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THE INFLUENCE OF ROTATION AND STELLAR WINDS UPON THE Be PHENOMENON

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A number of rapidly rotating B stars, not previously known as Be stars, were observed spectroscopically at Hα. These results were then combined with existing data to show that the spectral type of a star and the minimum velocity at which it must rotate in order to become a Be star are related. The trend of this relationship is found to have a natural explanation in terms of stellar winds.

Key words: Be stars — stellar winds — stellar rotation

I. Introduction

It has long been thought that the Be phenomenon is closely related to the rotational velocity of the star involved (which has been assumed to be rotating near the so-called break-up velocity predicted by the Roche model). Limber (1964) suggested that a stellar wind may also be a contributing factor. For the spectral types involved, this wind would have to be radiatively driven, as discussed by Lucy and Solomon (1970).

These ideas can qualitatively explain why fewer Be stars are observed at the later spectral types. This is because the rotational breakup velocity, and the observed rotational velocities remain about the same for B5–9, but the amount of flux in the region of the spectrum which is important to the formation of stellar winds decreases drastically. However, neither of these facts explains the infrequent occurrence of Be-type emission stars at the earliest spectral types (B0.5 and earlier). An observing program was undertaken to see whether a correlation could be found between the value of the rotational velocity required for the onset of the Be phenomenon, and the amount of flux present in the region of the spectrum important in the Lucy and Solomon theory.

The new observations will be discussed in section II. Along with existing data, they will be used to argue that for the spectral range B1–5 there exists a critical rotational velocity, beyond which all stars will show emission *at some time*; and that no star appears to be rotating at the gravitational break-up limit (§III). The fraction of the break-up limit with which a star must rotate in order to exhibit Be features is shown to depend on the amount of ultraviolet flux in its spectrum for the spectral range B1–8.5 (§IV). Finally, the low incidence of observed Be-type emission at the earliest spectral types is discussed in section V.

II. Observations

Table I lists those stars in the rotational velocity catalog of Uesugi and Fukuda (1970) which meet the following requisites: (a) $v \sin i > 300$ km sec^{-1}, (b) spectral class earlier than B9, (c) luminosity class other than I, II, or III, (d) do not appear in Wackerling's (1970) catalog of emission stars, (e) observable from Boulder, Colorado ($\delta > -40°$).

From the fall of 1973 through the fall of 1974 spectrograms were obtained of the stars in Table I. The spectrograms were obtained at the University of Colorado with the Boller and Chivens small Cassegrain spectrograph on the 24-inch Boller and Chivens telescope of the Sommers-Bausch Observatory. These spectrograms included the region of Hα, and were taken at a dispersion of 120 Å mm^{-1}. The emulsions used were Kodak IIa-F and both unbaked and nitrogen-baked Kodak 098-04.

Hα emission was found in the following stars.

λ *Eridani* — This spectrum appears quite normal in the region accessible to blue sensitive plates. However, Hα is distinctly a double emis-

1975PASP...87..777M

TABLE I

Table of Observed Stars

HD	Name	Sp. Type	$v \sin i$ (km sec^{-1})	Comments
180968	2 Vul	B0.51 V	332	
191495		B0 V	362:	underexposed - no strong features at Hα
52918	19 Mon	B1 V	336	
33328	λ Eri	B21 V	336	double emission at Hα
141637	1 Sco	B2.5 V	311	
142114	2 Sco	B2.5 V	321	
147933	ρ Oph A	B2 V	303	
144298	θ Lup	B3 IV	331	
20418	31 Per	B5 V	320	
26256	HR 1289	B5 V	320	double emission at Hα
34959	HR 1761	B5p	348	double emission at Hα
35407	HR 1786	B5 V	450	
42545	69 Ori	B5 V	303	
196740	28 Vul	B5 V	330	
219688	Ψ^2 Aqr	B5 V	331	
21362	HR 1037	B6V	385	
34863	ν Lep	B7 V	370	
87901	α Leo	B7 V	354	
178475	ι Lyr	B7 IV	310	
188293	57 Aql A	B6 V	350	
21551	HR 1051	B8 IV	340	
32040	HR 1610 A	B8 V	350	
38831	30 Cam	B8 V	400:	

