star. Si II $\lambda\lambda 4128-30$ is also enhanced, and there is a very peculiar line pattern between He and H δ . The spectrum shows variability in the Si II doublet, and possibly in the line pattern between He and H δ . A slightly enhanced $\lambda 4077$ line is responsible for the Cr: classification; the Sr II $\lambda 4215$ line is not visible (however, there is a Si II line near $\lambda 4077$, and this may be the source of the line). Thompson et. al (1987) have recently shown that this star possesses an extremely strong magnetic field.
HD 148199: Member of the Upper Sco Association. Spectrum is quite similar to that of HD 147010, but not as extreme.
HD 162305: Full spectral type: kB8 hB9 HeA0 IV ((metallic lines)). $\lambda 4481$ is slightly weak. Cores of hydrogen lines shallow?
HD 162576: Full spectral type: kB8 hB9 HeB9.5 III (Si) (metallic lines)
HD 162586: Close visual double. Spectral type is for combined spectrum.
HD 166937: Slight suggestion of emission wings around H β .
HD 169512: Non-member of NGC 6633. Close visual double.
HD 170000: A slight variability in the Si II $\lambda 4128-30$ doublet can be seen from plate to plate.
HD 170200 = N6633-102: Non-member of NGC 6633.
HD 170881: Probably not a member of NGC 6633.
HD 177756: Moderately broad-lined spectrum. K-line and He I lines almost invisible, Si II $\lambda\lambda 4128-30$ and $\lambda 4481$ marginally visible. Spectrum otherwise featureless.
HD 178065: B9 II standard.
HD 184707: Full spectral type: kB8 hB9 HeA0 Va (Sr Fe II). Hydrogen lines may show shell cores?
HD 196867: High- $v \sin i$, B9 IV standard and dagger standard.
HD 209952: High $v \sin i$; C II $\lambda 4267$ marginally visible.
HD 221507: Full spectral type: kB8 hB9 HeA0 IV HgMn ((metallic lines))
HD 222847: Hydrogen wings are very broad but shallow.
HD 224112: B8 V, low- $v \sin i$ standard.
HD 224113: Eclipsing binary.
HD 224686: B9 III, high- $v \sin i$ standard.
HD 225119: Full spectral type: kB8 hB7 HeB9.5 III Si metallic lines. Rich metallic-line spectrum includes $\lambda 4077$, $\lambda 4233$, $\lambda 4325$, $\lambda\lambda 4172-9$.

*Table 2 is presented in its complete form in the ApJ/AJ CD-ROM Series, volume 2, 1994. The first page of this table is presented here for guidance regarding its form and content.

drop for higher values of $v \sin i$. This effect was compared to the theoretical results of Collins & Sonneborn (1977), and was shown to be in qualitative agreement with that theory. The theory of Collins and Sonneborn predicts that a similar effect should be seen in the late B type stars if we correct the β index for temperature effects in the following way:

$$\delta\beta(c_0) = \beta_{\text{observed}} - \beta(c_0),$$

TABLE 3. Mean photometric indices.

Spectral types	$v \sin i$ group*	$\langle b-y \rangle$	σ	$\langle v \sin i \rangle$	N
B7 V, IV, III	$0 < v \sin i < 400$	-0.051	0.008	132.8	23
B8 V, IV, III	$0 < v \sin i < 400$	-0.042	0.007	182.9	52
B9 V, IV, III	$0 < v \sin i < 400$	-0.025	0.010	156.5	30

*Number was not sufficient to separate into luminosity and $v \sin i$ bins.

where $\beta(c_0)$ represents the standard β, c_0 relation of Crawford (1978). However, when we plot $\delta\beta(c_0)$ for all of the normal B type stars in our sample against $v \sin i$, we see no such effect. We note that Warren (1976) carried out a similar analysis on the OB stars in the Orion OB1 association and found, similarly, no systematic effect out to about 250 km/s, but a slight systematic deviation of $\delta\beta(c_0)$ toward negative values for more rapidly rotating stars. In any case, the observed effect is much less pronounced than in the early A type stars, whereas the theory of Collins and Sonneborn predicts an equally strong effect in the late B type stars. We show in the next paragraph that the lack of this rotational effect can be accounted for by consideration of the sources of error.

