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

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ABSTRACT

In the third of a series of papers on the A- and early F-type stars, we refine the MK spectral classification system for the late A-type stars (A3–A8) and consider the effect of rotation on both spectral classification and *uvbyβ* photometry for these stars.

We critically examine in some detail the spectral classification criteria for the late A-type stars. We have found, in particular, that the λλ4417/4481 ratio (commonly used for luminosity classification in the A-type stars) gives results in the A3 stars that are inconsistent with the Stark broadening of the hydrogen lines. This observation, combined with a similar result for the early F-type stars, suggests that this ratio is not a useful luminosity criterion at any spectral type. By carefully considering the effect of rotation on the classification criteria, we have extended the work of Morgan by the establishment of self-consistent sequences of narrow- and broad-lined standards.

We have confronted our classifications with Strömgren photometry. We have examined in some detail the relationship between the δc_1 index and the luminosity classifications. We have discovered a significant population of low-$v \sin i$ late A-type stars that have anomalously high δc_1 indices for their luminosity types. After the consideration of a number of explanations, including the possibility of faulty classifications and the photometric effect of convection, we conclude that these stars are rapid rotators seen nearly pole-on ($i < 30°$). This discussion also suggests that Strömgren photometry may not be reliable for estimating the ages and luminosities of low-$v \sin i$ A-type stars and that there are complications in using the δm_1 index to isolate metal-weak A-type stars (such as the λ Bootis stars) from the field.

Subject headings: photometry — stars: early-type — stars: rotation — stars: spectral classification

I. INTRODUCTION

This paper is the third in a series on the refinement of the MK spectral classification system for the B8–F2 stars. We have confronted this refined system of classification with Strömgren photometry and have investigated empirically the effect of rapid rotation on spectral classification, Strömgren photometry, and the relationships between these autonomous systems. This paper is concerned with the late A-type stars (A3–A8). The first paper in this series (Gray and Garrison 1987, hereinafter Paper I) dealt with the early A-type stars and defined our methods and observational samples. The second paper (Gray and Garrison 1989, hereinafter Paper II) dealt with the early F-type stars (A9–F2).

The late A-type stars are among the most difficult stars to classify. There are a number of reasons for this. The most fundamental is a problem that is encountered in both the A- and the B-type stars: the existence of a wide range of projected rotational velocities, which greatly complicates the comparison of a program star with the classification standards. This problem was recognized early on by Morgan (Morgan, Keenan, and Kellman 1943; Morgan and Keenan 1973; Morgan, Abt, and Tapscott 1978; Morgan 1984), who suggested that it could be ameliorated (*a*) by the use of low-dispersion (~ 150 Å mm^{-1} spectrograms), which would minimize differences in appearance between broad- and narrow-lined stars, and (*b*) by the establishment of a frame of reference consisting entirely of very broad lined stars. Morgan took the first steps along these lines by establishing a number of broad-lined standard stars, such as γ UMa. In this paper, and in Papers I and II, we have extended Morgan's work by providing more complete sets of standards for narrow- and broad-lined stars. Papers I and II also include a detailed discussion of the effects of rotation on classification spectra.

A second problem that is peculiar to the late A-type stars is the insensitivity of the classification criteria to luminosity. For example, in the early A-type stars, the luminosity classification is based on the sensitivity of the Stark wings of hydrogen to pressure, whereas in the early F-type stars it is based on the sensitivity to pressure of the lines of ionized iron and titanium. With decreasing temperature, the Stark wings of hydrogen lose their sensitivity to log *g*, becoming essentially insensitive to luminosity by spectral type A5. However, in the A5 and earlier stars the lines of ionized iron and titanium show only a fraction of the sensitivity to luminosity that they show at F0 and are most probably quite strongly influenced by at least one factor other than pressure. This means that the luminosity classification of the late A-type stars is based on rather subtle effects in the spectrum. For reliable results, the spectral classifier must work with the highest quality material available and be fully aware of the behavior of the various spectroscopic criteria, as well as the effects of rotational broadening.

II. THE CLASSIFICATION OF THE LATE A-TYPE STARS

a) *The Temperature Classification of the Late A-Type Stars*

The temperature classification of the late A-type stars as described by Morgan, Keenan, and Kellman (1943) and elaborated by Morgan, Abt, and Tapscott (1978) is guided by the behavior of three spectral criteria which, in the normal stars, vary consistently together. These three criteria are (1) the Ca II K line, (2) the metallic lines and blends, and (3) the hydrogen lines.

The Ca II K line strengthens significantly toward later types in the late A-type stars. In the early A-type stars the absolute strength of the Ca II K line may be estimated easily by eye (by reference to the standard stars), but in A5 and later stars, it is best to estimate the strength of the K line in ratio with another strong line. In the late A-type stars, the hydrogen lines decrease considerably in strength toward later types. Thus the ratio of the Ca II K line to hydrogen (as indicated by the Ca II K/Hδ ratio and the Ca II K/(Hε + Ca II H) ratio) is a sensitive indicator of the temperature type. The use of the Ca II K/hydrogen ratio is subject to three problems, however. First, chemically peculiar stars (Ap, Am, and proto-Am stars) often have K lines of unusual weakness or profile. While the chemically peculiar nature of many of these stars is obvious enough for this not to pose a problem, the K line can be affected in even marginal Ap and Am stars. A check on the consistency of the temperature types derived from the K line and from the general metallic-line spectrum (see below) can reveal many stars with marginal Am tendencies. The spectral classifier must be open to this possibility.

Second, at A3, the hydrogen lines are still quite sensitive to luminosity, and hence the use of the K/hydrogen ratio may introduce systematic effects into the temperature classifications with luminosity. We may, however, quite reliably avoid any such systematic effect by using the core of the hydrogen line for comparison.

The third problem, which concerns the effect of rotation on the strength of the hydrogen lines is potentially more serious. Inspection of the $\delta\beta$ versus $v \sin i$ diagram for the A3 stars (see Paper I) shows that the hydrogen lines of the high-$v \sin i$ A3 stars are systematically weakened. If this effect is not taken into account, a rapidly rotating A3 star may be given a classification which is too late. This problem persists at A4, but by A5 the effect of rotation on the hydrogen lines is substantially smaller (see § III*a*), and the Ca II K/hydrogen ratio may be used safely even for quite rapid rotators. Experience thus shows that for the most rapidly rotating stars ($v \sin i > 200$ km s^{-1}) it is very difficult indeed to distinguish temperature types in the range A2–A4. To classify these stars, greater weight must be given to the absolute strength of the Ca II K line (as opposed to its ratio with hydrogen) and the appearance of the intrinsically broad metallic blends such as λ4271.

We note that in the above discussion we have ignored the possible effects of rapid rotation on the absolute strength of the metallic lines and blends (including the K line). We know from theoretical studies, however, that rapid rotation has important effects on these line strengths. If we were to take, for instance, an A2 star and increase its angular momentum to nearly the critical point, its photometric temperature (as viewed in the equatorial plane) would be considerably reduced; the models of Collins and Sonneborn (1977) suggest that its photometric temperature would be similar to that of an F0 star. The spectral type would also change with rotation, and the star would probably appear to be a rapidly rotating F0 star. Using spectral classification we can never hope to detect this absolute change in spectral type (i.e., from A2 to F0); all that we can hope to detect are differential changes that would reflect the different sensitivities of the temperature criteria to rotation. What we are really saying in the above paragraph is that we cannot detect with classification spectra alone any of these differential effects in stars later than A4; i.e., later than A4, rapidly rotating stars look "normal." Earlier than A5, however, differential effects can be seen in the hydrogen lines (see Paper I), and this is why we must treat the K/hydrogen ratio with care in stars earlier than A5.

The strength of the metallic lines and blends is the second temperature criterion in the late A-type stars. Of most use are the broad blends at λ4271 (Fe I) and λ4030 (Mn I). The use of these broad blends helps to reduce systematic effects with rotation.

The strength of these blends increases very slowly between A3 and A5, so they are not very useful for distinguishing the temperature types of these stars. However, between A5 and F0 these blends show a uniform and easily detectable increase in strength. The Mn I blend also undergoes a change in morphology. At A3 this blend shows a rounded profile in narrow-lined stars. By A5 the profile appears more square. This trend continues through to the F0 stars. The morphology of this blend is also dependent on luminosity in A5 and later stars in that the Mn I blend becomes broader and shallower in luminous stars.

In the late A dwarf stars the behavior of the hydrogen lines undergoes a dramatic change with temperature. In A3 dwarfs the hydrogen lines show the very broad Stark wings characteristic of dwarfs near the Balmer maximum. By A5 only a minority (probably the high-temperature tail of the distribution) show these very extended wings. After A5 the decrease in the strength of the hydrogen lines is readily apparent to the eye and may be used on good quality spectra to estimate the temperature type of a star to an accuracy of about plus or minus one major subclass. (In this study the A4, A6, and A8 temperature classes are regarded as intermediate types and not as full classification boxes. The notes for Table 3 in Paper I contain a more detailed discussion of this terminology.)

b) *The Luminosity Classification of the Late A-Type Stars*

The luminosity classification of the late A-type stars presents problems that are an order of magnitude more difficult than those encountered in the temperature classification. There are essentially two criteria which may be used in the luminosity classification of the late A-type stars: (1) the Stark wings of the hydrogen lines and (2) the lines of singly ionized metals (see Morgan, Abt, and Tapscott 1978).

1. The Stark wings of hydrogen lose their sensitivity to pressure very rapidly as we move away from the Balmer maximum. At A3 the sensitivity of the wings to gravity is only slightly diminished from that of the early A-type stars, but by

A5, and certainly by A7, the eye cannot detect any difference between the hydrogen lines of most dwarf and giant stars, although the hydrogen line profiles do permit the separation of the supergiant classes. This dramatic change in the sensitivity of the hydrogen line wings can be confirmed by reference to the atmospheric models of Kurucz (1979); the relevant models are those at 8500 K (roughly A3) and at 8000 K (about A7).

