Peculiar Versus Normal Phenomena in A-Type and Related Stars
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ROTATIONAL VELOCITIES FOR THE BRIGHTER A-TYPE STARS

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ABSTRACT In 1968 van den Heuvel showed that the rotational velocities at many A types have peaks below V sin i = 45 km s^{-1} and above 90 km s^{-1}. We explored this bimodal behavior by obtaining new rotational velocities of 1761 A-type stars with coudé CCD spectra and, to date, new MK classifications for 956 of those. We find that the slow rotators consist of Ap, Am, and short-period binaries while the rapid rotators are normal and λ Bootis stars. The overlap is only 8-10% and can probably be attributed to undetected abnormal stars and binaries.

The λ Bootis stars discovered purely by their having weak λ4481 Mg II constitute about 18% of the early A-type stars but 4% at the late ones. Statistically all such λ Bootis stars have V > 100 km s^{-1} but they constitute only a small fraction of those stars.

More than half of the stars classified as A2 IV (and some at A1 IV and A3 IV) seem to be a hitherto unrecognized class of slowly-rotating abnormal-abundance stars of luminosities like those of class V stars.

INTRODUCTION

In 1968 van den Heuvel showed that many of the B- and A-type stars on the main sequence have bimodal distributions in rotational velocities at a given spectral type. One group has V sin i < 45 km s^{-1} ("slow rotators") and the other group has V sin i > 90 km s^{-1} ("rapid rotators"). This dichotomy holds for field stars, members of clusters and associations, and members of visual binaries, and therefore is probably a universal effect, according to van den Heuvel.

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Why should there be two distinct groups of rotators? Cosmologically one would expect a single broad distribution caused by the random accidents of some stars acquiring more or less angular momentum from the interstellar clouds from which they formed.

One study (Abt & Moyd 1973) considered the normal A5-A9 and the Am stars classified by Cowley et al. (1969) and with newly-measured coudé rotational velocities. The combined distribution in V sin i is bimodal. After a statistical deconvolution from V sin i to V, it turned out that all the Am stars had $V < 120$ km s^{-1} while all the normal stars had $V > 80$ km s^{-1}. The overlap was only 1.3 % of the combined stars and could easily be explained as small errors in the spectral classifications. Thus at least for the late A-type stars, the bimodal distribution can be attributed to a distinction between the abnormal stars (slow rotators) and the normal stars (rapid rotators).

This is not a good explanation for the existance of fast and slow rotators. The diffusion theory by Michaud (1970) and his colleagues showed that abundance abnormalities of the kind found in Ap and Am stars could be explained by elemental diffusion when the rotational velocities are less than about 120 km s^{-1}. In other words, the abnormality is the result of the slow rotation, not the cause of the slow rotation. So what is the cause for some stars being slow rotators and others being rapid rotators?

The only processes we know where the rotational velocities of stars are decreased are through tidal interactions in close binaries and through angular momentum losses by winds. The winds may be common to all stars of the same mass and rotational speed unless magnetic fields play a part. But we are not aware that the normal and Am stars have any large atmospheric magnetic fields. But at least we can expect that close binaries would have low rotational velocities <u>produced</u> by their duplicity.

Perhaps the weakness of a study like that of Abt and Moyd is that it did not include <u>all</u> the stars in a given interval of the main sequence. It included the Am stars and the normal stars, but no others in that spectral range, such as Ap stars. Therefore the purpose of the current study is to observe <u>all</u> the stars in an unbiased sample and to explore the reasons for the bimodal distributions in rotational velocities.

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OBSERVATIONAL MATERIAL

We wanted to obtain two new data sets for our complete sample: (1) new rotational velocities based on the new Slettebak et al. (1975) calibration, which gives values that average 5-15% smaller than the original Slettebak (1949) calibration and (2) new MK spectral types that may recognize a larger fraction of the abnormal stars than do the published types from heterogeneous sources.

The sample of stars is all the stars classified as A0-F0 in the Third Edition of the Catalogue of Bright Stars (Hoffleit 1964) and with declinations between -30° and $+70^{\circ}$. The declination limits were set by the Kitt Peak Coudé Feed telescope. However we obtained spectral types for some of the stars farther south and all of the stars farther north.