TABLE II

Photometry of HR 1761

	$U-B$	$B-V$	$V-R$	$V-I$
Unreddened	$-0\overset{\mathrm{m}}{.}52$	$-0\overset{\mathrm{m}}{.}16$	$-0\overset{\mathrm{m}}{.}02$	$-0\overset{\mathrm{m}}{.}13$
Intrinsic	$-0\overset{\mathrm{m}}{.}56$	$-0\overset{\mathrm{m}}{.}16$	$-0\overset{\mathrm{m}}{.}06$	$-0\overset{\mathrm{m}}{.}22$

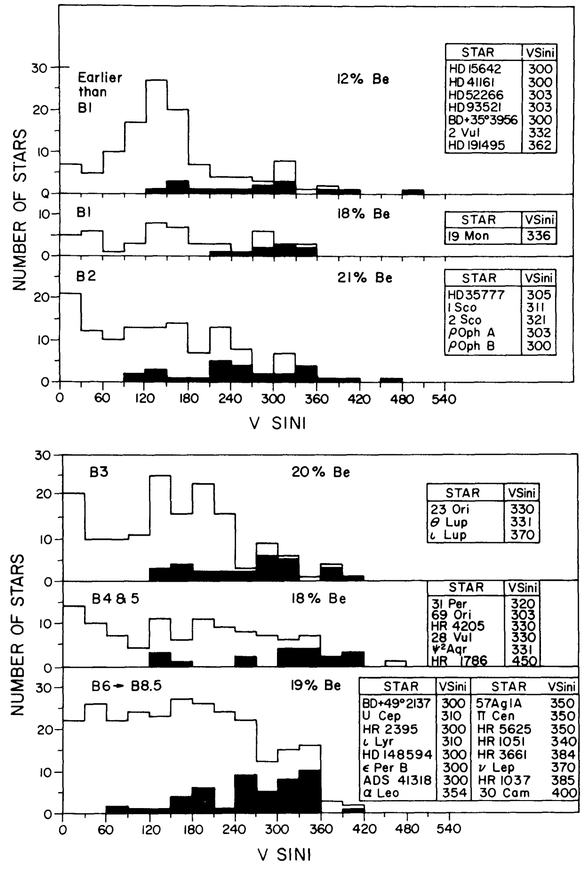
sion line, as is characteristic of a rotationally ejected envelope. The published color indices (Johnson et al. 1966) of the star seem to be within normal limits for its spectral type and luminosity class. So, aside from the star's large rotational velocity, there is no other hint of possible anomaly in its observed properties.

HR 1289 — This star also shows double emission at Hα, and Hβ is very weak. Although no *UBV* photometry could be found for this star, it should be noted that Andrews (1968) measured a photoelectric Hα index for this star which was normal for its classification. In all probability the emission feature is a recent occurrence.

HR 1761 — Double-peaked emission is observed at Hα. Andrew's Hα index for this star is well within the region of his index for emission, indicating that this star has probably had Hα emission for some time. Another interesting feature of HR 1761 is its *UBVRI* photometry. The color indices were unreddened by using the intrinsic $(B-V)$ index of a B5 V star (Johnson 1966). The resulting $E_{B-V} = 0.08$ was then used to unredden the other indices by using Johnson's (1968) color excess ratios for Perseus. The resulting unreddened indices and Johnson's intrinsic color indices for a B5 V star are given in Table II. It is seen that the observed color indices deviate more from the intrinsic ones at the longer wavelengths. The observed deviation is in the direction of a growing excess at longer wavelengths. The usual interpretation of such behavior is either a cool unseen companion, or the existence of a cool circumstellar cloud. Since the star appears to have a constant radial velocity (Abt and Biggs 1972), the latter argument is favored.

