SIGNIFICANCE OF TIME VARIATIONS IN THE Be PHENOMENON

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1. Preliminary Remarks

When I prepared the discussion in the subsequent sections I did not realize just how subject to question were certain basic ideas relating to the interpretation of the Be phenomenon. In view of the points already raised in the course of this Colloquium, I should like to preface my prepared remarks with certain additional ones.

There appears to be little question that the Be phenomenon has important things to tell us of stellar rotation. It appears almost equally clear that too superficial an approach could well lead to invalid conclusions at any one of a number of points. Some caution therefore, appears advisable. Nevertheless, there appear to be a number of reasons for believing that a relatively simple rotational interpretation of the phenomenon rests on much more solid ground than does any other yet put forward.

To give us something concrete on which to fix our attention, let us consider a mechanical model which, though much oversimplified, contains what I believe is the essence of the dynamics of the Be phenomenon. This model consists of an array of rigid spokes fixed in, and radiating outward from, a hub, the whole of which can be rotated about an axis through the hub and perpendicular to the plane of the spokes. Along each spoke a frictionless bead is constrained to move subject to three forces in addition to the force of constraint: (1) a $1/r^2$-force of attraction directed toward the center of the hub, (2) an outward-directed force falling off faster than $1/r^2$ due to a bumper spring coaxial with the spoke and attached to the hub, and (3) the centrifugal force consequent to the rotation of the whole (cf. Figure 1). The bead represents a mass element in the vicinity of a star's equator, the above three forces representing the gravitational force, the force due to the atmospheric pressure gradient, and the centrifugal force, respectively, on such a mass element. The force of constraint imposed on the bead by the spoke represents some kind of viscous force, that provided by magnetic field lines coupling the matter in the atmosphere and circumstellar envelope with the body of the star appearing to be the most likely candidate.

Consider now the stability of such a bead with respect to radial perturbations. In the limit of zero rotation, an outward-directed radial perturbation of the bead from its equilibrium position leads to a situation in which the inward-directed gravitational force exceeds the outward directed force due to the bumper spring; and the bead moves back toward its equilibrium position, the equilibrium being stable with respect to such perturbations.

In the case of intermediate angular velocities, a small outward perturbation from the equilibrium position will lead to a situation in which the net force after the pertur-

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bation will again be directed inward in spite of the increase in the centrifugal force on the mass element subsequent to the perturbation, and the equilibrium here, too, will be stable.

The situation is completely different for the case in which the system is rotating with that critical angular velocity at which the centrifugal force balances the gravitational force on the bead, the force due to the bumper spring being vanishingly small in equilibrium in this case. Here, an infinitesimal outward perturbation leads to a situation in which the centrifugal force becomes larger. Since the gravitational force becomes smaller, the net result is a continuing motion of the bead outward along the spoke and, hence, an instability with respect to such perturbations.

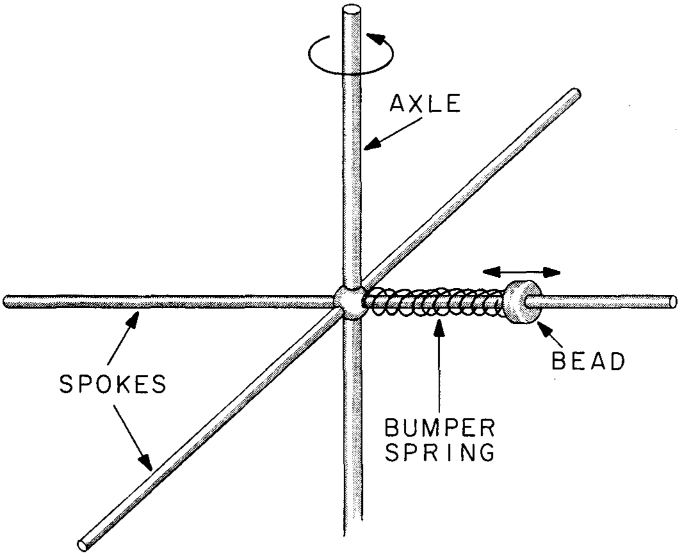

Fig. 1. Schematic mechanical model to illustrate the nature of the Be phenomenon as it is interpreted in this paper.

