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CONFIRMATION AMONG VISUAL MULTIPLES OF AN INCREASE OF Ap STARS WITH AGE

HELMUT A. ABT
Kitt Peak National Observatory[1]

AND

OCTAVIO CARDONA[2]
Instituto Nacional de Astrofisica, Optica, y Electronica, Tonantzintla
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ABSTRACT

Open clusters with ages below certain threshold values contain no Ap stars and those with greater ages contain numbers of Ap stars that apparently increase with age. But in view of the few young clusters studied, the data could also be interpreted in terms of random differences in the frequencies of Ap stars between individual clusters, rather than an age effect. We therefore obtained data on 77 field visual multiple systems (that originated from many different clusters and associations) in which the primaries are O5–A1 stars and the secondaries occur in the absolute magnitude range of the Ap stars. Again spectral classification shows no Ap stars in systems with ages $\leq 10^6$ yr and a steady increase in Ap stars thereafter. The numerical agreement with the cluster data is good, confirming that the cluster data are exhibiting a real age effect.

Subject headings: clusters: open — stars: evolution — stars: peculiar A — stars: spectral classification — stars: visual multiples

I. INTRODUCTION

There is evidence (Hartoog 1976; Abt 1979) that in open clusters the frequencies of peculiar A (Ap) stars are zero until a certain threshold age, that depends upon the kind of peculiarity, and then increase steeply with age. The threshold ages are approximately 10^6 yr for Ap(Si), 10^7 yr for Ap(Hg, Mn), and 10^8 yr for Ap(Sr, Cr) stars. The existence of thresholds makes sense because some of the overabundances (e.g., for Hg) must be very large before they are apparent observationally, and diffusion calculations indicate time scales for the buildup of atmospheric abundances of roughly 10^6 yr or more (Michaud *et al.* 1976). The frequencies of Ap stars among field stars agree with the averages for the older clusters; this, too, makes sense, because most of the field stars are escapees from the gradual disintegration of clusters.

However, there is one objection to these conclusions derived from open clusters. Some clusters, e.g., NGC 2516 (Abt and Morgan 1969) and NGC 2287 (Levato and Malaroda 1979), are rich in Ap stars, while other clusters of the same ages, e.g., the Pleiades, have few Ap stars. The differences may be due to different mean stellar rotational velocities because the diffusive separation of elements does not work for rotational velocities greater than roughly 90 km s^{-1} (Michaud 1982), and there seem to be real differences in the mean rotational velocities of stars in different clusters (Abt 1970). Although the frequencies of Ap stars have been determined for more than 20 open clusters, the most crucial data are those for the half-dozen youngest clusters. Although all observers (e.g., Hartoog 1976; Abt 1979; Joncas and Borra 1981; Borra, Joncas, and Wizinowich 1982) agree that young groups such as the Orion and Sco-Cen associations are poor in Ap stars, could it be that those deficiencies are due not to their young ages but to the random differences that occur between clusters? Thus, a criticism has been raised that the assertion that the number of Ap stars increases with age is not well established.

Another way to study a possible variation of Ap stars with age is to study visual multiples. Let us consider physical systems in which the primaries are OB stars and the secondaries have relative brightnesses that would place them in the absolute magnitude range of the Ap stars, i.e., $-1.4 \leq M_V \leq +2.5$ mag. Do the companions of the hotter primaries (O and early B) have fewer Ap companions than the cooler ones (late B or early A)?

Use of visual multiples to answer this question has the advantage over open cluster studies that the field visual multiples originated in many different clusters and associations, rather than just a few, and therefore better represent an average age effect, if one exists. Use of visual multiples, however, has a small disadvantage in that their ages as derived from the main-sequence primaries are only upper limits: e.g., a B7 V primary may just have arrived on the main sequence or it may be just about to leave, so all we know for such a system is that its age is $\leq 10^7$ yr.

In this study we have selected nearly all the observable ($\delta > -30°$) systems with normal O5–A1

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[2] Visiting Astronomer, Kitt Peak National Observatory.

primaries and common-proper-motion secondaries generally brighter than $B = 11$ mag that are probably in the observed range of Ap stars. We were aided, in part, by use of a copy of the filtered IDS catalog (see Poveda, Allen, and Parrao 1982). Spectra of the primaries and secondaries were obtained and classified. If we found a secondary that was actually outside the Ap range or that a secondary was not a physical member, despite its common proper motion, the only harm was in wasted time and not in distorted statistics. But the important point here is that the selection of systems was not based upon any previous knowledge of the secondary types.