2. In the late A-type stars there are two blends composed mostly of lines of singly ionized metals (iron and titanium) which are strong enough to be potentially useful in the luminosity classification. These two blends are (1) the Fe II, Ti II λ4417 blend and (2) the Fe II, Ti II λλ4172–4179 blend. The λ4417 blend is estimated in ratio with λ4481, a close Mg II doublet, and λλ4172–4179 is estimated in ratio with an Fe I blend at λ4203 (see Paper II for more details).

In the original Morgan, Keenan, and Kellman (1943) spectral classification atlas the λλ4417/4481 ratio was used as the primary luminosity criterion for the late A-type stars, and this criterion continues to be used by most spectral classifiers. We have tested the consistency of this blend in the A3 stars by comparing this ratio with the appearance of the hydrogen line wings. Figure 1 shows the plot of λλ4417/4481 versus the extent of the hydrogen line wings (both on arbitrary scales) for the low-$v \sin i$ A3 stars. We note that the distribution of stars in this diagram is not linear, but rather upper triangular; there are a significant number of stars, in particular dwarf stars, for which the λλ4417/4481 ratio indicates a greater luminosity than the hydrogen lines.

This lack of consistency between these two luminosity criteria is probably caused by a number of factors. First, the λ4481 line shows a range of line strengths in the spectra of

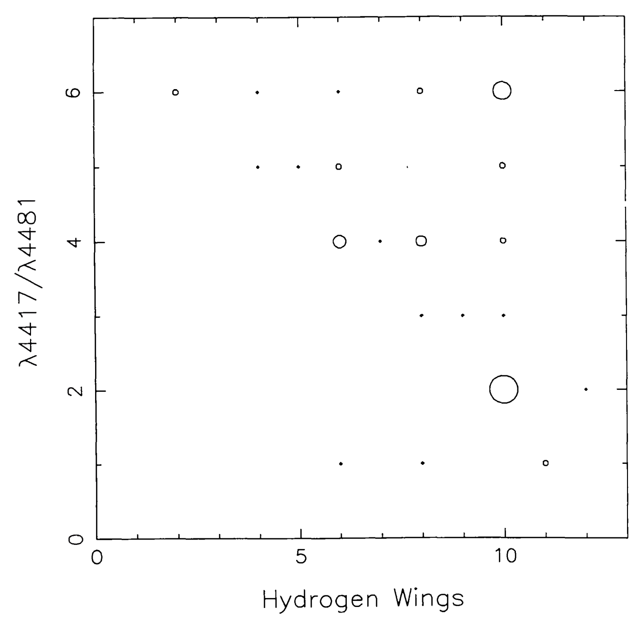

FIG. 1.—The relationship between the visual extent of the hydrogen wings and the line ratio λλ4417/4481 for the low-$v \sin i$ ($v \sin i <$ 150 km s^{-1}) A3 stars. Arbitrary scales are used for the hydrogen line wings and the line ratio. On the hydrogen line wing scale, dwarfs correspond to a value of 10 and giants to a value of 2. A value of 6 on the line-ratio scale corresponds to a real line ratio of about unity. The size of the symbol is proportional to the number of stars at each point.

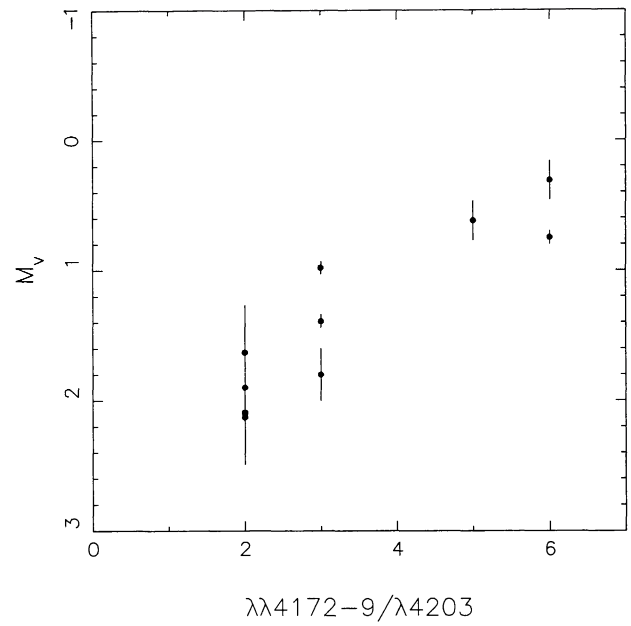

FIG. 2.—The correlation between the line ratio λλ4172–4179/4203 (on an arbitrary scale) and the absolute magnitude of the low-$v \sin i$ ($v \sin i <150$ km s^{-1}) A5 stars. A value of 2 on the line-ratio scale is typical of dwarf stars, 6 is typical of giants. The points with the largest error bars are parallax stars. The other absolute magnitudes are derived from cluster membership.

otherwise normal stars. The extreme limits of this range are the λ Bootis stars (which are not normal stars), in which λ4481 is essentially absent, and stars such as HR 4717, a member of the Coma cluster, in which λ4481 is exceptionally strong. Rapid rotation may also have a significant effect on the strength of the λ4481 line (see Paper I), although this may not be an important consideration here since Figure 1 contains only low-$v \sin i$ stars. We have, however, the general impression that most of the inconsistency in the λλ4417/4481 ratio is due to the λ4417 blend itself. (We have gained this impression by comparing λ4417 with other blends, such as Fe I λ4271.) Bolton (1971) showed that the λ4417 blend is composed of lines which, for the most part, lie on the flat part of the curve of growth. This implies that this blend may be more sensitive to microturbulence than to gravity. Thus, the dwarfs that lie above the diagonal line in Figure 1 may simply have higher than average microturbulent velocities. In any case, the λλ4417/4481 ratio does not appear to be a reliable luminosity criterion. The fact that we came to the same conclusion in Paper II for the early F-type stars suggests that this ratio is not useful at any spectral type.

The λλ4172–4179/4203 ratio shows a similar behavior in the A3 stars. By A5, however, this ratio seems to be a fairly reliable indicator of luminosity as can be seen from Figure 2 where we plot M_V versus λλ4172–4179/4203 (on an arbitrary scale). A similar plot of M_V versus λλ4417/4481 for the A5 stars is essentially a scatter diagram. The absolute magnitudes in Figure 2 are derived from parallaxes and cluster distance moduli. By A7 λλ4172–4179/4203 shows nearly the same sensitivity to luminosity as it does at F0. We emphasize, however, that the λλ4172–4179/4203 ratio does not show a very large range at A5, and thus spectra of high quality are required for accurate luminosity classification at this spectral type.

In summary, the hydrogen line wings may be relied upon for reasonably accurate luminosity classification up to temperature type A4. In A5–A7 stars, however, luminosity classification must be based on the appearance of the λλ4172–4179/4203 ratio. Later than A7, a number of other useful luminosity criteria become available (see Paper II).

c) *The Framework of Standard Stars*

The framework of standard stars adopted for this study and proposed for general use is based on the system of standard stars defined by Morgan and Keenan (1973) and Morgan, Abt, and Tapscott (1978). We have refined and extended this framework in three important ways. First, we have established a parallel system of broad-lined standard stars using the methods discussed in Papers I and II. Second, we have critically examined the existing MK standards and have rejected one star (α Oph) as a suitable standard (see below) and modified the spectral type of another (β Eri) to improve the consistency of the grid. Third, we have divided the V luminosity class for the A3 stars into Va and Vb (following the lead of Morgan, Abt, and Tapscott [1978] who first defined the Vb class for A0 stars) in order to take advantage of the still considerable sensitivity to luminosity shown by the hydrogen line wings at this temperature type, and we have formalized this by proposing an A3 Vb standard.

The standard stars proposed for general use are listed in Table 1. In Table 2 we list new spectral classifications of 284 late A-type stars by one of us (R. O. G.) on this refined system. The notation used in this table is discussed in detail in Papers I and II.

A note on α Oph: The spectral classification of this very rapidly rotating star ($v \sin i = 215$ km s^{-1}) is problematical, and thus it has not been included in our list of standards despite the fact that Morgan (1984) still considers this star as the A5 III standard. This star was apparently first selected as the A5 III standard on the basis of its λλ4417/4481 ratio, which is nearly unity. However, as mentioned above and in Paper I, the λ4481 line may be affected by rapid rotation. As a matter of fact, it is the rule rather than the exception that high-$v \sin i$ dwarf stars have λλ4417/4481 ≅ 1. The λλ4172–4179/4203 ratio of this star implies that it is a dwarf, and we have classified it as such. The δc_1 index, which measures the size of the Balmer jump, is closer to that of a giant. This large δc_1 value, however, may be understood in terms of its rapid rotation; § III*b* below points out that rapidly rotating stars generally have large δc_1 indices for their luminosity types. The absolute magnitude of α Oph (≅1.2) implies that it is subluminous for a giant ($M_V \cong 0.5$), but overluminous for a dwarf ($M_V \cong 2.0$). This discrepancy is most easily understood on the basis of its rapid rotation and its binarity (separation ≅ 0.″1). If it is an equal double, both components would have absolute magnitudes fairly typical for A5 dwarfs. For these reasons, we no not feel that α Oph is a suitable A5 III standard star.

d) *Notes on Am and Ap Stars*

Inspection of Table 2 and the accompanying notes reveals one or two interesting points about the Am and Ap stars, which have hydrogen line types in the range of the late A-type stars. First, many Ap stars show, in addition to specific chemical peculiarities, broad and diffuse Ca II K lines (denoted by "kn" in Table 2). The Am stars, on the other hand, generally show weak, but quite sharp, Ca II K lines. The Am stars also quite often show the "anomalous luminosity effect" (see Abt and Morgan 1976), in which different regions of the spectrum are best matched by MK standards of different luminosities. For this reason, the luminosity types of the Am stars in Table 2 are enclosed in parentheses, as they are probably not good guidelines to the evolutionary state of the star.