The rotational velocities were obtained with the 2.1-m coudé spectrograph on Kitt Peak receiving light from the 0.9-m Coudé Feed telescope. The dispersion was 15 A mm^{-1} and resolution was 15 km s^{-1}. We used a CCD detector to obtain the profiles of 4481 Mg II and, for the later A-type stars, 4476 Fe I. We measured the halfwidths of these lines and correlated them for the Slettebak et al. standards against their rotational velocities, dividing the stars in spectral-type intervals of B9.5-A4, A5-A9, and F stars. The relations are linear but not well defined for $V \sin i > 200$ km s^{-1} because of the blending of lines. Thus the uncertainties for the larger rotational velocities are indicated with colons. Our velocities for 35 standards with $V \sin i < 200$ km s^{-1} show a mean scatter per star of ±7.2 km s^{-1}.

We also derived equivalent widths of the 4481 Mg II line because the classifications showed that line to be weak in a significant number of stars.

The MK classifiactions were made with spectra of 39 A mm^{-1} dispersion and 1.2 mm wide. They were obtained photographically with the identical Cassegrain spectrographs on the Kitt Peak 2.1-m telescope and the Cerro Tololo 1.5-m telescope. The spectra were classified visually on a Boller & Chivens spectracomparator against MK standards by Morgan, Abt, and Tapscott (1978). Our agreement with Gray & Garrison (1987, 1989) is excellent, both in the abnormalities detected and the accuracy of the classification. The differences are ±1.1 spectral subclasses and ±0.8 luminosity classes.

At the time of this conference the rotational

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velocities for 1761 stars are complete but the classification of only 956 of the spectra have been made. The analysis below is based on this partial material.

THE λ BOOTIS STARS

The λ Bootis stars are B- and A-type stars with apparent deficiencies of metals, in contrast with the Am and Ap stars that have many metallic excesses. Michaud & Charland (1986) have found that diffusion in the presence of mass loss rates above 10^{-13} solar masses per year will produce atmospheric underabundances of the kind seen in λ Bootis stars while Charbonneau (1991) proposed an accretion/diffusion model with moderate mass loss. Abt (1984) noted that the easiest way to discover λ Bootis stars is by looking for weak 4481 Mg II lines. It is true that spectral classification will not distinguish between λ Bootis stars and truly metal-poor stars (throughout their interiors), but presumably the latter are very rare. The λ Bootis stars differ from the Ap stars, some of which also have weak 4481 Mg II, because the latter have some pronounced apparent overabundances.

To date we have discovered at least 50 likely λ Bootis stars. The percentages range from 18% of the stars at B9-A0 to 4% of the late A-type stars. We can check their peculiarities against the measures of 4481 equivalent widths. We see in Figure 1 that all the stars with 4481 equivalent widths less than 0.30 A were either classified as λ Boo or Ap; essentially all the stars with W(4481) > 0.40 A have normal abundances; between these values there is a mixture. Therefore visual classification agrees well with measured equivalent widths.

After the conference we checked the stars common to this study and the photoelectric Ca K-line photometry by Henry & Hesser (1971). We found that all of our proposed λ Boo stars in the common sample have K lines that are too weak for their types by an average of about one subclass, using either spectral types or B-V colors to compare them with normal class V stars. Thus the Mg II deficiency is associated with a Ca II deficiency too.

Nearly all λ Bootis stars found here have broad lines: 90% have V sin i > 100 km s^{-1} and the remaining 10% can be attributed to rapid rotators seen nearly pole-on.

