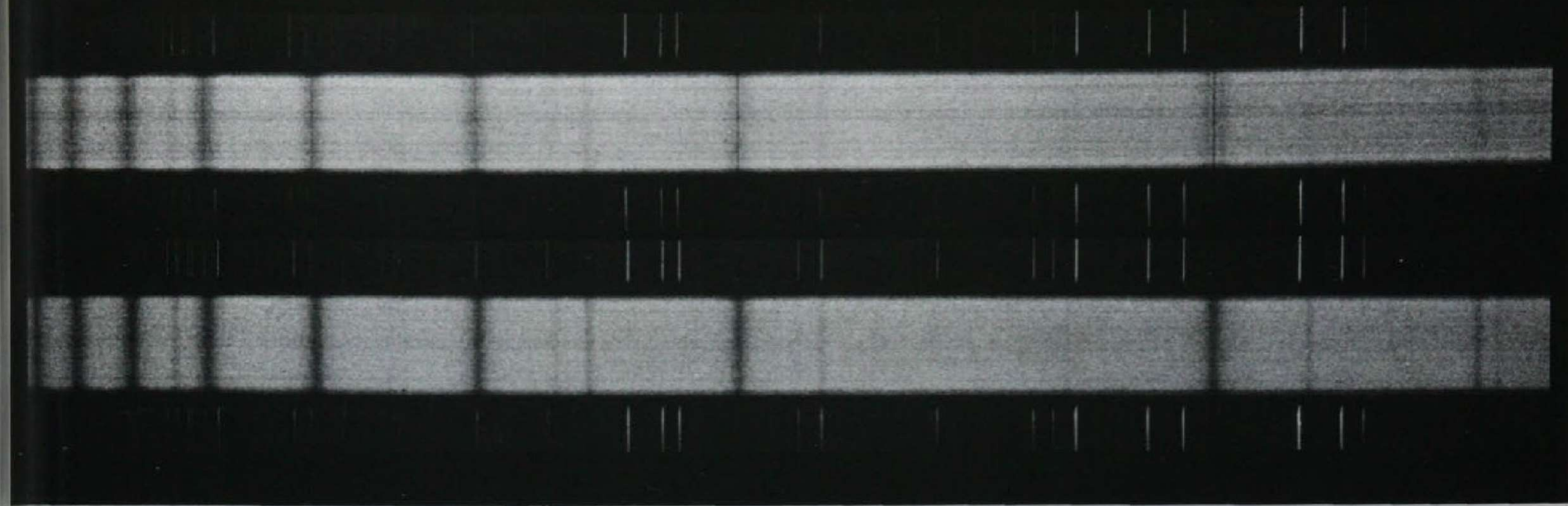

Spectra of the *B*5e star Psi Persei (above) and the *B*5V star 34 Persei, by Helmut A. Abt with the 84-inch reflector at Kitt Peak National Observatory. In the lower spectrum, the eight very strong dark lines are all of the hydrogen Balmer series, from Hκ (3750 angstroms) at extreme left to Hγ (4340) at right. In Psi Persei, note how Hγ has a sharp dark core flanked by emission components, all superposed on a very broad absorption line. The same structure appears in all this star's hydrogen lines, but with the emission weaker for each Balmer line to the left.

Interpretation of the *B*e Stars

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THE University of Michigan astronomer Dean B. McLaughlin devoted many years to spectroscopic observations of the *B*e stars, which are of spectral class *B* and have hydrogen emission lines. Because of his outstanding contributions, this field will always be associated with his name.

Having met Dr. McLaughlin only a few times and having exchanged few words with him, I know him as a person mostly from what friends at the University of Michigan have told me. But I know him extremely well as a scientist from having studied his numerous papers and having myself worked in the field of *B*e stars that he cultivated so well. This article, dedicated to him, describes McLaughlin's contributions to this branch of astronomy, together with some theoretical results I obtained from following his ideas and using his observational data.

We shall be concerned here with only what may be called the "ordinary" *B*e stars. Excluded are the extreme supergiants of luminosity class Ia, which Helmut Abt and John Golson estimate to make up about 10 percent of all *B* stars with bright hydrogen-alpha lines (Hα). Also omitted are the *B*e stars in nebulosity, surveyed by George Herbig.

THE EMISSION LINE PROBLEM

The ordinary *B*e stars have fairly normal spectra except for their emission features, which are usually hydrogen lines. In several cases bright lines of ionized iron and other elements are also observed, but the hydrogen lines are always the strongest. Each emission feature is usually seen superimposed on a broad absorption line, either as a double-peaked bright line with a dark core, or as a single bright feature.