There is one star, HD 150366, that, however, shows characteristics of both Ap and Am stars. This star shows a diffuse K line and slight enhancements of Sr II λλ4077 and 4216. Hence, it is classified as a Strontium Ap star. It also shows, however, a marked "anomalous luminosity effect" in that the λλ4395–4400, 4417, and 4444 blends are very weak while λλ4172–4179 is quite strong. This may prove to be an interesting star if studied in more detail.

TABLE 1
PROPOSED LATE A-TYPE STANDARD STARS

Spectral Type	Low-$v \sin i$ Standards	High-$v \sin i$ Standards
A3 Vb ...	β Cir	...
A3 Va ...	α PsA[1], β Leo	HD 23643
A3 IV ...	HR 4293	β Eri
A3 III ...	HR 3514	...
A5 V	HD 23194	HD 23886[2]
A5 III ...	HD 73210	...
A5 II	o Sco[1]	...
A6 II	HR 3426	...
A7 V	2 Hyi	21 LMi[1]
A7 IV ...	HR 3270	ι UMa[1]
A7 III ...	ϑ^2 Tau[1]	...

[1]Dagger standard star: Morgan and Keenan 1973.
[2]Standard star: Morgan, Abt, and Tapscott 1978.

III. CONFRONTATION OF THE REFINED CLASSIFICATIONS WITH *uvbyβ* PHOTOMETRY

a) *Mean Photometric Indices*

The mean photometric indices ($b-y$ and β) for the late A-type stars have been calculated using the procedures employed for the early A-type stars and the early F-type stars (see Papers I and II). For instance, for the A3 stars, there is no photometric dereddening procedure which does not depend upon some assumed relationship between $b-y$ and β, a relationship which may be invalidated by the effect of rotation on *both* indices. Hence, in the A3 stars, we used the same approach as in the early A-type stars: stars whose color indices are obviously reddened were eliminated from the sample. These included a few high-luminosity stars and stars in certain open clusters. A plot of $b-y$ versus V for the

TABLE 2

SPECTRAL TYPES OF LATE A-TYPE STARS

HD	HR/ID	Spectral Type	$b-y$	m_1	c_1	β	N
2262	κ Phe	A5 Vn	0.098	0.194	0.919	2.856	
2760	-	A5 V	--	--	--	--	
3112	ϑ Tuc	kA7hA7mF0 (IV)	0.148	0.187	0.984	2.814	
3283	146	A3 II	0.224	0.050	1.534	2.746	
4058	π Cas	A4 IV	0.085	0.228	0.901	2.857	
4490	59 Psc	A7 IV	0.165	0.178	0.929	2.773	
5382	67 Psc	A5 V	0.071	0.190	1.000	2.876	*
5448	μ And	A5 IV-V	0.068	0.194	1.056	2.867	
6619	323	kA2hA5mF0 (IV)	0.059	0.239	1.008	2.881	
6961	ϑ Cas	kA6hA7mF0 (IV)	0.087	0.213	0.997	2.845	
8538	δ Cas	A5 IV	0.080	0.192	1.111	--	
9063	--	kA9hA7mA7 (IV)	--	--	--	--	
9100	97 Psc	A3 Vb	0.090	0.166	1.093	2.817	*
9336	--	kA7hA7mF0 (V$^+$)	--	--	--	--	
10845	515	A8 III	0.158	0.173	0.979	2.777	
11502	γ^2 Ari	knA0hA3 (IV) SiSr	-0.046D	0.200	0.882	2.849	*
11636	ι Ari	A4 V	0.064	0.211	0.983	2.879	
12111AB	48 Cas	A3 Va	0.073D	0.218	0.899	2.842	
12447	α Psc A	kA0hA7 Sr	--	--	--	--	*
12563	606	kA3hA5mA7 (III$^-$)	0.063	0.217	1.074	2.872	
12573	60 Cet	A5 III-IV	0.081	0.183	1.076	2.840	
13041	58 And	A4 V	0.055	0.195	1.063	2.869	
13161	β Tri	A5 IV	0.071	0.191	1.065	2.848	
15633	732	A7 III	0.089	0.197	0.989	2.852	
16046B	ω For B	A5 V	--	--	--	--	
16555	η Hor	A7 Vn	0.173	0.170	0.762	2.763	
17093	38 Ari	A7 IV	0.136	0.185	0.843	2.797	
17943	859	A6 V$^+$	0.106	0.189	0.978	2.824	
18454	4 Eri	kA7hA7mF0 (III-IV)	0.132	0.222	0.857	2.823	
18622	ϑ^1 Eri	A5 IV	0.084D	0.161	1.094	2.844	*
18866	β Hor	A5 IVs	0.073	0.178	1.138	2.851	
18978	τ^3 Eri	A4 V	0.101	0.165	0.962	2.850	
19107	ρ^3 Eri	A6 V$^-$nn	0.114	0.186	0.905	2.823	
20060AC	--	A3 IV	--	--	--	--	
20322	--	kA3hA7mF0 (IV-V)	--	--	--	--	
21335	1036	A3 IVn	0.106	0.158	0.982	2.815	*
21688	1062	A5 IV-V	0.104	0.149	1.157	2.782	
21769A	1068	kA3hA5mA7 (III$^-$)	0.063	0.214	0.985	2.872	
22615	TS25A	A3 IV	0.080	0.197	1.093	2.880	*
23156	HZ158	A7 V	0.149	0.204	0.826	2.839	*
23194	HZ232	A5 V	0.118	0.197	0.908	2.882	*
23361	HZ652	A2.5 Van	0.126	0.192	0.970	2.875	*
23643	HZ1425	A3 Van	0.090	0.194	0.942	2.862	*
23863	HZ2195	A7 V$^-$n	0.128	0.201	0.861	2.826	*
23886	HZ2289	A5 V	0.093	0.208	0.921	2.880	*
24805	--	A3 IV	--	--	--	--	
27084	1330	A7 IV-V	0.138	0.182	0.963	2.788	
27176	Hyades-24	kA7hA7mF0 (V$^+$)	0.169	0.194	0.783	2.767	
27819A	Hyades-47	A7 IV	0.081	0.210	0.981	2.857	
27934	Hyades-54	A5 IV-V	0.070	0.200	1.054	2.864	
27946	Hyades-55	A7 V	0.149	0.193	0.840	2.784	
28319	Hyades-72	A7 III	0.102	0.196	1.014	2.832	*
28355	Hyades-74	kA6hA7mF0 (IIIb)	0.116	0.225	0.906	2.837	
28527	Hyades-82	kA5hA5mF0 (IIIb$^-$)	0.088	0.217	0.965	2.856	
28546	Hyades-83	kA5hA7mF2 (IV)	0.141	0.235	0.795	2.809	
29140	88 Tau	kA3hA5mA7 (IV)	0.095	0.194	0.949	2.834	
29388	Hyades-104	A5 IV-V	0.068	0.196	1.050	2.870	
29488	Hyades-108	A5 IV-V	0.089	0.193	1.012	2.852	
29559	--	A5 IV-V	0.101	0.176	1.036	--	
30210A	Hyades-112	kA2hA5mF0 (II-III)		0.252	0.954	2.844	
30422	1525	A3 Vb λ Boo	0.101	0.185	0.871	2.832	
30478	κ Dor	A8 IV	0.113	0.186	0.978	2.814	
32273B	1619B	A3 Va	--	--	--	--	*
32301	Hyades-129	A7 IV	0.078	0.203	1.037	2.847	*
32977	106 Tau	A5 V	0.044	0.204	1.030	2.891	*
33111	β Eri	A3 IVn	0.069	0.184	1.091	2.846	*
33204A	Hyades-131	kA5hA7mF2 (IV)	0.149	0.245	0.803	2.796	
33254A	Hyades-130	kA2hA7mF2 (III-IV)	0.136	0.252	0.834	2.830	
33641	μ Aur	kA2hA7mA7 (IV)	0.101	0.226	0.854	2.846	
35026	An(Bok)-1	A7 IV-V	0.164	0.178	1.012	2.784	
35094	An(Bok)-4	A5 III-IV	0.114	0.201	1.055	2.830	
35183	An(Bok)-7	A5 IV	0.090	0.183	1.086	2.857	
36811	--	A1mA3 IV	0.095	0.196	0.982	--	
37507	49 Ori	A4 Vn	0.075	0.185	1.015	2.849	
39014	δ Dor	A7 V$^+$n	0.124	0.184	0.956	2.790	
39060	β Pic	A6 V	0.094	0.196	0.891	2.860	
40873A	2123	kA5mA7 IV	0.100	0.190	0.985	2.823	
42126	41 Aur B	kA5hA5mF0 (IV-V)	--	--	--	--	*
43319A	2234	A3 Vas	0.028D	0.213	0.983	2.904	
44769	ε Mon A	A6 IV	0.115D	0.183	0.974	2.824	