III. The Role of Rotation

Figure 1 shows histograms for the stars listed in the rotational velocity catalog of Uesugi and Fukuda with spectral types B8.5 and earlier and of luminosity classes other than I, II, and III (very peculiar objects such as P Cygni are also omitted). No attempt was made to distinguish between the so-called "field stars" and cluster stars because Abt (1970) has pointed out that the same rotational velocity distribution is obtained from each sample when several clusters are included. Also shown, as the shaded region of each division, is the portion of stars in each block which has shown Be-type emission at any time. This includes not only those stars normally classified as Be, but also any star listed in Wackerling's catalog as having shown Be-type emission at any time and the stars discussed in the previous section (although the O stars were not observed, they are also included for the sake of completeness). The reason for this division of the histogram blocks is two-fold. First, few stars are often observed at Hα where emission is first visible, and although a star may appear normal in the region of the spectrum used for MK classification, it may have Hα in emission (see λ Eri). Second, it is known that the Be phenomenon tends to be very transient. This has been demonstrated by a photometric survey of hydrogen lines by Feinstein (1973) who reported that 40% of all Be stars observed over a 13-year period showed variations at Hβ. Therefore, it is believed that the classification scheme of Figure 1 is a valid one.



STAR	VSini
HD 15642	300
HD 41161	300
HD 52266	303
HD 93521	303
BD+35°3956	300
2 Vul	332
HD 191495	362

STAR	VSini
19 Mon	336

STAR	VSini
HD 35777	305
1 Sco	311
2 Sco	321
ρ Oph A	303
ρ Oph B	300

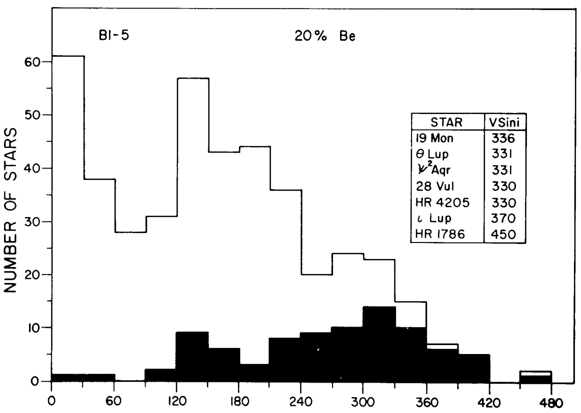
STAR	VSini
23 Ori	330
θ Lup	331
ι Lup	370

STAR	VSini
31 Per	320
69 Ori	303
HR 4205	330
28 Vul	330
ψ^2 Aqr	331
HR 1786	450

STAR	VSini	STAR	VSini
BD+49°2137	300	57 Agl A	350
U Cep	310	π Cen	350
HR 2395	300	HR 5625	350
ι Lyr	310	HR 1051	340
HD 148594	300	HR 3661	384
ϵ Per B	300	ν Lep	370
ADS 41318	300	HR 1037	385
α Leo	354	30 Cam	400

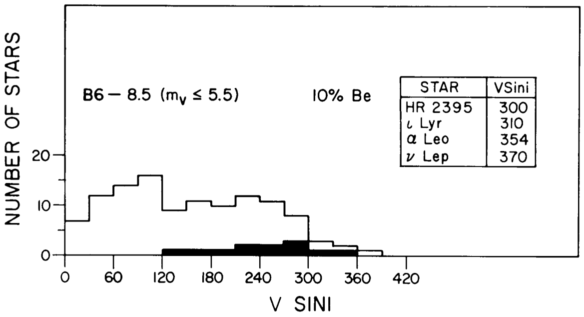
FIG. 1 — Histograms of $v \sin i$ vs. number of stars in 30 km sec^{-1} blocks from the data of Uesugi and Fukuda (1970). The Be stars, as defined in the text, are shown as the shaded portion of each block. Also shown is the percentage of Be stars in each histogram, the spectral range of each histogram, and the names of stars with $v \sin i \geqslant 300$ km sec^{-1} in each histogram which have *not* shown emission.