It is a phenomenon of this latter kind that I believe plays a major role in the Be phenomenon. To be sure, the viscosity is infinite in the model considered, but the nature of the situation with respect to stability is not altered in its essentials so long as there is a finite rigidity to the spokes, i.e. so long as there is a finite viscosity.

It is of interest here to point out that a star need not rotate such that its photosphere is at the rotational limit (that limit at which the centrifugal force balances gravity on mass elements at the equator) in order that the Be phenomenon take place. All that is required is that at points in the atmosphere where the rotation is at the rotational limit there be a density large enough to give rise to a significant mass outflow as a result of the above described instability. Rough considerations suggest that because of the relatively small density gradients in the atmospheres near the rotational limit, the rotation parameter, $\Omega r^3/GM$, characterizing the photospheres in the equatorial planes may well be as small as 0.9 when this condition is satisfied. This effect would act to help bridge the gap between the critical rotational velocities for the Be stars and the observed maximum values for their equatorial velocities, the latter characterizing their photospheres.

In concluding this introductory section, let me note briefly a number of arguments that appear to support – or at least are quite consistent with – the overall model of the Be phenomenon presented above.

(1) The observational evidence strongly supports the view that the Be stars are stars close to the rotational limit.

(2) Efforts to understand the dynamics of the circumstellar envelopes suggest that the transfer of angular momentum into the envelopes from the bodies of the stars appears much more probable than any alternative mechanism thus far proposed.

(3) The difficulties associated with alternative mechanisms is made even more acute by the Pleione-type of envelope behavior in which the circumstellar envelope is observed to come into being and to dissipate over a period of from 5 to 30 years, all without the rotational state of the star as a whole undergoing any significant change.

(4) The evidence for nearly uniform rotation in stars of moderate rotation in early evolutionary states, from work such as that described by Mrs. Faber (this volume, p. 39) lends support to the belief that there are significant viscosities operating at least within the interiors of such stars.

(5) The model calculations for the main-sequence evolution of uniformly rotating B stars by Miss Sackmann (1968) appear to provide quite good semi-quantitative agreement with the observations concerning the frequency of occurrence and position of occurrence in the main-sequence band of the Be stars on the assumption that a model for the Be stars of the kind described above is correct.

(6) The observed symmetry and geometry of Be envelopes supports the view that rotation over and above that consequent to the conservation of angular momentum within the envelopes is present and, hence, that there is a significant angular-momentum coupling of mass elements within such an envelope with the body of the star.

2. General Background

The Be stars are stars of spectral type B whose spectra show hydrogen lines in emission. It has long been known that this emission originates in tenuous circumstellar envelopes that extend outward from the stars' surfaces some 10 or more stellar radii. The stars themselves appear to be normal main-sequence B stars except that they possess rotational velocities at their surfaces that are considerably greater than those of the typical non-emission B stars on the main sequence.

It was realized more than a third of a century ago that the observed rotational velocities of the Be stars approached the limiting velocity at which such a star's gravitational force on a mass element at its equator is just balanced by the centrifugal force on that element. This suggested that the Be phenomenon was to be understood in terms of a model in which a star – as the result of evolutionary changes – finds itself rotating at (or near) the rotational limit. With the help of centrifugal effects, matter is then able to move outward from the star's equator, giving rise to a circumstellar envelope of the kind observed. Studies of the line profiles have strongly supported this picture. They indicate that the velocity fields in the envelopes are for the most part those corresponding to differential rotational motion, the circular velocity decreasing outward from the equator. The radial component of velocity is, in general, less than 10 km/sec – often only a few kilometers per sec or smaller.

The general picture outlined above is suggestive but is far from complete. That the rotation of a star at, or near, the rotational limit will make the problem of forming a circumstellar envelope simpler, other things being equal, is clear enough; but mass elements must still gain in moving outward from the equator to infinity as much energy again as they possess at the equator in the form of rotational energy. A recent study (Limber and Marlborough, 1968) of the role of the different possible forces that might act in the envelope to accomplish this energy transfer has strongly supported the view that the relevant force is a centrifugal one consequent to the transfer outward through the envelope of angular momentum from the body of the star either through magnetic fields coupling the envelope with the body of the star or through turbulent viscosity, the former appearing to be the more likely.