TABLE 2—*Continued*

HD	HR/ID	Spectral Type	$b-y$	m_1	c_1	β	N
46304	2386	A6 Vnn	0.157D	0.175	0.816	2.768	
48843	32 Gem	A8 II	0.239	0.116	1.414	2.760	
50019	θ Gem	A3 III-IV	0.060	0.178	1.163	2.848	
50241	α Pic	A6 Vn	0.123	0.178	0.999	2.788	
50506	ζ Men	A6 V$^+$n	0.123	0.163	1.103	2.810	
50747	2572	A5 IV-V	0.096	0.171	1.131	2.832	
52859A	2644A	A3 Va$^-$	0.037D	0.200	0.970	2.889	
52859B	2644B	A3 Va	--	--	--	--	
53811	2672	A5 V	0.064	0.185	1.075	2.866	
54801	47 Gem	A3 III-IV	0.066	0.183	1.095	2.838	
56537AB	λ Gem	A4 IV	0.048	0.198	1.055	2.875	
56731	2768	kA6hA7mF0 (IIIb)	0.105	0.228	1.010	2.823	
58187	1 CMi	A4 V	0.061	0.184	1.109	2.858	
59037	64 Gem	A4 Vn	0.062	0.202	1.013	2.871	
59612AB	2874	A5 Ib	0.171	0.084	1.516	2.704	
64145	φ Gem	A3 IV-V	0.052	0.190	1.068	2.856	
65456	3113	A6 II	0.096	0.133	1.485	2.782	
67456A	3183	A5 II	0.063	0.142	1.430	2.819	
68601A	3226	A5 Ib	0.133	0.091	1.543	2.709	
70060	3270	A7 IV	0.128	0.194	0.860	2.807	*
70313	3277	A3 Va	0.048	0.214	0.967	2.888	
71150	ϕ^2 Cnc B	A5 V	0.112	0.171	0.988	2.810	*
71297	2 Hya	A7 V	0.125	0.196	0.835	2.830	*
73210	KW50	A5 III	0.120	0.169	1.022	2.810	*
73449	KW150	A7 V$^+$nn	0.157	0.181	0.942	2.759	*
73576	KW207	A7 IV-Vn	0.104	0.199	0.969	2.812	*
73634	e Vel	A6 II	0.080	0.127	1.537	2.763	*
73709	KW279	kA2hA5mF0 *	0.099	0.260	0.937	2.843	*
73731A	KW300	kA3hA5mF0 (IIIb)	0.091	0.219	1.037	2.839	*
73819	KW348	A6 IVn	0.091	0.195	1.075	2.818	*
74028	KW445	A7 Vn	0.120	0.201	0.911	2.812	*
74050	KW449	A6 Vn	0.115	0.197	0.947	2.812	*
74272	3452	A5 II	0.098	0.111	1.532	2.773	
74517	IC2391-10	A3 Va	0.074	0.196	1.026	2.860	
75630	3514	A3 III	0.047	0.135	1.332	2.812	*
76483	δ Pyx	A5 III	0.055	0.207	1.089	2.863	
76543	o^1 Cnc	kA5hA7mF0 (IV)	0.069	0.230	0.965	2.882	
76644	ι UMa	A7 IVn	0.104D	0.216	0.856	2.843	*
76756	α Cnc	kA5hA5mF0 (IV)	0.070D	0.222	1.060	2.865	
78045	α Vol	kA2.5hA5mA7 (V)	0.077	0.188	0.960	2.871	
79439	18 UMa	A6 V	0.113	0.196	0.892	2.833	
80404	ι Car	A7 Ib	0.123	0.130	1.542	2.755	
81157	3732	A6 III-IVs:	0.101	0.212	0.928	2.836	*
82446	τ^2 Hya	A3 IV$^+$	0.071	0.144	1.182	2.810	
83446	3836	A5 IV-V	0.086	0.206	0.936	2.857	
85123	υ Car	A6 II	0.195D	0.099	1.401	2.730	
85364	6 Sex	A7 V$^+$	0.080	0.213	0.944	2.859	
87436	3966	A6 II	0.121	0.128	1.452	2.794	
87696	21 LMi	A7 V	0.102	0.204	0.880	2.840	*
88983	32 UMa	A5 IV-V	0.085	0.181	1.029	2.861	
90745	4108	A5 III-IVn	0.094	0.197	0.985	2.855	
90772	4110	A5 Iae	0.389	0.001	1.094	2.594	*
91312	4132	A7 IV-V	0.121	0.208	0.850	2.821	
92535	IC 2602-5	A5 Vn	0.124	0.190	0.888	--	
92769	40 LMi	A4 III	0.104	0.186	0.898	2.833	
93424	IC2602-24	A3 Va	0.091	0.190	0.944	2.886	
94180	4244	A3 Va	0.048	0.164	1.166	2.864	
95370	4293	A3 IV	0.059	0.179	1.116	2.868	*
95382	59 Leo	A6 IV	0.085	0.198	0.975	2.854	
95608	60 Leo	A0.5mA3 V	0.022	0.194	1.019	2.919	
96113	4311	A8 V$^+$	0.148	0.174	0.970	2.768	
97244	4341	A5mA7 (V$^+$)	0.116	0.201	0.840	2.825	
97534	4352	A5 Iae:	0.416	-0.017	1.146	2.602	
97603	δ Leo	A4 IV	0.073	0.183	1.042	2.869	
98058	φ Leo	A7 V$^+$n	0.128	0.174	1.037	2.777	
99211A	γ Crt	A7 V	0.119D	0.196	0.893	2.822	
100518	4454	kA2hA7mA7 (IV$^+$)	0.112	0.197	0.872	2.834	
102124	ξ Vir	A4 V	0.090	0.196	0.929	2.856	
102249	λ Mus	A7 IV	0.086	0.179	1.073	2.856	
102590AB	4531	kA7hA7mF0 (V)	0.171D	0.194	0.738	2.775	
102647	β Leo	A3 Va	0.043	0.211	0.974	2.900	*
103313	4555	A8 III	0.115	0.195	1.000	2.822	
104321	π Vir	A5 IV	0.066	0.179	1.134	2.844	
105805	4633	A3 IV-Vn	0.066	0.190	1.021	2.854	
107131	Coma-60	A4 IV-V	0.099	0.196	0.945	2.834	
107168	Coma-62	kA5hA5mF0 (III)	0.080	0.252	0.934	2.867	
107276	Coma-68	kA5mA7 (V)	0.108	0.193	0.908	2.833	
107566	ζ^2 Mus	A5 IV-V	0.107	0.175	1.075	2.832	
107935	Coma-104	A7 V$^-$	0.146	0.179	0.821	2.794	
107966	Coma-107	A3 IV	0.045	0.178	1.109	2.881	*

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TABLE 2—*Continued*

HD	HR/ID	Spectral Type	*b-y*	m_1	c_1	β	N
108382	Coma-130	A3 IV	0.058	0.176	1.129	2.867	
108486	Coma-139	kA3hA5mA7 (IV)	0.095	0.215	0.914	2.851	
108642	Coma-144	kA2hA7mA7 (IV)	0.097	0.226	0.909	2.843	
108844	74 UMa	kA5hA7mF0 (IV)	0.118	0.211	0.996	2.830	
109307	Coma-183	A3 IV-Vs	0.057	0.211	0.997	2.880	
109536	4794	A7 IV	0.130	0.198	0.824	2.823	
111463	4868	A5 IV	0.264	0.058	1.225	2.782	
111893	4886	A5 IV-Vnn	0.094	0.192	1.000	2.808	
111968	4889	A7 V	0.125	0.185	0.971	2.815	
115271	19 CVn	kA5hA7mF0 (IV)	0.109	0.209	0.944	2.856	
116706	5057	A3 Va	0.040	0.191	1.075	2.905	
116831	5059	A7 IV-V	0.095	0.205	0.967	2.843	
116842	80 UMa	A5 Vn	0.098	0.192	0.928	2.847	
118022	78 Vir	knA1hA5 *	-0.011	0.232	0.936	2.883	*
118232	24 CVn	A4 V	0.075	0.193	1.044	2.852	
118349A	5120A	A7 III-IV	0.130	0.186	1.012	2.820	*
118623AB	25 CVn	A7 Vn	0.150D	0.170	0.904	--	
120641	5207 B	A7 V	--	--	--	--	*
121164	5229	A7 III-IV	0.109	0.211	0.932	2.838	
122405	11 Boo	A6 V	0.107	0.200	0.990	2.824	
122408	ρ_2 Vir	A3 IV	0.062	0.164	1.177	2.843	
124675A	κ^2 Boo	A6 V^+	0.113	0.185	0.986	--	
125161A	ι Boo	A7 IV	0.128	0.198	0.834	2.817	
125489	5368	A7 V	0.108	0.200	0.890	2.838	
126200	5388	A2.5 IV	0.030	0.163	1.157	2.882	
127167	5418	A5 IV-V	0.086	0.200	0.987	2.851	
127762	γ Boo	A7 IV^+	0.116	0.191	1.008	2.815	
128898	α_2 Cir	knA7hA7 Sr	0.136	0.209	0.786	2.835	*
130841	α^2 Lib	A3 III-IV	0.074	0.192	0.996	2.849	
134482	κ^2 Lup	A5 Vn	0.074	0.206	0.946	2.888	*
135379	β Cir	A3 Vb	--	--	--	--	
135559	4 Ser	A5 V	0.097	0.200	0.897	2.850	
137422	γ UMi	A3 III	0.057	0.121	1.379	2.758	*
137909	β CrB	knA7hA7 Sr Eu	0.140	0.255	0.740	2.842	*
140417	η Lib	A7 IV-V	0.136	0.199	0.839	2.814	
141378	5875	A5 IV-V	0.053	0.209	0.976	2.892	
141795	ε Ser	kA2hA5mA7 (V)	0.067	0.220	0.948	2.886	
142500	40 Ser	A4 IVnn	0.100	0.180	0.967	2.827	
142629	ξ^1_1 Lup	A3 IV	0.059	0.195	0.973	2.889	*
143474AB	ι^1 Nor	A7 V^+n	0.143D	0.179	0.826	2.811	
145570	ψ Sco	A3 Va	0.048	0.179	1.066	2.893	
145689	6037	A4 IV-V	0.069	0.215	0.911	2.884	
147084	o Sco	A5 II	0.619	-0.025	1.639	2.787	*
148367AB	υ Oph	kA2hA3mA8 (V)	0.092D	0.219	0.870	2.850	
148898	ω Oph	knA3hA7 Sr ((Eu))	0.066	0.179	0.169	2.894	*
150366	6193	knA7mA7 (III-IV)*	0.132	0.178	0.908	2.827	*
150379	36 Her	A2mA3 IV^-	0.065	0.213	0.977	2.888	*
152107ABC	52 Her	kA0hA5 Sr Eu*	0.037D	0.218	0.938	2.882	*
154029	59 Her	A3 IV-Vs	0.001	0.171	1.103	2.885	*
154494	60 Her	A4 IV	0.061	0.209	0.994	2.881	
159170	6534	A4 III-IVnn	0.102	0.188	0.905	2.826	
159492	π Ara	A7 IV^-	0.099	0.210	0.883	2.859	
159561	α Oph	A5 Vnn	0.093	0.168	1.039	2.832	*
159877	6562	A7 II^-	0.252	0.097	1.310	2.805	
161817	--	kA1hA7mA1 (V) *	0.135	0.112	1.206	2.750	*
162514	N6475-40	A5 Vn	0.166	0.170	0.945	2.826	
164514	--	A3 Ia	0.765	-0.158	1.445	2.663	
165777	72 Oph	A5 IV-V	0.058	0.214	0.993	2.878	*
169958	N6633-61	A4 IV	0.164	0.133	1.173	2.858	*
170114	N6633-90	A5 IV *	0.243	0.101	1.104	2.793	*
170135	N6633-92	A4 IV	0.190	0.122	1.221	2.858	
170293	N6633-125	A5 III	0.227	0.130	1.180	2.851	*
170642	6942	A3 Van	0.036	0.185	1.077	2.898	
172555	7012	A6 IV	0.110	0.204	0.838	2.834	
173582	ε^1 Lyr A	A3 Van	--	--	--	--	*
173583	ε^1_2 Lyr B	A7 V	--	--	--	--	*
173607	ε^2_2 Lyr C	A5 Vn	--	--	--	--	*
173608	ε^2 Lyr D	A5 Vn	--	--	--	--	*
173648	ζ^1 Lyr	kA3hA5mF2 (IV)	0.101	0.230	0.996	2.849	
173880	111 Her	A3 Va^+	0.060	0.217	0.942	2.901	
175638	ϑ^1 Ser	A5 V	0.087	0.190	0.986	2.852	
175639	ϑ^2 Ser	A6 Vn	0.120	0.185	0.911	2.813	
177196	16 Lyr	A6 IV	0.106	0.200	0.901	2.845	
182564	π_2 Dra	A2mA3 IV	--	--	--	--	
184006	ι^2 Cyg	A4 V	0.080	0.177	1.055	2.833	
186219	7498	kA3hA7mF0 (V^+)	0.133	0.219	0.810	2.834	
186689	υ Aql	A5 V	0.101	0.193	0.892	2.854	
187642	α Aql	A7 Vnn	0.137	0.178	0.880	2.828	
188899	61 Sgr	A3 Va	0.019	0.180	1.125	2.887	
189741	63 Sgr	A2.5 Va	0.033	0.171	1.104	2.888	