Dean B. McLaughlin (1901-65) will be long remembered as a great observational astrophysicist, particularly for his extensive studies of the spectra of novae and of emission-line *B* stars, and for his interpretation of Martian surface markings as wind-blown volcanic dust. University of Michigan photograph.

As early as 1923, R. H. Curtiss at Michigan recognized that the widths of the emission lines in a *B*e star are proportional to their wavelengths; a similar proportionality holds for the spacings between the components of double lines. From this, he rightly concluded that the broadening of the lines and the separation of components result from the Doppler effect, since Doppler shift is proportional to wavelength. In other words, the emission-line profiles are conditioned by the velocities of the emitting atoms.

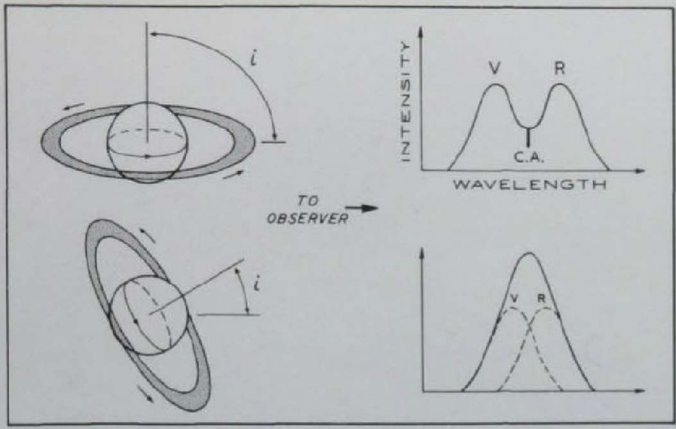
Otto Struve, a 20th-century astronomical giant, after his own extensive study of *B*e stars and taking advantage of Curtiss' clue, concluded that the emission-line profiles have something to do with rotation. When a star rotates, its spectral lines appear broadened, because different surface areas on the star are moving with slightly different line-of-sight velocities and their contributions to a spectral line are slightly shifted in wavelength. However, the degree of line broadening observed does not depend solely on v, the equatorial rotational velocity of the star.

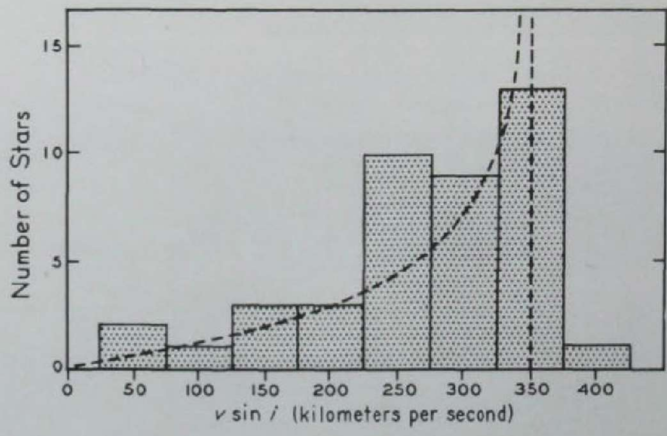
The broadening also depends upon the inclination angle, i, between our line of sight and the star's axis of rotation. Thus, if we look at a rotating star in the direction of its axis, so that i is zero, rotation causes every area of its surface to move perpendicular to the line of sight. No matter how rapid that star's rotation, it will produce no Doppler effect, since there is no line-of-sight motion.

However, since most stars will not be oriented with $i = 0$, their rotations do cause a Doppler effect. In general, what we can determine from measuring the rotational broadening of a spectrum line is $v \sin i$, the line-of-sight component of the velocity. From the spectrum alone, neither v nor i can be individually ascertained.

With this preliminary, we can now state Struve's conclusion precisely: Stars with double-peaked emission lines have broad, diffuse absorption lines characteristic of large $v \sin i$, while stars with single emission lines have narrow absorptions, indicating small values of $v \sin i$.

With his usual keen physical insight, Struve proposed a *B*e star model in which a ring revolves around a central star in its equatorial plane, in the same way that Saturn's rings revolve around the planet. He attributed both the emission and the





Left: The rotating-ring model of a *B*e star, with the ring presented edgewise to the observer (above) and obliquely (below). In the first case, the profile of an emission line (right) should show equal violet and red components, with a narrow central absorption (*CA*). In the second case the two emissions overlap to produce a single bright line, with no central absorption.