In the foregoing picture rotation not only brings the star to the rotational limit but also plays the decisive role in the envelope dynamics, as well. If this picture is correct, it then appears that information concerning the observed time variations in the envelopes of Be stars may well shed light on problems concerning the present rotational state and rotational evolution of the bodies of these stars and help us, as well, to better determine the properties of the magnetic fields at their surfaces and within their circumstellar envelopes.

3. The Observed Time Variations in the Be Phenomenon

At the present time it appears convenient to divide the observed kinds of time variations in the circumstellar envelopes into 3 classes on the basis of the time scales for the variations involved. These time scales are: (1) a main-sequence hydrogen-burning time-scale (a time scale ranging from 10^6 to 10^8 years, depending upon the spectral type of the Be star), (2) a time scale of the order of years, and (3) a time scale of the order of days – or less.

A. TIME VARIATIONS ON THE MAIN-SEQUENCE TIME-SCALE

Though we have no direct evidence pertaining to the first – and longest – of these time scales for individual stars, the indirect evidence appears conclusive at several important points. First, for the early type B stars, Be stars make up somewhat more than 10% of all main-sequence B stars. From this alone it follows that the early B stars spend *on the average* more than a tenth of their main-sequence lifetimes in the Be phase. If by reason of their rotational states at the times of their reaching the main sequence only a fraction f of all early B stars can become Be stars, then such stars would spend somewhat more than $0.1/f$ of their main-sequence lifetimes in the Be phase. At the present time there seems to be no sure way of estimating the fraction *f*. What can be said is that it must exceed 0.1 and, of course, be less than or equal to unity. The two limiting possibilities here are either that all early B stars pass through the Be phase and spend somewhat more than a tenth of their main-sequence lives in this phase or that only somewhat more than a tenth of all early B stars pass through the Be phase, those that do spending almost all their main-sequence lifetimes in this phase.

B. TIME VARIATIONS ON THE TIME-SCALE OF YEARS

There is a large body of direct observational evidence available concerning changes on the intermediate time scale of the order of a few years. Among a group of 40 of the brightest Be stars observed at Ann Arbor over many years, 26 have shown conspicuous changes in the spectral properties of their envelopes, 6 more have shown relatively small changes, while only 8 have failed to show convincing evidence of changes (McLaughlin, 1961). The changes observed include changes in the equivalent widths of the emission lines, changes in the forms of the line profiles, and changes in the radial velocities for the lines. Strictly periodic variations are not observed on this or any other time scale – except insofar as they simply reflect the orbital motion of Be stars that are components of binary systems. One rather characteristic type of variation on the intermediate time scale involves the alternation of 'active' intervals of 10 to 30 years, during which quasi-periodic changes with periods of 2 to 5 years are the rule, with more nearly time-independent intervals of roughly the same length. Representative stars showing this type of behavior are π Aquarii (McLaughlin, 1962) and HD 20336 (McLaughlin, 1961). A second type of variation, while not so common, appears important because of its overall simplicity; it may, in fact, be but a variation of the type just described. In this second type of variation – and here we shall simply describe the behavior of Pleione (Limber, 1969) – the star was first observed to have a circumstellar envelope in 1888. This envelope was observed through 1903 but was gone in 1905. From 1905 until 1938 there was no evidence for the existence of a circumstellar envelope, the star's spectrum being that of a rapidly rotating but non-emission B star. Beginning in 1938 a circumstellar envelope was observed to come into being, reaching its greatest strength in 1945 or 1946. The envelope then began to fade away and was essentially completely gone by 1954. Here the evidence strongly supports the view that we have on two occasions seen this particular rapidly rotating B star produce a circumstellar envelope and have it dissipate over an interval of some 15 years, the interval between the two 'shell' or envelope episodes being about 35 years. It appears quite possible that many or all of the Be stars that have not yet been observed to show significant time variations will show them over intervals of from 50 to 100 years.