TABLE 2—*Continued*

HD	HR/ID	Spectral Type	$b-y$	m_1	c_1	β	N
189849	15 Vul	kA5hA7mA7 (IV-V)	0.096	0.202	1.066	2.840	
192514	30 Cyg	A4 IIIn	0.068	0.150	1.410	2.811	
192696	33 Cyg	A3 IVn	0.056	0.178	1.093	2.834	
195093	ο Cap B	A6 V	0.110	0.204	0.840	2.826	*
195725	ϑ Cep	kA5hA7mF0 (III)	0.106	0.220	0.998	2.834	*
196078	7865	A7 V$^+$	0.110	0.199	0.911	2.837	
196180	ζ Del	A3 Va	0.066	0.176	1.107	2.868	
197051	β Pav	A6 IV$^-$	0.078	0.184	1.090	2.828	
200499AB	η Cap	A5 V	0.090D	0.192	0.946	2.861	
201601AB	γ Equ	knA5hA7 Sr	0.146D	0.238	0.761	2.819	*
202730A	ϑ Ind A	A5 IV-V	0.092D	0.213	0.868	2.849	*
203280	α Cep	A7 V$^+$n	0.125	0.190	0.936	2.808	
205767AB	ξ Aqr	A5 Vn	0.089D	0.196	1.021	2.835	
205835	74 Cyg	A5 V	0.122	0.172	0.970	2.820	
205924	4 Peg	A8 Vn	0.155	0.180	0.848	2.768	
207235	8332	A6 V	0.135	0.184	0.793	2.798	
210111	8437	kA2hA7mA2 Vas *	0.136	0.147	0.861	2.774	*
210139	--	kA3hA5mA7 (IV$^+$)	--	--	--	--	
210271	8444	A7 IV-Vn	0.135	0.182	0.943	2.798	
210300	8446	A5 V	0.074	0.191	1.052	2.863	
210739	8464	A5 Vn	0.091	0.195	0.921	2.858	
211356	8495	A5 Vnn	0.110	0.182	0.943	2.806	
214454	9 Lac	A7 IV-V	0.151	0.171	0.931	2.784	
214846	β Oct	A7 III-IV	0.125	0.190	0.917	2.817	
214853	--	A5 IV	--	--	--	--	
215863	--	A3 Va	--	--	--	--	
216627	δ Aqr	A3 IV-V	0.036	0.168	1.155	2.897	
216701	1 Psc	A7 IV	0.101	0.196	1.049	2.836	*
216956	α PsA	A3 Va	0.039	0.208	0.983	2.906	*
218003	--	kA5hA5mF0 (V$^+$)	--	--	--	--	
218918	59 Peg	A3 Van	0.076	0.164	1.091	2.821	
219860	--	A3 Va	--	--	--	--	
220061	τ Peg	A5 V	0.106	0.166	1.006	2.808	
220278AB	97 Aqr	A5 Vn	0.122D	0.173	0.935	2.793	
220506	--	A3 Va	--	--	--	--	
220606	--	A5 IV-V	--	--	--	--	
221943	--	A6 V	0.111	0.193	0.897	--	
222287A	ϑ Phe A	A7 IV	0.147D	0.181	0.852	2.806	*
222287B	ϑ Phe B	A7 V	--	--	--	--	*
222345	ω^1 Aqr	A8 IV	0.147	0.191	0.853	2.796	
222603	λ Psc	A6 IV$^-$	0.103	0.204	0.892	2.822	
222996	--	A5 V	--	--	--	--	
224596	--	A7 V	--	--	--	--	
224964	Blnco1-56	A3 Va$^-$	0.045	0.208	0.960	2.909	*

NOTES TO TABLE 2

The layout of this table is identical to that of Table 3 of Paper I (Gray and Garrison 1987), and that paper should be consulted for more details.

Notes on the 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 Bright Star Catalog number, in that order of preference. An upper case letter immediately following the designation refers to the component or components to which the spectral type applies. See Papers I and II for the key to the numbering systems used in the open cluster identifications. Three stars in this table are members of the Anonymous Bok—An(Bok)—cluster situated in the direction of the Large Magellanic Cloud. The numbering system used is that of Sanduleak and Philip (1968).

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 at the end of these notes.

Col. (4).—The $b-y$ color index on the Strömgren system. A "D" implies that the photometry is for the combined light of the star and its close companion.

Col. (5), (6), and (7).—The m_1, c_1, and β indices on the Strömgren four-color, Hβ system.

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

The $uvby\beta$ photometry has been derived from a merged catalog compiled by Dr. Erik Heyn Olsen and has kindly been made available by him. This catalog is based on the work of Crawford, Strömgren, Olsen, and coworkers (see Olsen 1987 for details).

Detailed remarks on the notation used in this table can be found in Paper I and in § II*d* of this paper.

Notes on Individual Stars

HD 5382.—Broad hydrogen wings.

HD 9100.—The hydrogen lines of this star show very broad, but rather shallow, wings and are reminiscent of the hydrogen lines of the PHL λ Bootis stars of Gray (1988). The β index of this star is surprisingly low for hydrogen lines with such broad wings, a characteristic which also recalls the PHL λ Bootis stars. The λ4481 line is slightly, but not obviously, weak. In the $b-y$, m_1 plane, this star lies within the λ Bootis "distribution."

HD 11502.—Visual binary with HD 11503, B9.5 IV$^+$ n. HD 11502 shows a weak, diffuse K line.

HD 12447.—Close visual double with HD 12446 (α Psc B), kA2hF2mF2 (IV).

HD 16046B.—Visual double with the bright star ω For, B9 Va. HD 16046B is situated 10″.8 from A, but does not have an individual HD number.

HD 18622.—Visual double with HD 18623, A1 Va.

HD 21335.—Metals may be slightly weak, but λ4481 is quite normal. Abt (1984) classifies this star as a marginal λ Bootis star. High $v \sin i$.

HD 22615, 23516, 23194, 23361, 23643, 23863, and 23886.—Members of the Pleiades Cluster. HD 23194 is the low-$v \sin i$ A5 V standard, HD 23643 is the high-$v \sin i$ A3 Va standard, and HD 23886 is the high-$v \sin i$ A5 V standard.

HD 28319.—A7 III low-$v \sin i$ standard.

HD 32273B.—Visual double with HD 32273A, B7 V.

HD 32301.—Close double.

HD 32977.—Broad hydrogen line wings.