Right: The shaded bars show the distribution of the observed rotational velocities of 42 *B*e stars, according to A. Slettebak. It agrees fairly well with the author's dashed curve, calculated on the assumptions that all *B*e stars rotate with equatorial velocities of 275 kilometers per second, and that their rotational axes are randomly oriented.

central absorption core to the gaseous particles in the ring. The inclination determines whether the emission is double-peaked or single. If i is 90°, so the ring is edgewise to us, the orbital motion of the ring produces two separate emission components, one from the approaching and one from the receding part of the ring. The portion in front of the star, moving perpendicularly to the line of sight and producing no Doppler shift, absorbs the star's light and produces the narrow absorption in the center of the emission.

At the other extreme, Struve noted, is the case of a rotating star seen nearly pole on, so the line-of-sight component $v \sin i$ is small. Consequently, the two emission components overlap as a single bright line. Since the ring is in or close to the equatorial plane, hence seen nearly face on, it does not intercept light from the star to the observer. Thus there is no absorption core, unless in addition to the ring the star has a gaseous envelope surrounding it on all sides.

Hence, Struve's rotating-ring hypothesis explains the basic observational facts of the spectrum line profiles of *B*e stars. With this interpretation, the actual profiles of the emission lines can be calculated. Such computations indicate that the motions of the emitting atoms in the ring are probably turbulent (widening the lines).

In this way, Struve considered all *B*e stars to be rotating rapidly. That some of them show little line broadening is due solely to small values of i. Therefore he attributed the formation of the rings to rotational instability. A star holds itself together by the mutual gravitational attraction of its parts. But if the star rotates so rapidly that centrifugal force at its equator balances the gravitational force, the star starts to shed matter from its equatorial regions.

Struve's model was further confirmed by Arne Slettebak. As we have mentioned, observation of an individual star yields only the product $v \sin i$, so we are not sure whether all *B*e stars are rotating rapidly, as Struve suggested. The question can only be answered by a statistical study, and Slettebak did just that.

There are reasons to believe that the rotational axes of stars are randomly oriented. The diagram shows the distribution of observed values of $v \sin i$ obtained by Slettebak for 42 *B*e stars. The dashed curve is calculated on the assumption that all these *B*e stars have the same equatorial velocity. Considering the smallness of the sample, we can conclude from the good agreement that the *B*e stars are all rotating with high velocity. Although Slettebak and his associates are redetermining the $v \sin i$ values for these stars, we believe that the general trend will not be changed.

SPECTRAL VARIATIONS

Most of the ordinary *B*e stars show spectra variations, which can be classified into three types. First is what McLaughlin called E/C variability — changes in the ratio of intensities of an emission line and the neighboring continuous spectrum. Second, the shell absorption spectrum can disappear and reappear. Third is the V/R variation, consisting of changes in the intensity ratio of the "violet" and "red" components of double emission lines.

As McLaughlin emphasized, the three types are not mutually exclusive. Some stars have only one kind of variation, others two, and a few have shown all three. My own feeling is that every *B*e star, in principle, shows all three kinds of change, perhaps at different times. That we have not observed them in some stars is perhaps due to our failure to monitor them at proper times, or to the orientation of the ring with respect to our line of sight.

Usually E/C variation is simply a fading or strengthening of the emission line, without appreciable change in width. Pleione in the Pleiades is an extreme case. In 1885, when the earliest spectrograms of it were taken at Harvard Observatory, it had double emission lines of hydrogen. The star lost its bright lines in 1906 and regained them in 1937. Pleione also shows the second kind of variation. The shell spectrum had weakened considerably when Slettebak observed this star in 1954, but its reappearance was recorded by W. W. Morgan and his associates on December 9, 1972.

In V/R variation, while the relative strength of the two emission components of a spectrum line changes periodically, their total intensity remains nearly unchanged. In extreme cases one component may nearly disappear, but usually the ratio does not exceed 3:1. The periods of variation are on the order of years to decades. In some stars, such as Pi Aquarii, these changes are irregular.