C. TIME VARIATIONS ON THE TIME SCALE OF DAYS

The body of observational data pertaining to time variations on the time scale of days is not at all large. Indeed, at this stage of our understanding it requires a rather arbitrary act to neatly separate the time variations of the intermediate and short time scales. I shall confine myself to a very brief description of 3 different studies that have revealed significant time variations over intervals ranging from one hour to one week. The variations include both significant variations in the equivalent widths of Hα as well as relatively small changes in the details of the line profiles for Hβ and Hγ. A study of HD 174237 by Lacoarret (1965) indicated that there were significant variations in the equivalent widths of Hα with a characteristic quasi-period of about 7 days. A study by Miss Doazon (1965) of the Be star HD 50238 gave evidence for significant changes in the radial velocities for the Balmer lines over a few days, for the appearance and disappearance of 'satellite' absorption features to the envelope lines in a day, and for 10% changes in the equivalent width of Hβ in a day and for 50% changes in a week. Finally, Hutchings (1967) has detected significant changes is the Hγ profile of γ Cassiopeiae over intervals of an hour through a photoelectric scanning technique.

4. Implications

A. TIME VARIATIONS ON THE MAIN-SEQUENCE TIME-SCALE

Let us now turn to a brief consideration of some of the implications – or possible implications – of these observed time variations. Consider first those of the time variations on the main-sequence time scale. Here the evidence strongly supports the view that a fraction f of all early B stars are brought reasonably close to the rotational limit and kept there during at least a fraction $0.1/f$ of their main-sequence lifetimes, where $0.1 < f \leq 1$. Several additional points should now be noted. First, as a result of hydrogen burning in the core, it appears highly probable that the equatorial radius will increase in time subsequent to such a star's contraction to the main sequence. If there were no angular momentum coupling between the different spherical or cylindrical shells making up the body of the star, this evolutionary change would act to move the star *away* from the rotational limit. Second, there appears to be no evidence that the Be stars are stars only in their earliest main-sequence stages. On the contrary, there appears to be some evidence that the Be stars represent stars either in the later main-sequence stages only or, in the extreme, stars spread over all main-sequence stages. This suggests that there is at least some continuing transfer of angular momentum from the inner parts of these stars to their equatorial regions that either moves the latter regions close to the rotational limit or keeps it there in spite of the reverse tendency consequent to its surface expansion. With further study it may become possible to determine this average rate of angular momentum transfer with considerable accuracy.

Two non-mutually exclusive possibilities have been suggested as sources of the angular momentum flows to the equatorial regions. The first was suggested by Crampin and Hoyle (1960). Model calculations for spherically symmetric, non-rotating stars during main-sequence and early post-main-sequence phases showed that although their surfaces expanded, their inner parts contracted more than enough to compensate, with the net result that – at least in the limit of infinitesimal rotation – the main-sequence hydrogen burning phase and, particularly, the stage of rapid core contraction subsequent to hydrogen exhaustion are phases in which for uniform rotation the changes are such as to move the equatorial regions in the direction of the rotational limit. More recent model calculations, which include the effects of uniform rotation, appear to support this conclusion, giving evidence that the effects even during the hydrogen burning phase prior to the state of rapid core contraction are large, indeed (Sackmann, 1968).

An alternative possibility arises from the circumstance that at least many stars, upon reaching the zero-age main sequence, may be in a state of differential rotation in which their inner parts rotate with angular velocities significantly larger than those in their equatorial regions as a consequence of their pre-main-sequence histories. If this is the case, then the operation of any 'viscous' agents (including magnetic fields and turbulent viscosity) will act to transfer angular momentum to the equatorial regions at the expense of that in the inner regions and may, conceivably, proceed at a rate more than sufficient to overcome the effects of the evolutionary expansion of the equatorial regions and move such stars toward the rotational limit.

In either case, the observations suggest that here are viscous agents operating in the interiors of main-sequence B stars that can significantly alter the rotational states of their equators over time scales of the order of the main-sequence one.