HD 33111.—High-$v \sin i$ A3 IV standard.

HD 42126.—Visual double with HD 42127, A2 Va$^+$.

HD 52859A and HD 52859B.—Close visual double. A is the more northerly of the pair.

HD 70060.—A7 IV low-$v \sin i$ standard.

HD 71150.—Visual binary with HD 71151, A2 IV.

HD 71297.—Low-$v \sin i$ A7 V standard.

HD 73210, 73449, 73576, 73709, 73819, 74028, and 74050.—Members of the Praesepe cluster.

HD 73210.—Low-$v \sin i$ A5 III standard.

HD 73634.—A6 II standard.

HD 73709.—kA2hA5mFo (III–IV) (Cr).

HD 73731.—Not a member of the Praesepe cluster.

HD 75630.—Low-$v \sin i$ A3 III standard.

HD 76644.—High-$v \sin i$ A7 IV standard.

HD 81157.—Spectral lines have different widths. The λ4046 line is very sharp, whereas the cores of the hydrogen lines look too broad for the width of the λ4077 line. The λ4481 line appears slightly peculiar; it has a very narrow core with wings. Circumstellar material?

HD 87696.—High-$v \sin i$ A7 V standard.

HD 90772.—A5 Ia standard.

HD 95370.—Low-$v \sin i$ A3 IV standard.

HD 102647.—Secondary low-$v \sin i$ A3 Va standard.

HD 107966.—The λ4481 line is exceptionally strong, so that the λλ4417/4481 ratio is remarkably low for the luminosity class.

HD 118022.—knA1hA5 Sr Si Cr Eu. Diffuse K line. Metals very peculiar.

HD 118349.—Visual double with HD 118349B, F0 Vn. See notes in Paper II on this double.

HD 120641.—Visual double with HD 120642, B8 Vnn.

HD 128898.—Diffuse K line.

HD 134482.—Wide visual binary with HD 134481, B9.5 IVnn.

HD 137422.—Listed in the BSC as a shell star, but appears normal in our spectra.

HD 137909.—Diffuse K line. Metals very strong and very peculiar.

HD 142629.—Visual double with HD 142630, A1 Va. HD 142629 may show slight Am tendencies.

HD 147084.—A5 II standard. Very highly reddened member of the Upper Scorpius Association.

HD 148898.—Diffuse K line.

HD 150366.—knA7mA7 (III–IV) ((Sr)). Diffuse K line. See § II*d* of the text for additional comments.

HD 150379.—Wide visual binary with HD 150378, A0 IV.

HD 152107.—kA0hA5 Sr Eu ((Cr)).

HD 154029.—Shows some mild spectral peculiarities: Mn I λ4030 is slightly weak, λ4233 is slightly enhanced, and λλ4417/4481 is exceptionally small.

HD 159561.—Johnson and Morgan (1953) A5 III standard. See § II*c* of this paper for additional comments.

HD 161817.—kA1hA7mA1 (V) weak metals. Field horizontal branch star.

NOTES TO TABLE 2—*Continued*

HD 165777.—Mn I λ4030 slightly weak.

HD 169958.—Probably not a member of NGC 6633.

HD 170114.—A5 IV metal-weak. This probable member of NGC 6633 (membership probability 91% according to Sanders [1973]) is curious because it appears to be distinctly metal-weak in our spectra. All metals except the Ca II K line and Mn I λ4030 appear to have strengths about like that of the A2 standards. The $b-y$ and β indices seem to indicate that the star is later than A5, while the m_1 index reinforces the suspicion that the star is metal-weak. This star is a close visual binary, and so its peculiarity may be due to the composite nature of the spectrum (see Corbally 1987).

HD 170293.—The profile of the λ4030 blend appears unusually narrow. Many Am stars show this same feature (see Paper II).

HD 173582, 173583, 173607, and 173608.—Components of the famous "double-double" in Lyra. HD 173582 and 173583 are a close pair which form a wide system with HD 173607 and 173608. These spectral types may be slightly affected by contamination from the companions.

HD 195093.—Wide visual binary with HD 195094, a rapidly rotating A1 Va star.

HD 195725.—Profile of λ4030 very narrow.

HD 201601.—Diffuse K line.

HD 202730.—Visual double with HD 202730B, G0 V.

HD 210111.—kA2hA7mA2 Vas λ Boo. See Gray (1988) for more comments.

HD 216701.—λ4077 has a narrower profile than the other metallic lines.

HD 216956.—Low-$v \sin i$ A3 Va standard.

HD 222287 A and B.—Close visual double. Spectra are probably contaminated.

HD 224964.—Member of the young Blanco 1 cluster, but this star appears to be slightly metal-weak. The K line indicates a spectral type of A3, but the metals appear more like those of the A2 standards. This star is not a λ Bootis star, as λ4481 is quite strong. The photometry does not confirm the metal-weak appearance.

remaining stars shows no systematic trend in $b-y$ with V. This procedure was also used for the A5 stars. For the A7 stars it is possible to use the dereddening procedure of Crawford (1979). Even though this procedure assumes a relationship between $b-y$ and β, a plot of $E(b-y)$ versus $v \sin i$ shows no systematic trend. This, plus the fact that the mean indices are hardly changed if we use the "early A star" procedure, implies that rotation does not change the relationship between β and $b-y$ in stars with spectral types of A7 and later.

We may further confirm this by examining the effect of rotation on the β index. A plot of $\delta\beta$ versus $v \sin i$ for the A3 stars shows properties similar to those of the early A stars (see Paper I) in that the upper envelope of the distribution clearly drops for higher values of $v \sin i$. However, the plot for the A5, A6 and A7 stars shows only a suggestion of this behavior; at most the effect is $\delta\beta \cong -0.01$ at 250 km s^{-1}, similar to the result obtained by Hartwick and Hesser 1974. Neither result is likely to be significant.

It is probably not coincidental that this change in behavior of the $\delta\beta$ index coincides exactly with the loss in sensitivity of the hydrogen wings to gravity at A5. It therefore seems that the behavior of the β index in the early A-type stars can be interpreted best as primarily a gravity effect; rapidly rotating early A-type stars have systematically weaker hydrogen lines because their equators have substantially lower gravities.

The mean indices (listed in Table 3) show a behavior that is interestingly intermediate to those of the early A-type stars and the early F-type stars. In the early A-type stars, high-$v \sin i$ stars have significantly redder $\langle b-y \rangle$ indices than low-$v \sin i$ stars of the same spectral type, but there is no difference in $\langle b-y \rangle$ between different luminosity classes. In the F-type stars this behavior is reversed; there is no effect with rotation, but giants are slightly bluer than dwarfs. In the late A-type stars, the A3 and A5 stars mimic the behavior of the early A-type stars, but in the A7 stars, we begin to see some differences in $\langle b-y \rangle$ between the luminosity classes while still seeing some effect with rotation. The mean β index also shows a similar behavior. This change in behavior of the mean indices may reflect a gradual change in some stellar parameter. For instance, it might reflect a change in the rotation law as convection becomes more important for stars of later spectral types.

TABLE 3A

MEAN $b-y$ INDICES

Spectral Types	$v \sin i$ Group	$\langle b-y \rangle$	σ	$\langle v \sin i \rangle$	N
A3 V–III	$0 < v \sin i < 150$	0.054	0.021	83	24
A3 V–III	$150 < v \sin i < 350$	0.066	0.019	202	9
A5 V–III	$0 < v \sin i < 100$	0.072	0.016	70	14
A5 V–III	$100 < v \sin i < 300$	0.090	0.021	166	22
A7 V–III	$0 < v \sin i < 100$	0.104	0.021	70	13
A7 V............	$100 < v \sin i < 300$	0.125	0.022	170	20
A7 IV, III	$100 < v \sin i < 300$	0.103	0.023	132	8

TABLE 3B

MEAN β INDICES

Spectral Types	$v \sin i$ Group	$\langle \beta \rangle$	σ	$\langle v \sin i \rangle$	N
A5 V–III	$0 < v \sin i < 300$	2.835	0.052	117	40
A7 V............	$0 < v \sin i < 200$	2.817	0.024	126	21
A7 V............	$200 < v \sin i < 300$	2.793	0.023	235	8
A7 IV, III	$0 < v \sin i < 200$	2.830	0.018	95	18

b) The δc_1–Luminosity Class Relation for the Late A-Type Stars

In Paper II we showed that there is an excellent correlation between δc_1 and luminosity class for the low-$v \sin i$ early F stars, and we might expect to find a similarly good correlation for the late A-type stars since δc_1 remains a good measure of gravity. Figures 3*a* and 3*b* show, however, that there is a disappointingly poor correlation between these two parameters for the normal low-$v \sin i$ A5 and A7 stars; there exist a significant number of stars with δc_1 indices considerably larger than one would expect on the basis of their luminosity classes.