Analysis of the process we went through to obtain $\delta\beta(c_0)$ reveals one or two effects that are large enough to com-

pletely mask any systematic effect of rotation on β . The dereddening procedure of Crawford (1978) has an intrinsic error of about 0.01 mag in $(b-y)$. However, because of the steepness of the standard $(b-y)$, β relation, this error translates into an error of at least 0.04 mag in β in the late B type stars, which is about the size of the rotational effect predicted by the Collins–Sonneborn theory. Second, the effect of rotation on c_1 may tend to mask the effect of rotation on β . The theory of Collins and Sonneborn predicts that for a given c_1 , rotating stars of any inclination then to have redder $(b-y)$ colors than nonrotating stars. This implies that $E(b-y)$ will be overestimated for rotating stars, making the “dereddened” c_0 obtained from Crawford’s method too small and the corresponding $\beta(c_0)$ too small. This will tend to minimize the difference between β_{standard} and $\beta(c_0)$ and to mask any rotational effect on β . This points out the importance of the early A type stars in the study of the photometric effect of rotation; the broad maximum in the β , $(b-y)$ envelope which occurs in the early A type stars greatly diminishes the importance of the “masking” effects described above.

5. THE PECULIAR B TYPE STARS

5.1 The Spectral Classification of the Peculiar B Type Stars

In our sample, the peculiar B type stars can be divided into the traditional groups, each characterized by certain abnormal line strengths which in ensemble do not match any standard star in the normal sequence. In order to take full advantage of the information in the classification spectrum, we have followed the lead of Osawa (1965), who classified 244 peculiar stars by specifying spectral types for the He I lines, the Balmer lines, and the K line. For the 14 stars in common between our list and Osawa’s the classes agree quite well, though there are a few interesting exceptions, which we note below.

Examination of the classifications (Table 2) reveals the existence of three major categories and several subgroups. These categories are: (1) the mercury–manganese (Hg–Mn) stars, (2) the silicon (Si) stars, and (3) the helium-weak (He-weak) stars. We discuss these classes and some interesting subclasses below.

5.1.1 The Hg–Mn stars

An excellent review of this class of star can be found in Wolff (1983). We add the following remarks. The Hg–Mn stars in our sample are about evenly divided between those that show a mild helium-weak nature and those that do not. There is a very interesting possibility that the helium-weak nature of these stars may be slightly variable. Our helium and hydrogen types for the Hg–Mn stars do not agree very well with those of Osawa (1965), whereas the agreement with Osawa for the silicon stars is very good. Among the Hg–Mn stars in common with Osawa, we classify some as helium-weak that he sees as normal and vice-versa. We have duplicate spectra in our own sample for only a few stars, and within a relatively short time interval, but we detect no variability for any of them. However, it is of interest to note that Rakos & Kamperman (1977) and Rakos *et al.* (1981) have

reported *IUE* spectroscopic variability for alpha Andromedae, a complex star that shows, in addition, mild Si II enhancement. Also, Renson & Manfroid (1981) have reported variability in the *uvby* indices of HR 2202, but this Hg–Mn star is not in our sample.

5.1.2 The Si stars

It is well known that the Si stars can be divided into two groups: the Si stars (which show enhanced Si II $\lambda\lambda 4128-31$) and the Si–4200 stars (in which both $\lambda\lambda 4128-31$ and Si II $\lambda 4200$, as well as several other high excitation Si II lines, are enhanced). The Si stars tend to have redder colors and later hydrogen line types than the Si–4200 stars.

