PART I

THE EFFECTS OF ROTATION ON STELLAR INTERIORS AND EVOLUTION

OBSERVED ROTATIONAL VELOCITIES OF SINGLE STARS

(Review Paper)

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Abstract. Mean observed rotational velocities for single, normal, main-sequence stars are reviewed and compared with the mean observed $v \sin i$'s for giant and supergiant stars, Be stars, peculiar A-type and metallic-line stars, and Population II objects.

One advantage of helping to organize a conference such as this one is that one can do some fairly outrageous things; such as scheduling oneself to give the very first paper on the program. I hope that you will excuse my presumption on the grounds that a brief overview of the observations of rotations of single stars would be both appropriate and useful before we become involved in the many facets of stellar rotation on our program for the next $3\frac{1}{2}$ days. My remarks will, in any case, be brief and can, in fact, be summarized in the two figures which accompany this text.

Figure 1 illustrates some recent determinations of mean observed rotational velocities for stars on the main sequence. The means given by the different investigators

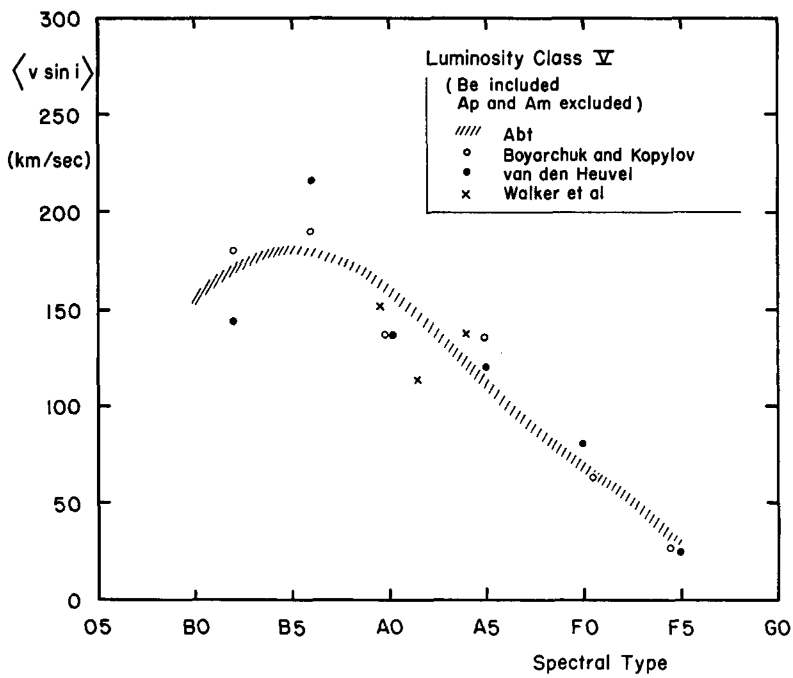

Fig. 1. The distribution of mean observed rotational velocities with spectral type for single, normal, main-sequence stars.

A. Slettebak (ed.), Stellar Rotation, 3–8.

https://doi.org/10.1017/S0252921100026981 Published online by Cambridge University Press

listed on the figure have observed rotational velocities in common and are therefore not necessarily independent, as will be pointed out. In all cases Be stars have been included in the statistics under the assumption that they may be regarded as the most rapidly rotating B-type stars, while Ap and Am stars have been excluded on the grounds that their abnormally low observed rotational velocities may represent later modifications.

The open circles in Figure 1 indicate mean rotational velocities for a total of 485 normal B1-G0 main-sequence stars from the catalogue of Boyarchuk and Kopylov (1964). The means were obtained from Table 2 of their statistical paper (Boyarchuk and Kopylov, 1958) by grouping their data as follows: B1-3, B5-7, B8-A2, A3-7, A9-F2, F3-6, F7-G0. The filled circles are from the curve of mean observed rotational velocities vs. spectral types of Van den Heuvel (1968), which was derived using the values in the Boyarchuk-Kopylov (1964) catalogue plus Kraft's (1965) measurements of stars in the Hyades and Coma clusters and Slettebak's (1966a) measurements of B6-B9e stars. The crosses represent means for 359 normal B9-A5 main-sequence stars from the catalogue of Palmer *et al.* (1968), as listed in the statistical paper by Walker (1965). Finally, the cross-hatched continuous curve is due to Abt (Abt and Hunter, 1962) – you have seen it many times, in his papers on stellar rotation in clusters, as representing the field stars. The curve is derived from the observed rotational velocities of Herbig and Spalding (1955), Slettebak (1954, 1955) and Slettebak and Howard (1955).