However, careful inspection of the δm_1 indices of these stars reveals an interesting fact: those stars that have anomalously high δc_1 indices also have quite large positive δm_1

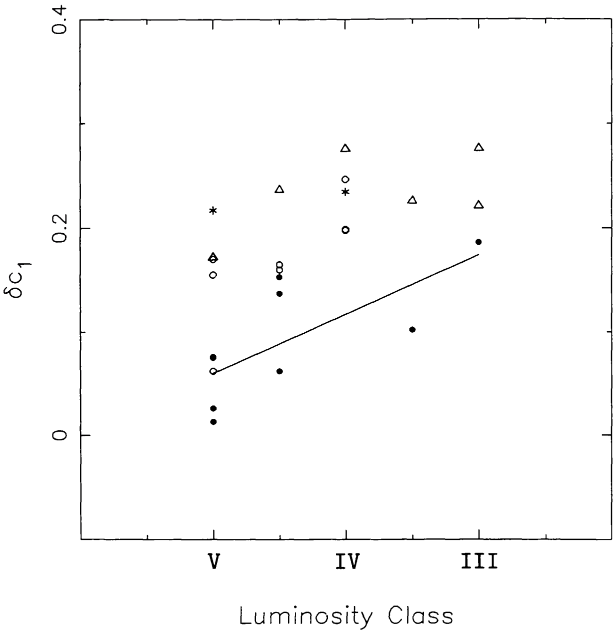

FIG. 3*a*

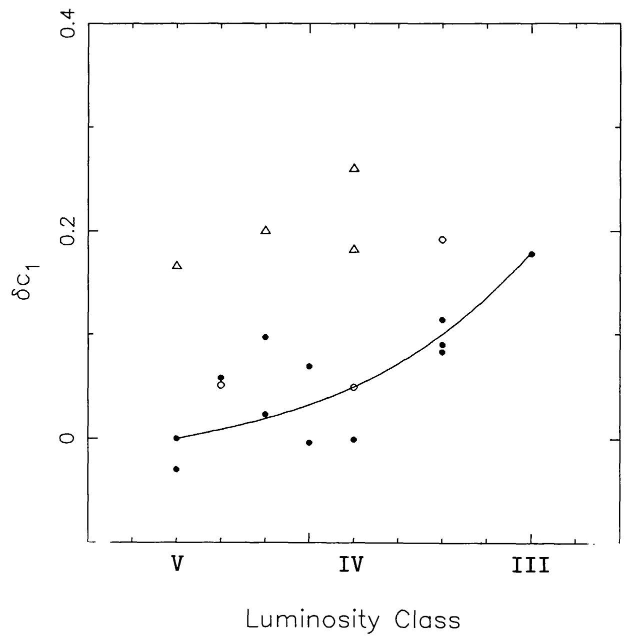

FIG. 3*b*

FIG. 3.—(*a*) The relationship between the luminosity class and the δc_1 parameter for the low-$v \sin i$ A5 stars ($v \sin i < 150$ km s^{-1}). The symbols represent stars with different values of the δm_1 parameter: filled circles represent stars with $\delta m_1 < 0.01$, open circles, $0.01 < \delta m_1 < 0.02$, triangles, $0.02 < \delta m_1 < 0.035$, and asterisks, stars with $\delta m_1 > 0.035$. The straight line is fitted to the stars with $\delta m_1 < 0.01$. (*b*) The relationship between the luminosity class and the δc_1 parameter for the low-$v \sin i$ A7 stars ($v \sin i < 115$ km s^{-1}). The symbols represent stars with different values of the δm_1 parameter: filled circles represent stars with $\delta m_1 < 0.01$, open circles, $0.01 < \delta m_1 < 0.02$, triangles, stars with $\delta m_1 > 0.02$. The line is fit to the stars with $\delta m_1 < 0.01$.

indices. This is illustrated in Figures 3*a* and 3*b* by the use of different symbols. The δm_1 index is a photometric measure of the line blanketing in the v band; a positive value of δm_1 in a main sequence A, F, or G star is usually taken to mean that the star is metal-weak relative to the Hyades. Our result, however, implies that the δm_1 index may be affected simultaneously with the δc_1 index by some other factor.

The correlation between δm_1 and δc_1 in the A-type stars was first noted by Crawford (1979). Crawford suggested that this correlation may be partly due to the fact that the Am stars (which usually have negative δm_1 indices) also have δc_1 indices near zero. However, if we remove all of the classical and proto-Am stars from our sample, this correlation persists, as can be seen in Figure 4 in which δm_1 is plotted against δc_1 for all of the normal, low-$v \sin i$ A5, A6, A7, and A8 stars in our sample. If we plot only the dwarf stars the correlation still remains, as can be deduced from Figures 3*a* and 3*b*. It is interesting to note, however, that this correlation is not present in the early F-type stars, neither among the stars of our sample, nor in the investigations of Crawford (1975).

Careful inspection of the spectra of the "anomalous δc_1" stars in Figures 3*a* and 3*b* reveals that the classifications cannot be very wrong; while the classification criteria in the A5, and even in the A7, stars do not permit as good a discrimination of the luminosity classes as in the early A- and the early F-type stars, it seems improbable that we could have mistaken, for instance, a low-$v \sin i$ dwarf for a giant as the photometry implies. Random errors in classification would not have led to such a clear separation of the stars in Figures 3*a* and 3*b* on the basis of the δm_1 index; note that giants with "normal" δc_1 indices have $\delta m_1 \cong 0.00$. Thus a dependence of δm_1 on gravity coupled with faulty classifications cannot explain the distribution of stars in Figures 3*a* and 3*b*. A few of these "anomalous δc_1" dwarfs have trigonometric parallaxes (HR 8880 and HR 4889 are two examples), although the errors are beyond the Lutz-Kelker limit (Lutz and

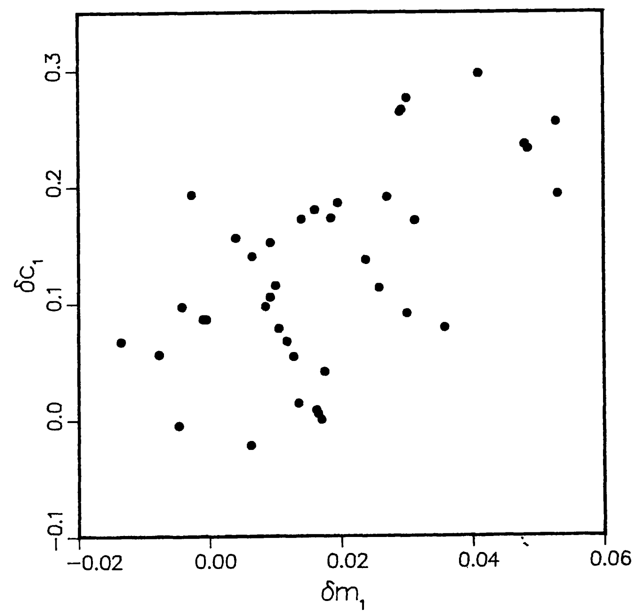

FIG. 4.—The correlation between δm_1 and δc_1 in the normal low-$v \sin i$ late A-type stars ($v \sin i < 150$ km s^{-1}). As can be seen, the correlation between these two parameters persists even when the Am stars are removed from the sample.

Kelker 1973) of $\sigma/\pi = 0.18$. The parallaxes imply absolute magnitudes for these two stars in the vicinity of 2.0, about what one would expect for late A dwarfs (see Corbally and Garrison 1984). The errors are such that we can place considerable doubt upon, but not entirely rule out, the hypothesis that these two stars are giants ($M_V \cong 0.4$). HR 2672 is an A5 dwarf which shows broad hydrogen line wings (which imply main-sequence pressures), but also an anomalously high δc_1 index. In addition, the photometry implies that giants make up a remarkably high percentage of the field star population; the classifications imply a much more realistic balance between giants and dwarfs. For these reasons we feel that we cannot explain the poor correlations in Figures 3*a* and 3*b* on the basis of faulty classifications.

The anomalous δc_1 stars do not appear to be spectroscopically metal-weak as would be implied by their positive δm_1 indices. But postulating that they are, nonetheless, metal weak, does not help to explain the anomalously high δc_1 indices.

Relyea and Kurucz (1978) showed that the presence or absence of convection in a stellar atmosphere model can have an effect on both the c_1 and the m_1 indices. Thus a purely radiative model differs from a (partially) convective model of the same $b-y$ color by a few times 0.01 mag in both c_1 and m_1. The changes in c_1 and m_1 are correlated in the sense that convective models have larger values of c_1 and smaller values of m_1 than purely radiative models of the same color. What this means is that if there is a natural variation in the amount of convective transport in the atmospheres of real A-type stars, the result will be a correlation between δc_1 and δm_1 that will qualitatively resemble the correlation that we actually observe. However, in the observed correlation, δc_1 ranges over a few times 0.1 mag and thus shows an order of magnitude greater variation than would be expected from convection. We conclude, therefore, that convection cannot be the explanation for the observed correlation.

Rotation, however, can affect δc_1 and δm_1 in a way similar to that observed. Figures 5*a* and 5*b* show the effect rotation may have on m_1 and c_1 in the A- and early F-type stars. The plotted points are derived from the rigidly rotating main-sequence models of Collins and Sonnenborn (1977). Each point represents a rotating model star seen at a specific inclination angle. It is clear that for A-type stars ($\beta > 2.8$) both m_1 and c_1 can be affected by rotation: rotation causes δm_1 to become more positive by a few times 0.01 mag and δc_1 to become more positive by up to 0.15 mag. This is quantitatively much closer to what we actually observe in the late A-type stars than the predicted photometric effects of convection, discussed above. For the F-type model stars ($\beta < 2.8$) the effect of rotation on δm_1 essentially disappears. This is also in accord with what we have actually observed. However, we note that the stars for which we have actually observed this correlation between δm_1 and δc_1 are low-$v \sin i$ stars. Is this behavior consistent with the models of Collins and Sonneborn? Figure 6 shows, indeed, that the models of Collins and Sonnenborn do predict a strong correlation between δm_1 and δc_1 even when the $v \sin i$ is restricted to values below 150 km s^{-1}. Careful inspection of Figure 6 shows that those low-$v \sin i$ rigidly rotating main-sequence models that have "anomalously high" δc_1 indices and positive δm_1 indices correspond to rapidly rotating stars viewed at quite low inclination angles ($i \leq 30°$). We suggest, therefore, that the