When classified by the above method, 20% of the B1–5 stars in Figure 1 have shown emission at some time. To be certain that this is not a selection effect due to an interest in the rotational velocities of emission stars by Slettebak (1966*a*) and others, all stars with $m_v \leqq 5.5$ and the same spectral and luminosity restrictions were selected from Hoffleit's (1964) catalog, regardless of whether or not they had rotational velocity data. For the B1–5 range it was found that 21% of this sample had shown emission at some time. So the stars in the rotational velocity catalog seem to represent a fairly unbiased sample for the B1–5 range and they are presented as a group in Figure 2. However, the B6–8.5 stars did not survive the same scrutiny. For this reason, Figure 3 shows only those stars in the spectral range B6–8.5 for which $m_v \leqq 5.5$. Of this less biased sample, 22% have no rotational velocity data. However, of the group without data 12% are Be stars and 11% of those with data are Be stars. So it is believed that the sample of Figure 3 is representative of the B6–8.5 spectral



STAR	VSini
19 Mon	336
θ Lup	331
ψ^2Aqr	331
28 Vul	330
HR 4205	330
ι Lup	370
HR 1786	450

FIG. 2 — The same as Figure 1 for the combined spectral range of B1–5 stars.



STAR	VSini
HR 2395	300
ι Lyr	310
α Leo	354
ν Lep	370

FIG. 3 — The same as Figure 1 for the spectral range B6–8.5 stars with $m_v \leq 5.5$.

range, while the raw data of the rotational velocity catalog are not. Due to the scarcity of bright stars of type B0.5 and earlier, no attempt was made to find a less biased sample for this spectral range. Of the B0.5 and earlier stars in Figure 1, 12% have shown emission. It is quite possible, however, that this value may be too large due to the aforementioned interest in emission-line stars.

From Figure 2 (the B1–5 stars) it is seen that only two stars have a $v \sin i \geqq 340$ and have never shown emission. These stars will now be discussed in detail.

1. HR 1786, B5 V, $v \sin i$ = 450 km sec^{-1}

Only one investigation, Abt and Hunter (1962), has provided a measure of the rotational velocity of this star. Although their results are given a high weight by Uesugi and Fukuda, it should be noted that they did not consider the star to be a binary. On the other hand, Plaskett and Pearce (1931) reported that this star had a double spectrum. Since Abt and Hunter took only one spectrogram, it is very possible that an erroneous $v \sin i$ was deduced from an overlap of two lines appearing as a single broad line.

2. Lupi, B3 V, $v \sin i$ = 370 km sec^{-1}

This star has only been measured once by Huang (1953), in a set of observations given a weight of only 2–3, where the best data were given a weight of 12 by Uesugi and Fukuda. Even so, an error of only plus 10% would give this star a value of $v \sin i <$ 340 km sec^{-1}. However, this star was too far south to be observed from Boulder and deserves further investigation.

From these considerations, it seems that any star in the B1–5 range with a true rotational velocity greater than about 350 km sec^{-1} will show emission at some time. This velocity is chosen because, as may be calculated from the work of Chandrasekhar and Münch (1950), the probability of observing a star with $v \sin i > 0.95$ v is approximately 30%. From the large number of stars with $v \sin i$ near 330 km sec^{-1} it seems likely that we are observing stars near the true maximum velocity that a star in this spectral range may have without becoming an emission star at some time.

Another method of demonstrating the above effect is by rectification of the observed rotational velocity distribution of Figure 2 for all of the B stars (HR 1786 was omitted for the reason stated above) and then application of a similar rectification to the Be stars of the same figure. The histograms were rectified by following the method of Lucy (1974) except that curves obtained by the method of Chandrasekhar and Münch (1950) were used for the initial iteration. The results obtained after four iterations are shown in Figure 4. It is seen that the rectified curve for the Be stars effectively merges with the rectified curve of all B stars at V = 360 km sec^{-1}. This value is very close to the estimate of the preceding paragraph which was arrived at by more intuitive means.