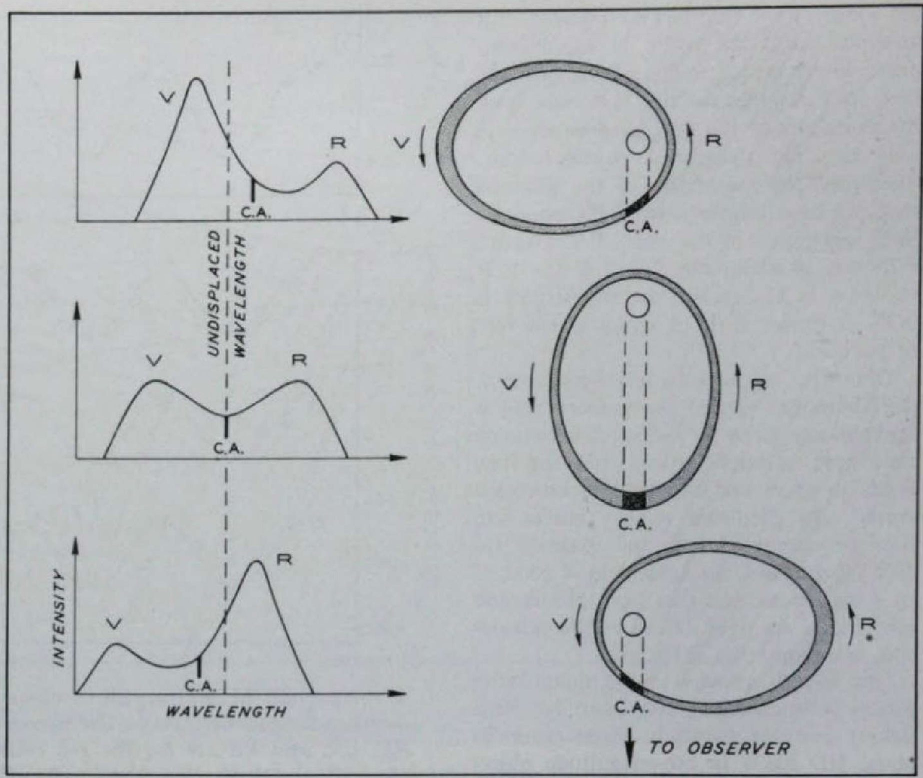
The periodic V/R variations are always accompanied by other variations, such as in the radial velocities of the emission edges and the central absorption core. The general behavior is sketched in the left half of the figure at the top of the facing page. Here we see the changes in profile and wavelength of a line as the value of V/R changes (top to bottom) from maximum to minimum. Any satisfactory theory has to account for this behavior in detail.

McLaughlin first tried to explain the V/R variation by a model in which a rotating ring expands and contracts, the red emission component dominating during expansion and the violet during contraction. He abandoned this model because of difficulty in explaining why a detached ring would pulsate, and because the model simply does not explain the radial-velocity shifts of the line edges and core.

He next considered a more elaborate model, involving an inner, emitting ring and an outer, absorbing one. The assumption was made that the red and violet emission components would be of equal intensity whenever the entire ring was in simple rotation around the star. If the inner ring began to expand, the red component would be weakened by absorption in the outer ring. Later, when the expansion was transferred to the outer ring, its absorption would weaken the violet component. Then the outer ring would be blown off and the inner one would become stable, restoring the initial equality of the red and violet components. Finally, a new cycle would begin.

McLaughlin realized the artificiality of this ingenious model, and discarded it also, before finally adopting an elliptical-ring model. This idea had been casually mentioned by Struve, but it was McLaughlin who elaborated it.