II. OBSERVATIONS AND CLASSIFICATIONS

The 77 systems observed are listed in Table 1 by ADS (Aitken 1932) and HD numbers. The spectra were obtained with the Kitt Peak 2.1 m telescope and white spectrograph. They have a dispersion of 39 Å mm^{-1}, resolution of 1.0 Å, and width of 1.2 mm for the stars brighter than $B = 9$ mag and half that for the fainter ones. They were photographed on Eastman Kodak IIa-O plates and underdeveloped (to reduce grain) in D76. The spectra were classified on a Boller and Chivens spectra comparator against standards by Morgan, Abt, and Tapscott (1978). The classifications are listed in Table 1. When published types are available, the agreement with those from the more experienced classifiers is the usual ± 1 subclass in type and $\pm\frac{2}{3}$ luminosity class.

The absolute magnitudes corresponding to the classifications are taken from Blaauw (1963) and are listed in the fourth column of Table 1. An asterisk indicates that allowance was made for a known duplicity. The differences in absolute magnitude between primary and secondary are given in the fifth column. We collected published apparent magnitude differences, ΔV, and those are listed in the sixth column. When the ΔV's were based on photoelectric photometry (Blanco *et al.* 1968; Echevarria, Roth, and Warman 1979; Hoffleit and Jaschek 1982), they have two decimal places; otherwise, they are usually from eye estimates or photographic photometry as listed in the IDS (Jeffers, van den Bos, and Greeby 1963). When the absolute magnitude differences based on the classifications differed from the apparent magnitude differences by more than about 2.0 mag, we assumed that the secondary is an optical one, and it is so labeled in the last column of Table 1 (18 cases). The reasons for allowing such large discrepancies as ± 2.0 mag are that (1) some components are unknown spectroscopic or nonastrometric doubles of nearly equal components, and (2) the luminosity and spectral type uncertainties correspond to roughly ± 1 mag in absolute magnitude. For the remaining 87 secondaries to 77 primaries, $\Delta M_V - \Delta V = -0.08 \pm 0.70$ (s.e.) mag, indicating no significant systematic errors and the expected scatter.

There are several additional abnormal stars among the secondaries, namely a λ Bootis star in ADS 13672, a helium-weak star in ADS 3910, and three Am stars in ADS 1681, 2057, and 5103. These abnormalities are outside the kinds being considered in this project and will not be discussed further.

III. DISCUSSION

The main-sequence lifetimes of the primaries can be obtained from various sources, i.e., Sandage (1958), Stothers and Chin (1979), and Mengel *et al.* (1979). However, for this work in which only upper limits to the ages can be used, the differences between the sources are small. We shall adopt the ages, *t*, and limiting spectral types given in Table 2 (cols. [1] and [2], top half). For primaries off the main sequence, we used the published evolutionary tracks to determine their main-sequence origins. The primaries—and hence the physical systems—were grouped into the four ranges in age, and the assignments are given in the next-to-last column of Table 1.

Previous classifications in clusters (Abt 1979) indicated that the three main kinds of Ap stars each occur in certain ranges of absolute magnitude; those are specified in Table 2 under the kinds of peculiarities (cols. [4]–[6]). Each entry in those columns is the number of Ap stars divided by the total number of secondaries in that absolute-magnitude range. The final column, column (7), gives the total of Ap stars in the whole absolute-magnitude range of such stars: those fractions are converted to percentages. The lower half of Table 2 quotes the corresponding data from the open clusters (Abt 1979).

The number of useful secondaries among the visual multiples is 64; the number of classified stars in open clusters in the absolute-magnitude range of the Ap stars is 393. Therefore the statistics from the visual multiples are poorer and will be useful only for confirmatory evidence.