While discussing the histograms, it should be pointed out that, with the exception of HR 1786 mentioned above, no star appears to be rotating near the gravitational break-up limit predicted by the Roche model. Table III lists the maximum rotational velocities observed, along with the minimum calculated break-up velocity from

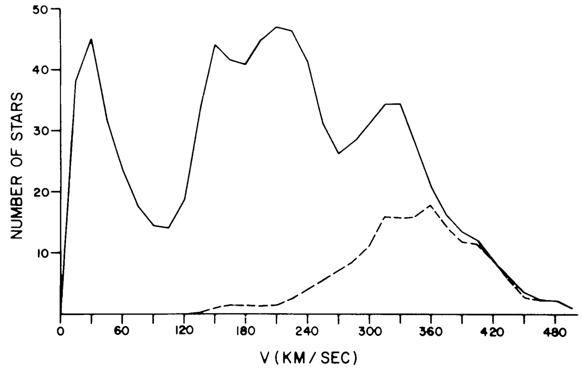


FIG. 4 — Rectified distribution of all B stars (including Be stars) of Figure 2 (solid curve) and Be stars only (dashed curve) of the same figure.

the Roche model given by Slettebak (1966*b*).

The values listed in Table III assume that the $v \sin i$ deduced by simple Doppler broadening of lines is a true indication of rotational velocity. However, it is known (see, for example, Slettebak 1949 and Stoeckley 1968) that other effects may cause the observed $v \sin i$ to give a value which is less than the "actual value." The major predicted effect, gravitational darkening, has not been observed (Bless and Savage 1972). The other effects, geometrical deformation and differential rotation, are model dependent. The model predictions for geometrical deformation vary widely (Sackman and Anand (1970) give values of 1.2%–1.9% for the decrease of the polar radius, while Roxburgh, Griffith, and Sweet (1965) give a value of 10.8%), and since there is not presently a theory which treats differential rotation consistently, the assumption of strict Doppler broadening of the spectral lines seems reasonable.

IV. The Role of Radiation Pressure

Figure 5 shows the percentage of Be stars in each block of the histograms of Figure 1 for spectral types B5 and earlier, and in Figure 3 for spectral types B6–8.5. The abscissas have been adjusted to represent the fraction of the minimum break-up velocity appropriate for each spectral type. In the case of the B0.5 and earlier stars the break-up velocity was taken to be 600 km $\sec^{-1}$, even though this value is too low for most of the stars in this range.

Figure 6 shows the ultraviolet flux from $\log g = 4.0$ model atmospheres of Kurucz, Peytremann, and Avrett (1972). The range of temperatures is chosen to represent the stars of interest. The fluxes are normalized to $F_\lambda = 1$ for 18,000° K (B3) since this temperature is about in the middle of the range in which Be stars are most prevalent.

An interesting correlation may be inferred from a comparison of Figures 5 and 6. For the stars of the spectral range B1–8.5 it is seen that as the amount of flux in the stellar wind region of the spectrum decreases (Fig. 6), the curves of Figure 5 become progressively skewed toward the break-up limit. This would seem to imply that a star need not rotate at its break-up velocity to become a Be, and that the fraction of the break-up velocity at which a star must rotate in order to become a Be star decreases with increasing ultraviolet flux. Therefore, it appears that stellar winds play a significant role in the formation of a Be star's emitting envelope. This may have been expected, since Limber (1964) has pointed out that although rotation decreases the surface gravity of a star it is incapable of forming an envelope. Rather, some other mechanism is required to move matter away from the stellar surface. The results of this section imply that the necessary mechanism is radiation pressure. The relative lack of Be stars at the earliest spectral types will be discussed in the following section.