Most of the Si stars in our sample show only mild helium deficiencies (judged from the difference between the helium and hydrogen temperature types), while the Si–4200 stars show strong helium/hydrogen discrepancies. However, this may be a selection effect because the full extent of the helium/hydrogen discrepancy for the Si stars cannot be ascertained at classification dispersion. That is because, for many of the Si stars, the helium lines are simply not visible in our spectra. Thus they have been given a helium line type of A0, so if the Ca II K line is also weak, the stars may actually be later than A0.

5.1.3 The helium-weak stars

These stars are characterized by the following peculiarities (see also Garrison 1967, 1973).

(a) Many show peculiar hydrogen line profiles characterized by a sharp, essentially normal hydrogen line core, and very broad, unusually shallow wings. Quite often the helium lines also appear broad and “washed out.”

(b) The presence, usually but not always, of C II ($\lambda 4267$) and Si III ($\lambda 4552$) lines, which are characteristic of B3 stars.

(c) The presence, occasionally, of faint lines of Fe II and Ti II, which are characteristic of A type and late B type stars.

(d) In several spectra, characteristics (b) and (c) coexist, clearly indicating the presence of non-LTE effects.

In addition to these defining spectroscopic criteria, the colors of the helium-weak stars are often peculiar. In particular, a helium-weak star with a helium line type of, say B8, quite often has colors more characteristic of B3 or B4 stars. The hydrogen line types are usually closer to the colors than the helium line type, but even then the color is usually too blue for the hydrogen line type.

Among the stars that show the C II doublet at $\lambda 4267$ there are some intriguing trends, but our sample is too small to be very useful in delineating the trends significantly. Statistical investigation of the appearance of C II in a large number of B stars would be rewarding. However, we would like to mention two interesting stars, HR 4975 and HR 3327, both classified as normal B8 dwarfs, which do not seem to exhibit any pronounced helium deficiency, but which show the C II $\lambda 4267$ doublet at unusually late hydrogen line types. The hydrogen line types of these stars are, incidentally, in excellent agreement with their colors; hence the presence of C II in the spectrum is indicative of non-LTE or other unknown effects.

5.2 Comparison of Strömgren Photometry and Spectral Classification of Peculiar B Type Stars

Crawford (1978) established a relationship between temperature type and the intrinsic $(b-y)$ index for the B type stars that agrees within a few thousandths of a magnitude with the relation for the late B type stars in Table 3. If we use Crawford's relationship, it is clear that the helium line type for those peculiar stars with discrepant helium and hydrogen classes is much too late for the dereddened color of the star, whereas the hydrogen line type generally lies somewhat closer to the mean color relation. It is interesting, however, that the dereddened color (using Crawford's dereddening technique) indicates a spectral type which is earlier than even the hydrogen type in the majority of the peculiar B type stars, even for those that do not show a helium deficiency. This discrepancy could be caused by:

(a) The slightly peculiar hydrogen line profiles noted in many Bp stars, which may be reflective of a different atmospheric structure, or a peculiar energy distribution which affects the $(b-y)$ color.

(b) The presence of an ultraviolet excess in these stars, possibly due to a hotter secondary. This would give a smaller c_1 index which would cause the dereddening procedure to give too blue an intrinsic $(b-y)$ index. This hypothesis will not work for the silicon stars, as their binary frequency is considerably lower than normal (Abt & Snowden 1973), nor can it be applied to the Hg-Mn stars, as their binary frequency is nearly normal (Wolff & Preston 1978). No similar study of the binary characteristics of the helium-weak stars has been made.

(c) Extra line blanketing in the v filter could decrease the c_1 index and increase the m_1 index. This effect has been observed by Cameron (1967) who found that the Bp stars had, for a given c_1 index, larger values of m_1 than normal late B type stars. However, Wolff (1967) found that the line blanketing in the Hg-Mn stars is too small to distort the colors sufficiently to allow detection by intermediate or broadband photometric techniques.