The data in column (7) of Table 2 are plotted in Figure 1. The data (*circles* and *straight lines*) from the open clusters show a well-defined threshold of 10^6 yr and a linear rise thereafter. The data (*crosses*) from the

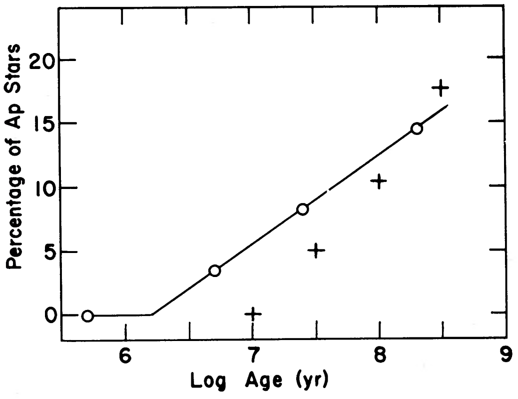

FIG. 1.—The circles and interpolated straight lines represent the frequencies of the Ap stars in $-1.4 \le M_V \le +2.5$ mag in 14 open clusters of ages $10^{5.7}$–$10^{8.8}$ yr (Abt 1979). The crosses represent the frequencies of Ap stars among the 64 useful visual secondaries to primaries of various ages. The ages in the latter case are only upper limits.

TABLE 1

CLASSIFICATION OF SELECTED VISUAL MULTIPLES

ADS	HD	Classification	M_V	ΔM_V	ΔV	Log t (yr)	Comments
719 AB	5005	O5 V	-5.8			≤6.5	
C	...	O9 Vn	-4.8	1.0	1.1		
1148 A	8803	B9 V	0.0			8.5	
B	...	F2 V	+2.8	2.8	2.8		
1670 A	13053	B9 V	0.0			8.5	
B	...	B9.5 V	+0.2	0.2	0.5		
1681 A	13247	B9 V	0.0			8.5	
B	...	Am(K/H/M=B9.5/A1/A1)	+0.8	0.8	0.8		
1683 A	13294	B9 V	0.0			8.5	
B	13295	A0: Vn	+0.5	0.5	0.47		
1717 A	13633	B8 III	-1.0			8.5	
B	...	B9 IV	-0.2	0.8	1.3		
1723 A	13746	B9.5 V	+0.2			8.5	
B	...	B9.5 V	+0.2	0.0	0.0		
2057 A	16772	B9.5 Vn	+0.2			8.5	
B	...	Am(K/H/M=A0/A1V/A3)	+0.8	0.6	0.7		
2270 A	18537	B7 V	-0.4			8.0	
B	18538	B9 V	+0.6	1.0	1.46		
2397 A	19822	B2 IV	-3.3			7.5	
B	...	B8 V	+0.1	3.4	0.2		Optical
2443 A	20283	B9.5 Vn	+0.2			8.5	
B	...	A2 Vp(Sr,Cr,Si st.; Ca wk)	+1.2	1.0	1.3		
2582 A	21743	A1 V	+0.8			8.5	
B	...	A3 V	+1.5	0.7	0.5		
2699 A	22951	B1.5 IV	-3.7			7.5	
B	...	A1 Vn	+0.7	4.4	5.10		
2772 A	23625	B3 V	-1.7			7.5	
B	...	B8.5 V	+0.3	2.0	2.5		
2888 A	24760	B1.5 III	-4.0			7.0	
B	...	B9 IV	-0.2	3.8	4.5		
2924 A	24992	B3 III	-2.9			7.5	
C	...	B4 V	-1.4	1.5	1.5		
2984 A	25638	B1 IIn	-5.0			7.0	NGC 1502
B	25639	B0 V	-4.4	0.6	0.01		
59	...	G0 V	+4.4	9.4	0.73		Optical
C	...	A2 V	+1.2	6.2	0.96		Optical
D	...	B2 V	-2.5	2.5	2.43		
60	...	A3 V	+1.5	6.5	2.53		Optical
37	...	B1.5 V	-3.1	1.9	2.56		
61	...	B2: Vn	-2.5	2.5	2.57		
26	...	B1.5 V	-3.1	1.9	2.65		
E	...	B2 V	-2.5	2.5	2.77		
3161 A	27638	B9 Vnn	0.0			8.5	
B	...	F8 V	+4.0	4.0	2.1		Optical?
3179 A	27778	B3 V	-1.7			≤7.5	
B	...	A1 V	+1.5	3.2	2.4		