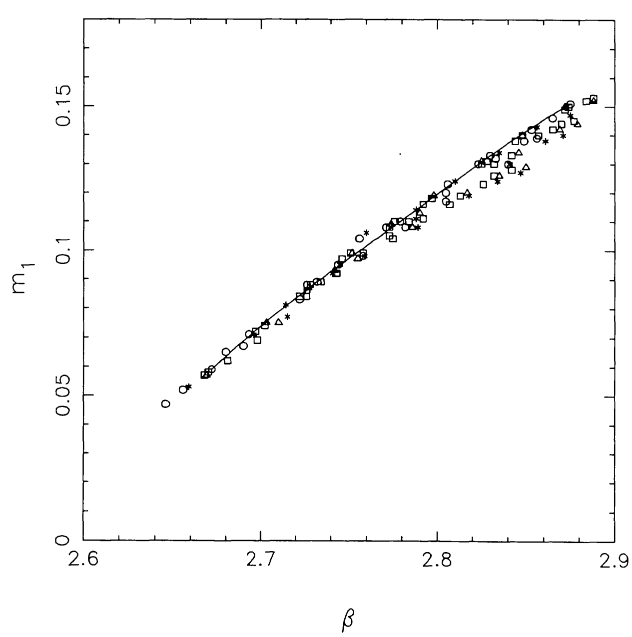

FIG. 5*a*

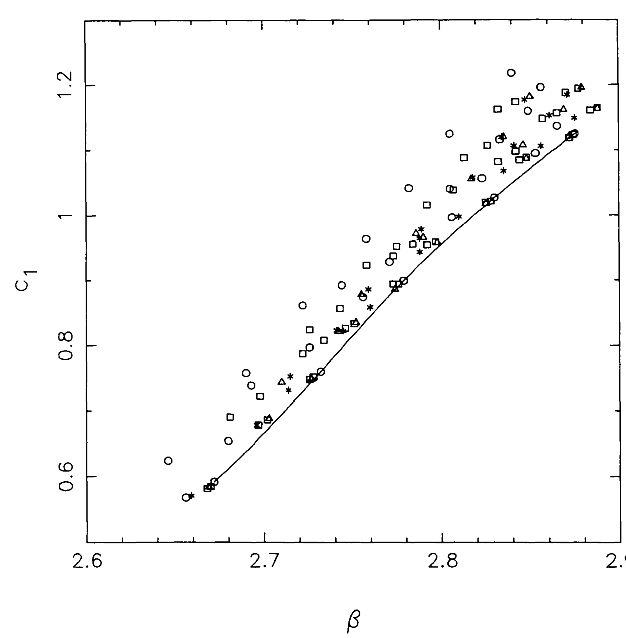

FIG. 5*b*

FIG. 5.—(*a*) The distribution of the rigidly rotating models of Collins and Sonneborn (1977) in the β, m_1 plane. The solid line is drawn through the nonrotating models. These models have $b-y$ indices in the range 0.05–0.30, approximately the range spanned by stars in the spectral region A3–F5. Circles represent models calculated with inclination angles of 90°, squares, 60° and 45°, triangles, 30°, and asterisks, 0° (pole-on). (*b*) The distribution of the rigidly rotating models of Collins and Sonneborn (1977) in the β, c_1 plane. The solid line is drawn through the nonrotating models.

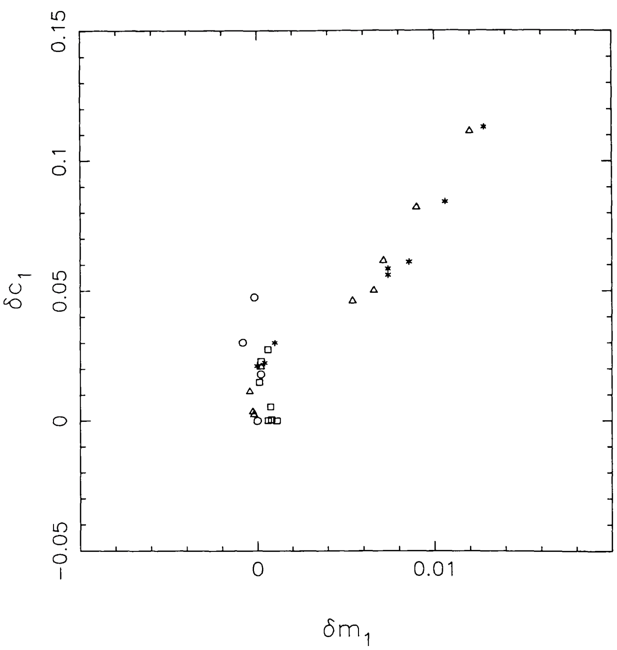

FIG. 6.—The distribution of the rigidly rotating models of Collins and Sonneborn (1977) with $v \sin i < 150$ km s^{-1} in the δm_1, δc_1 plane. These models have $b-y$ indices in the range 0.07–0.15, approximately the range of the late A-type stars. The symbols have the same significance as in Fig. 5*a*.

low-$v \sin i$ stars that we observe with anomalously high δc_1 indices for their luminosity types *are actually rapid rotators seen at quite low inclination angles* ($i \leq 30°$).

Is this hypothesis consistent with the statistics? If we limit our attention to dwarf stars, we can see from Figures 3*a* and 3*b* that $\delta c_1 = 0.150$ marks an adequate dividing point between the "normal" and the "anomalous" δc_1 dwarfs. On this basis, our sample of late A (A5–A8) low-$v \sin i$ ($v \sin i <$ 150 km s^{-1}) normal dwarfs amounts to 43 stars, 15 of which have $\delta c_1 > 0.150$, i.e., 35%. This percentage seems rather large for stars that combine two relatively rare attributes: rapid rotation and low inclination. However, we point out below three factors which can probably fully account for this high percentage.

First, the sample under consideration includes only low-$v \sin i$ stars. Placing an upper limit on the $v \sin i$ increases the percentage of near pole-on ($i \leq 30°$) rotators in the group, simply because most high-$v \sin i$ stars have, for geometrical reasons, inclination angles near to 90°. Second, Abt and Moyd (1973) have demonstrated that the equatorial rotational velocity distribution for *normal* late A-type stars is essentially truncated below 100 km s^{-1}; essentially all A-type stars with $V_{eq} < 100$ km s^{-1} are Am stars. It is easy to show that if Abt and Moyd's rotational velocity distribution for normal late A-type stars is convolved with the probability distribution for the inclination angle

$$\phi(i)\, di = \sin i\, di ,$$

then 25.0% of the stars with $v \sin i < 150$ km s^{-1} have $i < 30°$, and 18.8% have both $i < 30\%$ and $V_{eq} > 150$ km s^{-1} (i.e., near pole-on rapid rotators).

There is yet another factor which should further increase these numbers. The models of Collins and Sonneborn predict that rapidly rotating stars—even those seen nearly pole-on—will be slightly more luminous than slowly rotating stars of the same color. In extreme cases, rapidly rotating stars may be more luminous by a magnitude or more. We point out that if the anomalous δc_1 dwarfs are, on the average, 0.5 mag brighter than normal dwarfs, then their numbers will be doubled in a magnitude-limited sample (our sample is essentially magnitude-limited). This implies that our interpretation of the anomalous δc_1 stars as near pole-on rapid rotators is not inconsistent with the observed numbers of anomalous δc_1 stars in our sample.

To carry this analysis further, we have attempted to reproduce the actual distribution of the δc_1 index for a simulated population which obeys the probability distributions discussed above by carrying out a Monte Carlo calculation similar to that discussed in Paper II. This calculation successfully reproduced the predicted numbers of low-inclination rapid rotators, but the δc_1 indices of these stars (calculated from the models of Collins and Sonneborn 1977) were, while large, generally a factor of 1.5 to 2.0 smaller than for the observed anomalous δc_1 stars. This discrepancy may imply that our interpretation of the anomalous δc_1 stars as rapid rotators is wrong, but it may just as easily reflect a deficiency in the models, or imply that the late-A dwarfs rotate nonrigidly. We do not feel that this discrepancy is large enough to warrant the rejection of our hypothesis.

Indeed, we can formulate no other hypothesis that accords so well with the observations. If our hypothesis is indeed correct, then this result is important for a number of reasons. First, it suggests that through the agency of precise spectral classification and *uvbyβ* photometry, *quite stringent and interesting constraints may be placed on the inclination angles of certain* A-*type stars*. Second, it brings into serious question the use of δc_1 indices to estimate the ages and possibly the luminosities of even low-$v \sin i$ A-type stars. And, third, it suggests that a positive δm_1 index for an A-type star need not imply metal deficiency. This is of obvious importance when one attempts to use *uvbyβ* photometry to isolate metal-weak A-type stars (such as λ Bootis stars and horizontal branch stars) from the field (see, for instance, Gray 1988).

IV. SUMMARY AND CONCLUSIONS

Spectral classification of the late A-type stars is difficult because of the general weakness of the spectral lines, the complicating influence of rapid rotation, and the insensitivity of the classification criteria to luminosity. However, with care, high-quality spectra, and constant reference to the standards in Table 1, the late A-type stars may be classified with sufficient accuracy to reveal certain interesting results. Some of these results follow.

Our investigations have shown that the traditional luminosity criterion for the late A- and early F-type stars, the λλ4417/4481 ratio, is unreliable. We have also shown that the mean photometric indices of the late A-type stars show an intermediate behavior with rotation and luminosity to the early A-type and the early F-type stars. This change in behavior may be related to a change in some stellar parameter toward later types; possible candidates are the increasing importance of convection in the stellar atmosphere and/or a change in the rotation law.

Finally, a detailed comparison of our spectral classifications and *uvbyβ* photometry has revealed a set of low-$v \sin i$ A-type stars which show anomalously large δc_1 indices for their luminosity types. We propose, after the consideration of a number of possible causes, that these stars are rapid rotators seen at fairly low inclination angles ($i \leq 30°$).

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