B. TIME VARIATIONS ON THE TIME-SCALE OF YEARS

The time variations observed over a time scale of the order of years – especially those involving variations in which envelopes are observed to come into being and to disappear – provide the strongest kind of evidence that the rate at which matter leaves these stars' equators often varies markedly over the course of 5 or 10 years and that the matter that forms an envelope dissipates in the course of a few years when left to itself. The important thing to be noted here is that individual envelopes characteristically come and go on a time scale of from 5 to 50 years and not on anything like the main-sequence time scale. Since the mass lost during such an envelope episode is of the order of $10^{-6}\ M_{\odot}$ or less and since the time scale is so much shorter than the hydrogen-burning one, the rotational state of the star as a whole can scarcely change in any significant way during such an envelope episode. This has been taken by some as evidence that, although rotation plays a significant role in the Be phenomenon, there must be something else that actually triggers it. If the stars were constrained to rotate in detail as solid bodies, this argument would be compelling indeed. However, in the absence of any direct evidence for a nonrotational triggering mechanism, it appears reasonable to seek to understand the situation in terms of rotation's doing the triggering – but for non-uniformly rotating stars in which the flow of angular momentum outward from the inner portions of the stars to their equators is not smoothly continuous – at least in the vicinity of the stars' equators – but is, instead, rather 'lumpy'. Rough calculations have been carried out for a simple model in which an equatorial band of arbitrary thickness rotates uniformly out to that distance from the rotation axis at which centrifugal force balances gravity and on the assumption that the rate of mass loss is proportional to the density at this critical surface. The calculations show that if at time zero the equatorial band possesses angular momentum enough to lead to an appreciable rate of mass loss and if the angular momentum supplied to this band is abruptly cut off at this time, then the subsequent mass loss will have effectively come to an end some ten or twenty years later for the case in which the equatorial band includes only that part of the star lying more than eight-tenths of the equatorial radius from the star's rotation axis; the decay time for the mass loss is of the order of a week or so if the equatorial band includes only that part of the star's mass exterior to 0.96 of the star's equatorial radius. In both cases the decay times for the rate of mass loss from the equators set lower limits to the times required for the envelopes to disappear, the latter depending, as well, upon the velocity field within the envelopes. (For purposes of comparison, the decay time-scale for the case in which the star as a whole rotates uniformly is a thousand years or more.) In none of the above cases (except that for uniform rotation throughout) would the stars' observed rotational velocities be perceptibly smaller at the termination of the envelope formation than at its peak.

What is suggested to me is that the variations on the time scale of years are to be understood in terms of the transfer of angular momentum into the equatorial regions in a manner exhibiting variations over intervals of this same order – or smaller. Work is in progress that may help to put certain aspects of this problem on a more quantitative footing.

C. TIME VARIATIONS ON THE TIME SCALE OF DAYS

Time variations on a time scale of a day are in all probability the manifestations of rather localized phenomena insofar as the envelope as a whole is concerned; this conclusion appears all the more certain for the variations that have been observed by Hutchings to take place within an hour. At the sound speed within these envelopes the time required to cover one stellar radius is about a week; a time-scale of an hour would imply an active volume whose characteristic dimension was one one-hundredth of a stellar radius or smaller. (Use of the Alfvén velocity rather than the sound speed doesn't appear likely to alter this conclusion drastically.) Consequently, it is tempting to think in terms of a rather localized instability's being responsible for these short-time variations. The time scales involved suggest flare-like activity. Indeed, a simple extension of a mechanism suggested for explaining solar flares, involving the electromagnetic energy release consequent to the reconnection of magnetic field lines in the differentially rotating envelopes appears promising. If this – or a related mechanism – is found to explain these short-term variations, we shall have further support for the view that magnetic fields play an important role in the dynamics of the envelopes of Be stars.

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Discussion

Roxburgh: It is clear that the material in the shell has to be ejected with considerable energy. It is probably necessary that some instability sets in for high angular velocity, such that the equatoria regions can acquire this energy.

Another possibility is that a slow pressure-driven 'wind' is possible for high angular velocity.

Buscombe: Two aspects of the variation of flux from Be stars in an interval of weeks or months need more intensive observational surveillance – the ultraviolet brightening and variations in intrinsic polarization. Some Be stars in high galactic latitudes are especially favorably located for the separation from interstellar effects. Is there a sporadic burst of electron plasma, or what?

Limber: The mechanism that has suggested itself to me for accounting for the very short-term time variations of the order of hours is one involving the reconnection of magnetic field lines with a consequent conversion of magnetic energy into the kinetic energy of charged particles. This latter energy would presumably manifest itself insofar as the observations are concerned as a sudden heating of relatively small elements within the circumstellar envelopes.