TABLE 1—*Continued*

ADS	HD	Classification	M_V	ΔM_V	ΔV	Log t (yr)	Comments
3273 A	28503	B7 III	-1.6			≤8.0	
B	...	B8 IV	-0.7	0.9	0.2		
3579 A	31764	B7 III	-1.6			8.0	
B	31747	B8 V	+0.1	1.7	1.45		
C	...	A0 V	+1.0	2.6	3.61		
3623 A	32273	B7 IV	-1.2			8.0	
BC	...	Am(K/H/M=A3/A6/A8)	+1.9	3.1	1.1^{*}		Optical
3709 A	32990	B2 IV	-3.3			7.5	
C	...	A5 V	+1.8	5.1	3.1		
3910 A	34798	B5 Vs	-1.0			8.0	
B	34797	B7 Vp(He wk)	-0.4	0.6	0.2		
3962 A	35149	B1 Vn	-3.6			7.0	
B	35148	B5 V	-1.0	2.6	2.2		
4134 A	36486	O9 III	-5.7			7.0	
C	36485	B4 IV	-2.2	3.5	4.6		
4150 A	36646	B6 V	-0.7			8.0	
B	...	A0 V	+1.0	1.7	1.7		
4254 AB	37643	B8 V	-0.5			8.5	
C	...	A2 V	+1.2	1.7	2.1		
E	...	K5 III	-0.3	0.2	2.0		Optical
F	...	F4 V	+3.1	3.6	1.7		Optical
4483 A	39477	B8 IV	-0.7			8.5	
B	...	B8.5 IV	-0.5	0.2	1.5		
5103 A	45542	B7 IIIn + shell (HI)	-1.6			8.0	
BC	...	Am(K/H/M=B9/A0/A1)	+1.0	2.6	3.8^{*}		
5153 A	45995	B1.5 Vne	-3.1			7.5	
B	...	A0 Vp(Si)s	+1.0	4.1	2.95		
5944 A	56306	B7.5 V	-0.3			8.5	
B	...	A0 p(Si v. st.)	+1.0	1.3	1.0		
6208 A	60855	B4 III:n + shell (HI)	-2.6			7.5	
C	...	A0 V	+1.0	3.6	4.01		
10049 A	147933	B2 V	-2.5			7.5	
B	147934	B2.5 V	-2.1	0.4	0.90		
C	147932	B7 V	-0.4	2.1	2.11		
10266 A	152909	B7.5 V	-0.3			8.5	
B	...	B9 V	+0.6	0.9	2.0		
10947 A	163998	B8 II-III	-2.4			7.5	
B	...	B9 II-III	-2.1	0.3	1.0		
10966 A	164353	B5 Ib (standard)	-5.7			7.0	
C	...	B3 IV	-2.5	3.2	4.15		
10984 A	164404	B3 V	-1.7			7.5	
B	...	B4 V	-1.4	0.3	0.6		
11024 A	164947	B3 IV + neb. em.	-2.5			7.5	
B	...	B2.5 V + neb. em.	-2.1	0.4	0.4		
11078 AB	165689	B2.5 V	-2.7^{*}			<7.5	
C	...	B2.5 V	-2.1	0.6	2.1		