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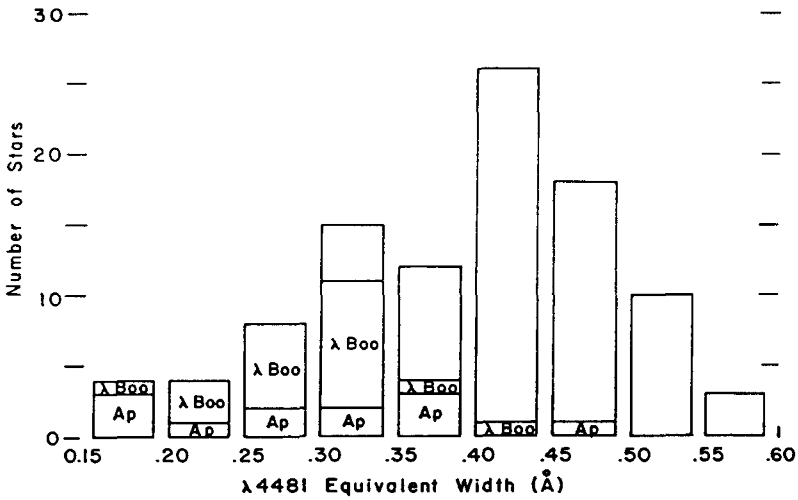

Fig. 1. The numbers of B9-A0 IV or V stars with various equivalent widths of the 4481 Mg II line are labelled as Ap, λ Boo, or normal (blank boxes) stars.

ROTATIONAL VELOCITY DISTRIBUTIONS

The distributions in V sin i do not show very pronounced bidmodal distributions but the divisions between normal and abnormal stars are distinct. Figures 2-3 show the distributions for B9-A0 IV or V, A1-A4 V, and A5-A9 IV or V stars. In each case the normal stars have broad distributions with maxima near 150 km s^{-1} while the abnormal stars and close binaries have peaks below 50 km s^{-1}. For these distributions the λ Bootis stars were included among the normal stars because their distributions in V sin i are similar. Among the SB2s we also included some SB1s with periods less than 20 days.

For the combined normal plus abnormal distributions in V sin i, the deviations from single broad distributions can be attributed to the few closely-spaced binaries in which the rotational velocities have been reduced by tendencies toward synchronous rotation. Therefore among the A-type stars there are no pronounced bimodal distributions; a single broad cosmic distribution plus a few percent of close binaries will fit the observations. Why, then, did van den Heuvel find such a pronounced

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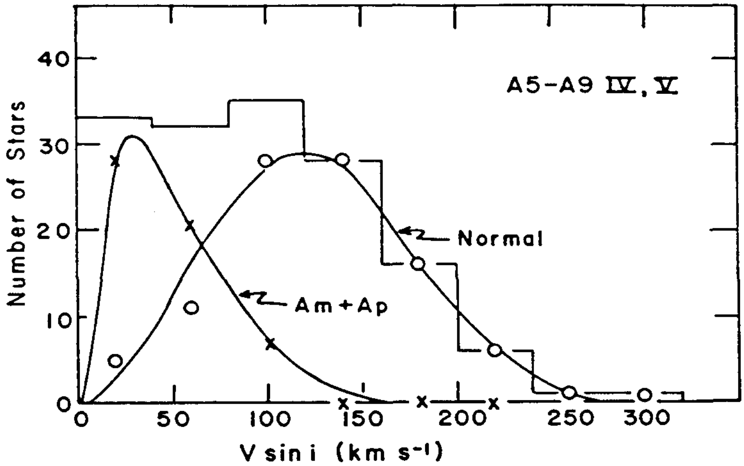