V. The Early-Type Be Stars

By the simple arguments of the preceeding section, one would expect the curve of Figure 5 for the B0.5 and earlier stars to be the least skewed, which it is not. However, this may or may not be a real effect, due to the rapid variability which is observed in many of the existing Be stars in this range. For example, Barker and Brown (1974) found that the emission features of ζ Ophiuchi (O9.5) lasted only on the order of months and dissipated over a period on the order of days. Conti and Frost (1974) reported that the emission features of λ Cephei (O6) vary on a time scale which may well be on the order of hours. Merril and Burwell (1949), in a note to their Table 1, report that HD 46056 (O8) has shown Hβ emission on four of eight radial velocity plates, while at other times the same star has shown only absorption at Hα. Also, it is well known that γ Cassiopeiae (B0.5) has ejected

TABLE III

Ratios of Maximum Observed Velocities to Break-Up Velocities for B Stars

Sp. Type	Star	Max. Obs. Vel. (km sec^{-1})	Break-up Vel. (km sec^{-1})	% of Break-up Vel.
B0.5 and earlier	HD 206773	480	590	81
B1	8 Lac A	348	560	62
B2	φ Per	450	525	86
B3	48 Lib	400	510	78
B4-5	α Eri	411*	460	89
B6-8.5	30 Cam	400†	440	91
	HR 1037	385		88

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*This star was measured only once by Huang (1953).

†This value was in doubt by the observer (Palmer et al. 1968).

Note: all stars in this table of spectral type earlier than B6 have shown emission.

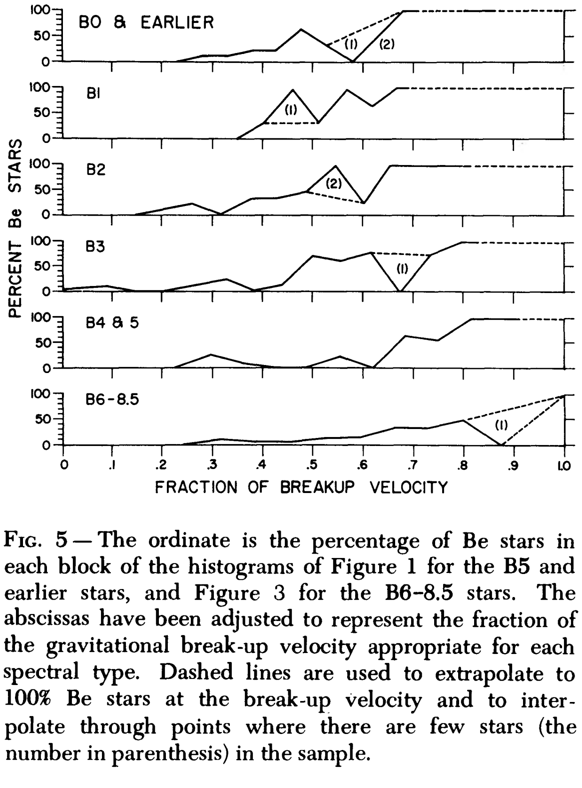

Fig. 5 — The ordinate is the percentage of Be stars in each block of the histograms of Figure 1 for the B5 and earlier stars, and Figure 3 for the B6-8.5 stars. The abscissas have been adjusted to represent the fraction of the gravitational break-up velocity appropriate for each spectral type. Dashed lines are used to extrapolate to 100% Be stars at the break-up velocity and to interpolate through points where there are few stars (the number in parenthesis) in the sample.