TABLE 1—*Continued*

ADS	HD	Classification	M_V	ΔM_V	ΔV	Log t (yr)	Comments
11168 A	166934	B3 III	-2.9			≤7.5	
C	...	B5 V	-1.0	1.9	1.2		
11169 A	166937	B9 Ia	-7.1			7.0	
D	...	B2 IV	-3.3	3.6	5.75		Optical
E	...	B2.5 V	-2.1	5.0	5.37		
11232 A	167863	B7 V	-0.4			8.0	
B	...	B9 V	+0.6	1.0	3.0		
11356 A	170111	B4 V	-1.4			7.5	
C	...	A2 V	+1.2	2.6	2.0		
11414 A	170740	B2 V	-2.5			7.5	
B	...	B9 V	+0.6	3.1	3.3		
11546 A	172421	B6 V	-0.7			8.0	
B	...	B9 Vnn	+0.6	1.3	1.2		
11593 A	173087	B5 V	-1.0			8.0	
B	...	B8.5 V	+0.3	1.3	1.58		
11596 A	172979	B8 V	+0.1			8.5	
B	...	B9 V	+0.6	0.5	0.5		
11715 A	174261	B4 V	-1.4			7.5	
B	...	B9 V	+0.6	2.0	1.6		
11870 A	176795	B9.5 IV	0.0			8.5	
B	...	A2 V	+1.2	1.2	0.8		
11910 A	176582	B5 IV	-1.8			8.0	
B	...	A6 V	+1.9	3.7	2.3		
12038 A	177880	B5 V	-1.0			8.0	
B	...	A0 Vp(Sr v. st.; Cr,Si)	+1.0	2.0	2.4		
12162 A	179709	B9 IV	-0.2			8.5	
B	...	B9.5 IVp(Hg,Si)	0.0	0.2	1.1		
C	...	K1 V	+6.1	6.3	2.5		Optical
12197 A	180163	B2 V	-2.5			7.5	
B	...	B8.5 V	+0.3	2.8	4.20		
12451 A	183014	B4 V	-1.4			7.5	
B	...	B6 Vn	-0.7	0.7	0.1		
12508 A	183442	B7 V	-0.4			8.0	
C	...	A1 V	+1.5	1.9	1.9		
12778 A	185915	B5 III	-2.2			8.0	
B	...	F0 V	+2.4	4.6	2.3		Optical
12849 A	186618	B0 V	-4.4			7.0	
C	...	A3 V	+1.5	5.9	1.7		Optical
13041 A	187961	B7 IV	-1.2			8.0	
B	...	A5 V	+1.8	3.0	2.9		
13087 A	188293	B5 Vn	-1.0			8.0	
B	188294	B8.5 V	+0.3	1.3	0.78		
13117 A	188651	B7 V	-0.4			≤8.0	
B	...	A3 V	+1.5	1.9	2.2		

(*continued*)

TABLE 1—*Continued*

ADS	HD	Classification	M_V	ΔM_V	ΔV	Log t (yr)	Comments
13198 A	189432	B4 III	-2.6			≤7.5	
B	...	B8 III	-1.0	1.6	1.1		
13312 A	190429	O5 If	...			6.5	
B	...	O9.5 III	-5.4	...	0.6		
C	...	B1 IIIs	-4.4	...	1.9		
13666 A	193220	B2 V	-2.5			7.5	
C	...	A1 V	+1.5	4.0	2.9		
13672 AB	193322	O9.5 III	-5.4			7.0	
C	...	B9.5 Vn	+0.8	6.2	5.22[a]		
D	...	A0 Vp(met. wk.)	+1.0	6.4	5.36[a]		
13783 A	194206	B7 IV	-1.2			8.0	
B	...	B1 Ib-II	-5.4	-4.2	2.4		Optical
14126 AB	197018	B8 III	-1.6*			8.0	
C	...	B9.5 V	+0.8	2.4	2.5		
14504 A	199955	B7 IVn	-1.2			8.0	
B	...	B7 IV	-1.2	0.0	1.3		
14526 A	200120	B1 Vne?	-3.6			7.0	
B	...	A4 V +A4 V (SB2)	+1.6,1.6	4.4*	4.42		
14575 A	200614	B8 IVs	-0.7			8.5	
B	...	B9 V	+0.6	1.3	1.0		
14710 A	201671	Am(K/H/M=A0/A2V/A2)	+0.5			8.5	
B	201670	A4 V	+1.6	1.1	0.8		
14969 A	204172	B0 Ib	-5.8			7.0	
C	...	F4 V	+3.1	8.9	4.70		Optical
15032 A	205021	B0.5 IIIs	-4.7			7.0	
B	...	A1 V	+1.5	6.2	4.9		
15147 A	205811	A1 V	+0.8			8.5	
B	...	F1 V	+2.6	1.8	1.47		
15184 AB	206267	O7 V	-5.4			6.5	
C	...	B1.5 V	-3.1	2.3	2.4		
D	...	B1 V	-3.6	1.8	2.39		
15405 A	208095	B7 V	-0.9			8.0	
B	208063	A1 Vp(Si,Sr st; Ca wk)	+0.8	1.7	0.91		
15601 A	209744	B1 V	-3.6			7.0	
C	...	K0 II	-2.0	1.6	2.24		
D	209810	B9 Vn	+0.6	4.2	1.19		Optical
E	209809	B8 III	-1.0	2.6	0.33		Optical
F	209830	B9.5 V	+0.8	4.4	1.48		Optical
15942 A	212883	B2 V	-2.5			7.5	
B	...	B9 Vn	+0.6	3.1	3.6		
16095 A	214168	B1 Vne:	-3.6			7.0	
B	214167	B1.5 Vs	-3.1	0.5	0.68		
D	...	B7 Vn	-0.4	3.2	3.39		
16298 A	216227	B6 Vn	-0.7			8.0	
B	...	B8 Vn	+0.1	0.8	1.7		
16381 A	216916	B2 IVs	-3.3			≤7.5	
C	...	F5 V	+3.2	6.5	3.0		Optical