An inspection of Figure 1 shows that the various symbols are in fair agreement with Abt's curve. The high mean found by Van den Heuvel at B6 probably represents a disproportionate weighting in favor of B6-7e stars relative to Be stars of earlier type. The low mean at A1.5 from Walker's (1965) paper may be due partly to the admixture of Ursa Major stream stars, as was suggested by Abt and Hunter (1962) to explain the dip at A2 in the averages of Boyarchuk and Kopylov (1958).

The data in Figure 1 have been grouped in order to smooth out irregularities and show the broad features of rotation of single, normal, main-sequence stars. It is interesting to compare this illustration with Figure 3 in the paper by Abt (this volume, p. 193) in which the maxima and minima in the curve have been retained. Whether one believes in the reality of these irregularities or not, certain general features do stand out: rotation increases from very low values in the F-type stars to some kind of maximum in the B-type stars. The exact behavior of the curve as it moves on into the region of the early B-type and O-type stars is still quite uncertain since we do not know the relative importance of rotation and macroturbulence as line-broadening agents in these objects.

Several attempts to explain the observed distribution of rotational velocities for main-sequence stars of different spectral types have been made. The work of Schatzmann (1962), Roxburgh (1964a, b), Dicke (1964), Huang (1965), and Kraft (1968) should especially be mentioned in this respect.

Figure 2 shows Abt's (Abt and Hunter, 1962) curve for main-sequence stars again, plus mean rotational velocities for a number of other types of objects. The region of the O-type stars is shown, with values of the mean rotational velocities (Slettebak, 1956) marked with crosses. None of the O5-O8 stars measured in that sample show really sharp lines, indicating that macroturbulence must play an important role in the line broadening. The relative importance of rotation in these stars is therefore quite uncertain, as has been mentioned. A further uncertainty lies in the difficulty of luminosity classification for the O-type stars.

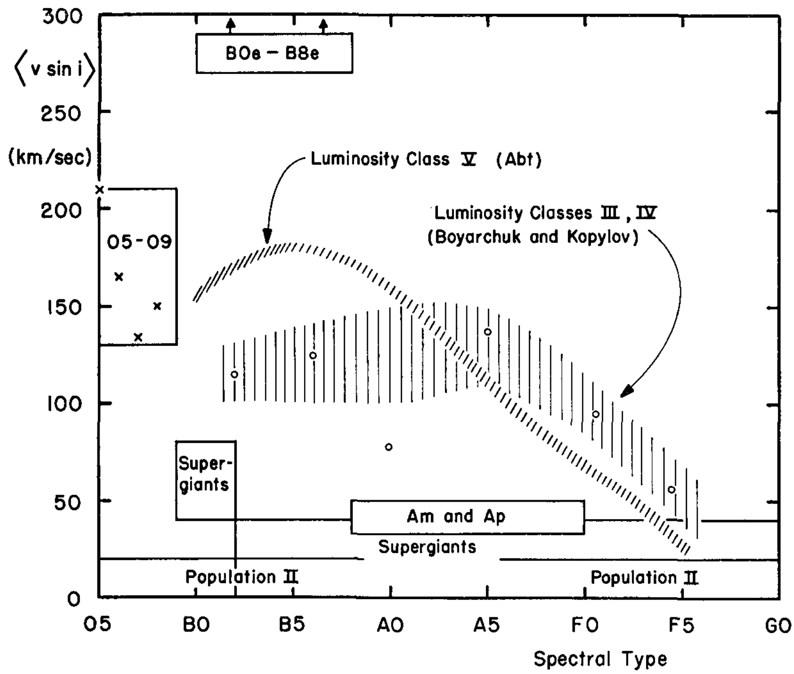

Fig. 2. Mean observed rotational velocities for a number of different classes of stars as compared with normal main-sequence stars.

The open circles in Figure 2 represent mean rotational velocities for 246 normal luminosity class III and IV stars from the paper of Boyarchuk and Kopylov (1958), arranged in the following spectral-type groups: B1-3, B5-7, B8-A2, A3-7, A9-F2, F3-6. The circles (except for the point at A0) are connected by a broad cross-hatched band, suggesting the uncertainties in the means. The curve indicates that early-type giants appear to rotate more slowly than main-sequence stars of corresponding type, that giants and main-sequence stars rotate with comparable velocities in the middle A's, and that giants rotate more rapidly than their main-sequence counterparts in the late A- and F-types. This behavior of the giant relative to the main-sequence rotation curve can be interpreted as an evolutionary effect: F-type giants, which evolved from rapidly rotating B- and A-type main-sequence stars, still show more rotational broadening than the intrinsically slowly rotating main-sequence stars of corresponding type. Several investigators, including Oke and Greenstein (1954), Sandage (1955), Abt

https://doi.org/10.1017/S0252921100026981 Published online by Cambridge University Press

(1957, 1958), and Kraft (1966), have discussed stellar rotation along evolutionary tracks, and you will hear several papers on this subject at this Colloquium.