Unfortunately, it is difficult to test photometrically whether these stars have unusual c_1 indices because we cannot deredden the c_1 and $(b-y)$ indices independently. However, there is one silicon star for which the c_1 index is definitely too large for its $(b-y)$ color (alas, the opposite of what we require to explain this discrepancy photometrically): HR 612=HD 12767 has $(b-y) = -0.077$ and $c_1 = 0.508$. According to Crawford's standard relation, a star with a c_0 index of this size should have $(b-y)_0 = -0.60$. Thus the dereddening procedure gives a negative reddening for this star. If we assume that the intrinsic $(b-y)$ index of this star is -0.079 , then this would make the hydrogen type discrepant by at least four temperature types (i.e., 88 as opposed to B4). An error of this magnitude in spectral classification is highly improbable, and thus it seems that our first hypothesis, the presence of unusual hydrogen line profiles or a peculiar energy distribution in at least some of these chemically peculiar B type stars is a distinct possibility, and should be investigated further.

TABLE 4. Normal B stars

Luminosity Class	$\delta\beta$	σ	N
V	0.023	0.021	29
III	0.086	0.036	30

5.3 The Luminosity Classes of Bp Stars

The question of the evolutionary state of the Bp stars is an important one, and has received considerable attention in the literature (e.g., Abt 1983; North & Kroll 1989; North 1993). The study by North suggests that all Ap and Bp stars are main-sequence objects—that is, they lie between the ZAMS (zero-age main sequence) and the TAMS (terminal-age main sequence). In the temperature range relevant to our sample of stars, the TAMS corresponds roughly to a luminosity class of III. Thus, if North is correct, we should not expect to see Bp stars with luminosity classes of II or higher. On the contrary, in our sample, we have classified six Bp stars as bright giants mostly from their hydrogen lines. These stars span the full range of peculiar types as outlined above, with the exception of the Si-4200 stars. Two rather exceptional stars are HD 147010 and HD 148199, which are members of the Sco-Cen association. These stars show a metallic line spectrum which places them in the Ib luminosity class, although the hydrogen lines indicate a lower luminosity (II or III). Does Strömgren photometry confirm these luminosity classes? For the B type stars, the primary luminosity indicator in the Strömgren system is the $\delta\beta$ index defined by Crawford (1978). A statistical study of this parameter for the normal B stars in our sample is shown in Table 4, whereas the results for the Bp stars are found in Table 5.

It is clear that the $\delta\beta$ index is well correlated with luminosity class for both the normal and the peculiar stars. However, for the same luminosity class, the $\delta\beta$ index for the peculiar stars is smaller by about 0.02–0.03 mag. The interpretation of this effect is complicated by the fact that the derivation of the $\delta\beta$ index involves the dereddening of the star, and this assumes that the energy distribution of the star is normal. It is well known, however (see Sec. 5.2), that the colors of the Bp stars are not normal. Indeed, in the small group of bright giant Bp stars, the $\delta\beta$ index ranges from 0.002 for HD 147010 to 0.128 for HD 40312. We can only suggest that this small set of bright giant Bp stars be studied more closely before it is concluded that all Bp stars lie between the ZAMS and the TAMS, though we believe that the results are probably due to non-LTE effects.

6. CONCLUSIONS

We have refined the MK classification system for the late B type stars and have introduced a parallel system of stan-

TABLE 5. Peculiar B stars

Luminosity class	$\delta\beta$	σ	N
V	0.003	0.010	6
III	0.057	0.036	6
II	0.065	0.041	6

dards for the broad lined stars. We have investigated the effects of rotation on the inter-relationship between the spectral types and their Strömrgren colors, and have found no observable effect. We have reclassified a number of peculiar B type stars, and have noted specific examples in which non-LTE effects seem to be present. In addition, we have pointed out a number of bright giant Bp stars, which should be investigated more closely before it is concluded that all Bp stars are main-sequence objects.

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