(*continued*)

TABLE 1—*Continued*

ADS	HD	Classification	M_V	ΔM_V	ΔV	Log t (yr)	Comments
16481 A	217943	B2 V	-2.5			$\leq$7.5	
B	...	B8 Vn	+0.1	2.6	2.7		
16795 AB	221253	B3 V	-1.7			7.5	
CD	221237	B8 Vn	+0.1	1.8	2.20		
F	...	F7 IV-V	+2.8	4.5	5.36		
17140 A	224572	B2 IV	-3.3			$\leq$7.5	
B	...	B3 V	-1.7	1.6	2.2		

* Allows for known duplicity

[a] Meisel (1968)

TABLE 2

FREQUENCIES OF Ap STARS AMONG VISUAL SECONDARIES AND IN OPEN CLUSTERS

t (yr) (1)	Primary Type (2)	No. Sec. (3)	Ap(Si) $-1.3 \leq M_V \leq +1.4$ (4)	Ap(Hg, Mn) $-1.4 \leq M_V \leq +0.5$ (5)	Ap(Sr, Cr) $-0.9 \leq M_V \leq +2.5$ (6)	Σ Ap $-1.4 \leq M_V \leq +2.5$ (7)
Visual Multiples						
$\leq 10^{7.0}$	$\leq$B1 V	24	0/5	0/3	0/7	0/8 = 0.0%
$\leq 10^{7.5}$	$\leq$B4 V	26	1/15	0/10	0/16	1/20 = 5.0%
$\leq 10^{8.0}$	$\leq$B7 V	19	1/15	0/8	1/19	2/19 = 10.5%
$\leq 10^{8.5}$	$\leq$A1 V	19	1/15	1/7	1/17	3/17 = 17.6%
Open Clusters						
$10^{5.7}$			0/15	0/7	0/17	0/18 = 0.0%
$10^{6.7}$			3/81	0/80	0/65	3/85 = 3.5%
$10^{7.4}$			7/85	2/47	0/109	9/110 = 8.2%
$10^{8.3}$			10/136	6/76	10/173	26/180 = 14.4%

visual multiples show a similar pattern, and if one allows for the fact that the ages of the visual multiples are only upper limits, it appears that the quantitative agreement is also good. Thus the classifications in visual multiples confirms that after an initial threshold, the frequencies of Ap stars increase with age.

If we look at the results of individual kinds of Ap stars, we again see no discrepancies with the cluster data. The clusters show a threshold for Ap(Si) stars of 10^6 yr; the visual multiples show them occurring first at upper limits of $\leq 10^{7.5}$ yr. The clusters show no Ap(Hg, Mn) stars before 10^7 yr; the visual multiples show them starting at $\leq 10^{8.5}$ yr. The clusters show no Ap(Sr, Cr) stars before 10^8 yr; the visual multiples show them starting at the same age. Although the total number of Ap secondaries is not large enough to define these thresholds and growth rates for each kind of Ap star, the available data confirm the larger data from the clusters.

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HELMUT A. ABT: Kitt Peak National Observatory, Box 26732, Tucson, AZ 85726

OCTAVIO CARDONA: INAOE, Apartados Postales 51 y 216, Puebla, Pue., Mexico