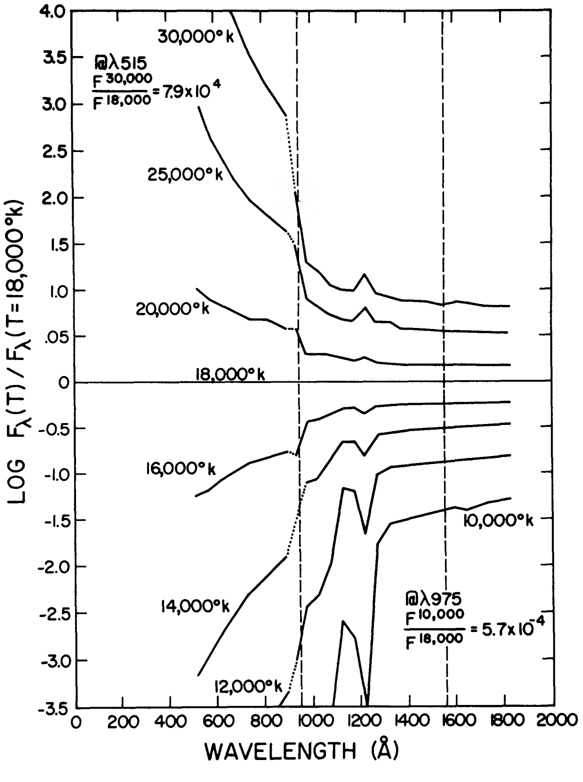

Fig. 6 — Log g = 4.0 model atmospheres of Kurucz et al. (1972) normalized to the T = 18,000° K model. The vertical broken lines indicate the region of the spectrum considered by Lucy and Solomon to be of importance to stellar winds.

a shell on a time scale on the order of a year (Cowley and Marlborough 1968). This same star has been observed by Hutchings (1970) to have variations in its emission features which are on the order of days. These observations seem to indicate an increasingly transitory nature of emission features in the earliest stars. Therefore, the probability of observing emission in a particular star at any given time may be quite small, except in the most extreme cases, and the relative lack of Be stars near the expected cutoff value of $v \sin i$ may simply be an observational effect. Also, Slettebak (1956) has pointed out that few sharp-lined stars can be found in this spectral region. So the observed values of $v \sin i$ may be too large due to a contribution of macroturbulence of the observed profile.

On the other hand, it may be that these early stars just do not form emission disks except in extreme cases. One possible reason for this would be the increasing strength of their stellar winds, due to an enormous increase in their ultraviolet flux. As may be seen in Figure 6, a 30,000° K star (B0–09.5) has about ten times as much flux in the ultraviolet region of the spectrum longward of the Lyman jump, and as much as ten thousand times as much shortward of the Lyman limit as compared to an 18,000° K (B3) star. To give an idea of the magnitude of the winds involved, one should note that Morton, Jenkins, and Macy (1972) found a stellar wind of 1840 km $\sec^{-1}$ for ξ Persei (O7.5), Morton, Jenkins, and Matilsky (1972) gave 900 km $\sec^{-1}$ for ζ Oph (O9.5), and Bohlin (1970) reported 450 km $\sec^{-1}$ for γ Cas (B0.5). This is to be compared with the fact that no noticeable stellar winds have been detected in the B1 and later spectral range except for the supergiants. So it is quite possible that the enormous increase in the ultraviolet flux of the earlier stars generates such large winds that the formation of the circumstellar disk is either inhibited altogether, or else blown away in a short time span.*

VI. Conclusions

On the basis of the preceding arguments, the following relation of the Be phenomenon to the spectral sequence is suggested. First, the B9 and later stars have difficulty forming a disk since there is not sufficient radiation pressure available to move material away from the star. Next, in the spectral range B1–8.5 there is adequate radiation pressure to move matter away from the star when the surface gravity is reduced by rotation. Also, the extent to which rotation must aid the process declines as the capacity to generate a stellar wind increases. Finally, in the spectral range B0.5 and earlier, the wind may become so strong that, except in extreme cases, it either causes the disk to be so transient that it is rarely observed, or inhibits the formation of the disk altogether.

For the sake of completeness, the following conclusions are also restated.

1. No star is observed to be rotating at the gravitational break-up limit predicted by the Roche model.
2. When classified by the condition that any star that has shown Be-type emission lines at any time is a Be star, one finds that almost 20% of the stars of luminosity classes IV and V and spectral types between B1–5 fall into this category. This result is at odds with the hypothesis that gravitational core contraction is the *sole* cause of the Be phenomenon.
3. All stars of spectral classes B1–5 and luminosity classes IV and V with a true rotational velocity greater than about 350–360 km $\sec^{-1}$ will, at some time, appear as Be stars.

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*I am indebted to P. S. Conti for suggesting this possibility.

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