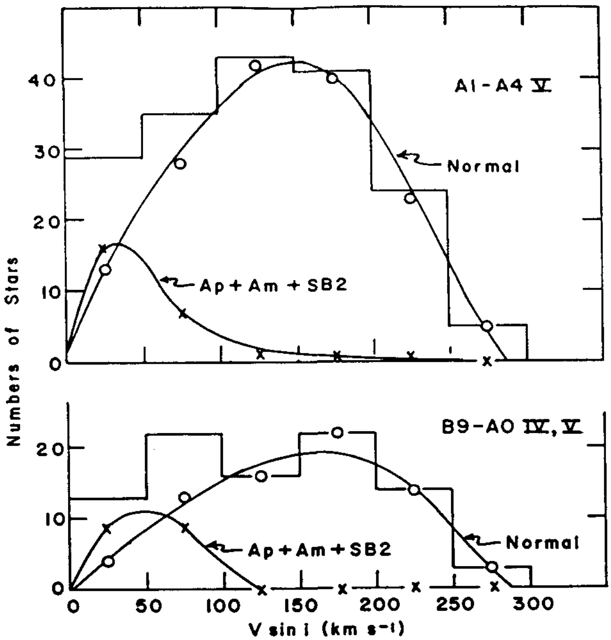

Fig. 2-4. The numbers of stars with various projected rotational velocities, V sin i, are shown for three groups by spectral type. In each case the numbers of Ap + Am + close binaries are indicated with Xs and the normal plus λ Boo stars with circles, and the overall distributions with straight lines.

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bimodal distribution at many types? We suspect it is mainly because the Ap stars were misclassified due to their helium underabundances.

When we deconvolve the measures to obtain distributions in V (Fig. 5, 6), the separations are more pronounced with essentially no normal stars with V < 50 km s^{-1} and nearly no abnormal stars with V > 150 km s^{-1}. The overlaps in V between normal and abnormal stars can easily be attributed to our lack of knowledge of all the short-period binaries in our sample and to small errors in classification. For instance, we usually cannot detect the Ap(Hg) stars at our dispersion.

We conclude this section by saying that among the A-type stars the distributions in V sin i do not show very pronounced bimodal distributions and the small effects can be attributed to those few stars (closely-spaced binaries) in which the rotational velocities have been modified by tendencies toward synchronization. However the rapid and slow rotators divide nearly completely between the normal and abnormal stars.

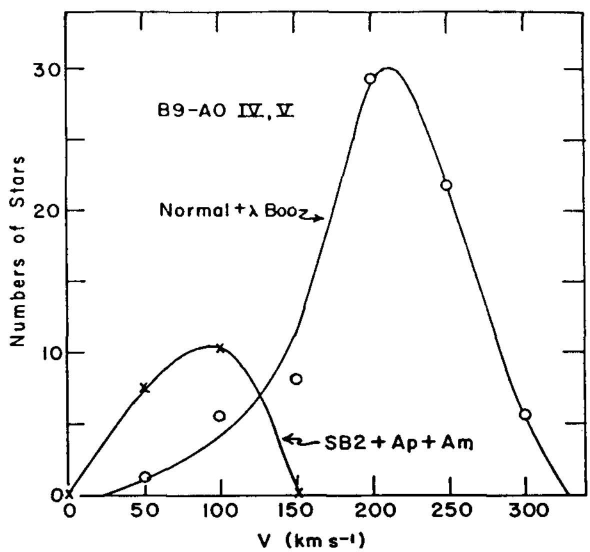

Fig. 5. For the B9-A0 IV or V stars shown in Figure 4 we have deconvolved the distribution, assuming a random orientation of rotational axes, to get a distribution in equatorial rotational velocity.

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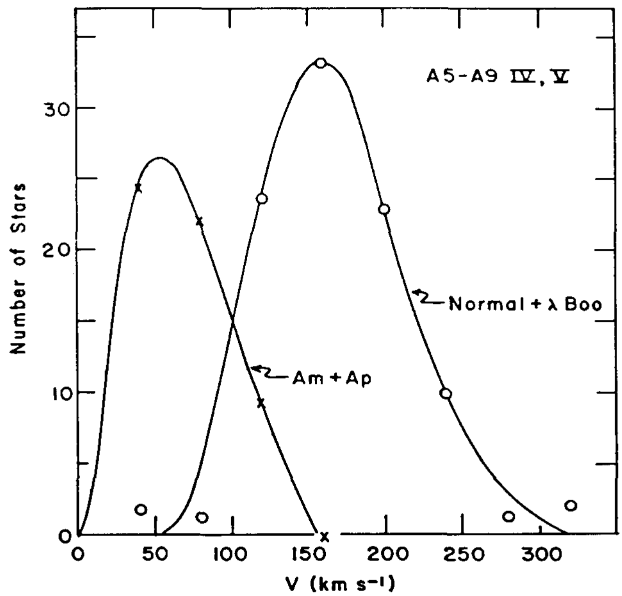

Fig. 6. For the A5-A9 IV or V stars shown in Figure 2 we have deconvolved the distribution, assuming a random orientation of rotational axes, to get a distribution in equatorial rotational velocity.