The very low point at A0 in the giant curve can probably be interpreted in terms of selection effects. The classification of stars into luminosity classes near A0 is very difficult. In addition to differences in the strength of the Balmer lines (which is not a very sensitive criterion in the luminosity range III–V), one looks for enhanced lines of Fe II, Si II, and other ions in the giants. The latter lines, which appear weak on low-dispersion spectrograms, are more easily visible in the sharp-lined stars than in rotating stars and therefore one is more likely to associate the giant stars with low rotation.

The supergiant stars are shown schematically near the bottom of Figure 2. Supergiants of all spectral types have been shown by a number of investigators never to show conspicuous line broadening. On the other hand Huang and Struve (1954) first pointed out that while supergiant stars have relatively small values of $v \sin i$, none has a zero velocity, suggesting the presence of a broadening agent with spherical symmetry, such as macroturbulence. Attempts to distinguish between rotation and macroturbulence in these stars have been made by Huang and Struve (1953), Slettebak (1956), Abt (1958), Kraft (1966), Rosendhal (this volume, p. 122), and others, but the problem is a difficult one.

The Be stars are shown separately in Figure 2, with arrows indicating that their mean rotational velocities are in reality larger than shown. The position of the Be box derives from measures of 40 B6-8e stars (Slettebak, 1966a) and 47 B0-5e stars (Boyarchuk and Kopylov, 1964), averaging 278 km/sec and 284 km/sec, respectively, but the inclusion of gravity darkening in the calibration of the $v \sin i$'s (Slettebak, 1949, 1966b; Friedjung, 1968; Hardorp and Strittmatter, 1968) will tend to increase these means significantly. The corresponding 'true' equatorial rotational velocities, computed under the assumption that the axes of rotation are randomly distributed in space, are very close to the calculated velocities such stars should have for equatorial 'break-up'. Thus, the original picture of Be stars as rotationally-distorted B-type stars with equatorial gas rings, proposed by Struve in 1931, is still supported by the present data.

Mean rotational velocities for the peculiar A-type stars and metallic-line stars are shown in the box near the bottom of Figure 2, centered at about 40 km/sec (Slettebak, 1955). It may be seen that the mean rotational velocities for these objects are considerably smaller than the means for normal stars of corresponding spectral types. The reasons for this have been discussed by Abt (1961, 1965a, b), Deutsch (1958, 1965), Babcock (1958), Steinitz (1964), Kraft (1968), and others, and you will hear more about these matters at this Colloquium.

The box at the very bottom of Figure 2 indicates schematically that Population II stars have in general small rotation, a result due originally to Greenstein (1960). I have examined slit spectra at moderate dispersion of early-type halo population objects at both the north and south galactic poles, including O- and B-type subdwarfs, horizontal-branch stars, and F- and G-type subdwarfs, and have found no evidence of rotational line broadening (i.e., no values of $v \sin i$ higher than about 40 km/sec) for these stars. Greenstein (1969) has examined coudé spectrograms of several horizontal-branch stars and finds their lines to appear sharp even at high dispersion.

Many interesting classes of objects (i.e., pre-main sequence stars, pulsating stars, etc.) have been omitted in Figure 2, and of course only single stars have been considered; observations of axial rotation in double stars and in stars in clusters will be discussed later at this conference.

In conclusion, I would like to point out that, with the exception of the supergiants and the O-type stars, in which the precise role of rotation vs. macroturbulence is not yet clear, rotational velocities can be estimated from spectrograms with an accuracy of 10 to 15%. Obtaining accurate spectral types and luminosity classes so that meaningful correlations can be made continues to be a problem, however, especially in view of the fact that rapidly rotating stars are more difficult to classify than sharp-lined stars. The use of photometric indices should help here, but rotation will also affect the colors of the stars, as several investigators have shown. We will hear more about these matters in the papers to follow.

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Discussion

Abt: The speaker is overly generous in attaching my name to a mean curve, because the curve is based entirely on Slettebak's data. The curve ignored some of the maxima and minima in those data, but in view of some of the recent data, such as Walker's *et al.*, we begin to take the maxima and minima more seriously.

Jaschek: According to recent work by the Jascheks and the Cowleys, the average $v \sin i$ velocities for giants and subgiants do not drop at all between B9 and F0. It is therefore questionable how much weight should be attached to Kopylov and Boyarchuk's single point at F5 which determines the decrease of the mean $v \sin i$.

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