THE A2 IV STARS

There is something strange about most of the stars classified at or near A2 IV. First, we have noticed for years that most of the stars classified as A2 IV have sharp lines. And in some cases the 4481 Mg II, 4077 and 4215 Sr II, and some other lines are too weak. Let us compare the characteristics of the A2 V and A2 IV stars.

First, the 51 stars that we classified as A2 V have a mean V sin i = 149 ±9 km s^{-1} but the 25 stars classified as A2 IV have a mean of only 47 ±9 km s^{-1}. In fact, only two of the latter had V sin i > 100 km s^{-1}. This large difference cannot be attributed to the small evolutionary expansion between the bottom and top of the main sequence band. The rotational velocities of the A2 IV stars are more like those of Ap stars: for eight A2 Vp stars we obtain <V sin i> = 58 ±16 km s^{-1}.

Second, the strengths of 4481 Mg II are less in A2 IV stars (0.452 ±0.015 A) than in A2 V stars

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(0.500 ±0.008 A) and are more like the strengths in Ap stars (0.466 ±0.034 A).

Third, could it be that the A2 IV stars represent an undiscovered class of peculiar stars that may not even be class IV stars, despite their narrower hydrogen lines? If so, let us determine the absolute magnitudes of the A2 IV and A2 V stars. We found that 18 A2 V stars had trigonometric parallaxes greater than 0.010" (only two stars had parallaxes less than that value and were not included) and they yielded $\langle M_V \rangle = 1.55 \pm 0.21$. The 12 A2 IV stars with parallaxes greater than 0.010" (one had a lower value and was not included) yielded $\langle M_V \rangle = 1.43 \pm 0.18$. Therefore there is no significant difference between the absolute magnitudes of the A2 IV and A2 V stars.

We checked these results by using the classifications by Gray & Garrison (1987) instead of ours, but with our rotational velocities. Gray & Garrison find more broad-lined A2 IV than we did, but their types give a bimodal distribution in V sin i (Fig. 7). The broad-lined stars are probably the real A2 IV descendents of the early-A main-sequence stars but the sharp-lined ones may be something different. For the 17 A2 V stars the $\langle V \sin i \rangle = 135 \pm 11$ km s^{-1} and $\langle W(4481) \rangle = 0.503 \pm 0.013$ A. For the 11 sharp-lined A2 IV stars $\langle V \sin i \rangle = 52 \pm 8$ km s^{-1} and $\langle W(4481) \rangle = 0.465 \pm 0.023$ A. These numbers

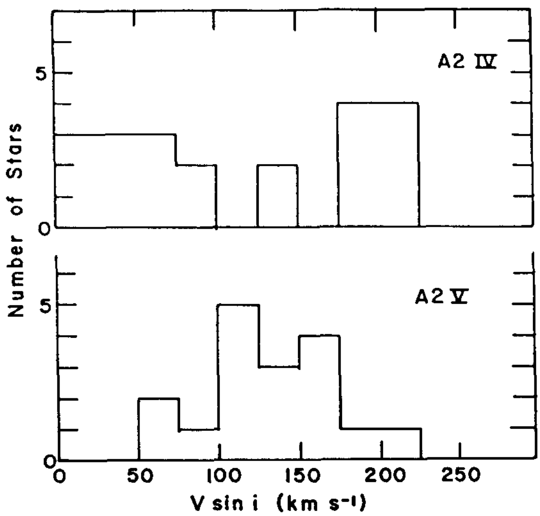

Fig. 7. For the stars classified as A2 IV and A2 V by Gray & Garrison and with rotational velocities by us, we plot the distributions of projected rotational velocities.

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confirm the results from our own classifications.

Therefore we tentatively conclude that half or more of the A2 IV stars respresent a new class of peculiar A2 V stars. The same excess of slow rotators occurs at A1 IV and A3 IV, but there are fewer data for analysis.

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