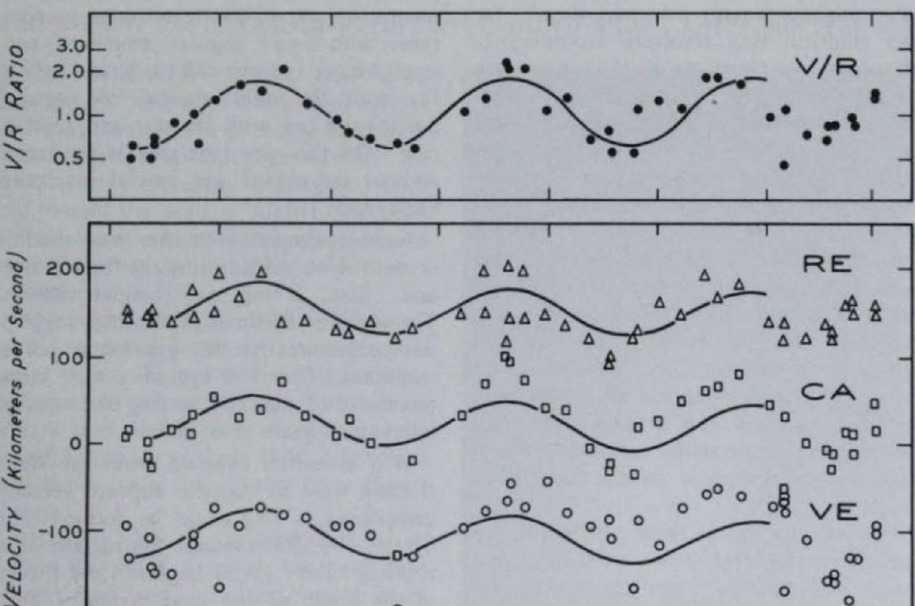
The manner in which an elliptical ring explains the observed facts is shown in the right-hand side of the adjacent diagram. As the gas particles in such a ring revolve around the star, they travel fastest at periastron and slowest at apastron, in accordance with Kepler's second law of planetary motion. As a result, matter piles up near apastron, just as automobiles on a highway crowd together where the driving is slow. Hence, in the top sketch, the observer sees more emitting atoms on the approaching side of the ring than the receding, so the violet component of the emission line appears stronger than the red one. Also, the part of the ring through which the star is seen (shaded in the diagram) is receding from us, so the core absorption is displaced toward longer wavelengths. All this agrees nicely with the top sketch of the line profile, as indicated in the diagram above.



The author's elliptical-ring model for *Be* stars is illustrated at right. The ring is nearly edgewise to the observer in each case, but depending on the angle between the longest ring diameter and the line of sight, the emission line profile (at left) can show differing relative intensities of the violet and red components, and the central absorption can be displaced.

If the orientation of the ring in space did not change, we would observe a permanently strong violet component and weak red one. But because of the gravitational effect of the equatorial bulge of the rotating star, the longest axis of the ellipse slowly advances. (Such an advance of the line of apsides is quite common in close binary systems.) When the advance has amounted to 90 degrees (second sketch), the observer looks along the line of apsides from apastron to periastron. Because the advancing and receding parts of the ring are symmetrical, the violet and red emission components appear equally strong, and the core absorption is undisplaced.

After the ellipse has turned through a further 90 degrees, the situation is that shown at the bottom (just the reverse of the top sketch). The red component of the emission is now stronger than the violet. On the whole, there is a complete qualitative agreement between what happens and what the model predicts.



The elliptical-ring model is tested with over 30 years of McLaughlin's observations of the *Be* star 105 Tauri, as explained on page 362. Here, filled circles represent observed values of the V/R intensity ratio; triangles, squares, and open circles represent measured radial velocities of the red emission edge (*RE*), central absorption (*CA*), and violet emission edge (*VE*). The curves were calculated by the author assuming that the period is 11.5 years and the ring eccentricity is 0.2. The period seems to have become shorter after 1950. Adapted from the *Astrophysical Journal*.

PROPERTIES OF ELLIPTICAL RINGS

The elliptical-ring model has been put into mathematical form for a quantitative check by the observations. The observational data consist of a curve of the V/R ratio variation with time and of three radial-velocity curves: for the violet emission edge, the central core absorption, and the red emission edge. The details of the calculation (given in *Astrophysical Journal, 183,* 541, 1973) are quite involved, but the result can be easily described.

In general, the V/R variation depends primarily on the eccentricity of the ring;

the width of the ring is also a factor, but unimportant if the width is small compared to the overall radius of the ring. In fact, we know that the ring is narrow from the sharpness of the central absorption as well as from dynamical considerations. Therefore, the eccentricity of the elliptical ring can be determined from the observed V/R variation. In the case of 105 Tauri, a *Be* star in which the period of the V/R variation is 11.5 years, the eccentricity is 0.20, as shown in the diagram at the foot of page 361.

Once the eccentricity has been found, the semimajor axis of the gaseous ring is immediately given by the spreads between the three velocity curves (for the two emission edges and the central absorption core). The predicted velocity curves can then be computed. As the diagram for 105 Tauri shows, the agreement is good, if we consider the fact that both phases and amplitudes are rigidly fixed by the calculation and cannot be adjusted.

The overall success of the quantitative model in interpreting 105 Tauri led Elise Albert and me to study three more *Be* stars: HD 20336 (a 5th-magnitude object in Perseus), 25 Orionis, and Beta[1] Monocerotis. The observations for the first of these had been published by McLaughlin, for the second by Helen Dodson, and for the third by Anne Cowley and Elaine Hendry. In the case of Beta[1] Monocerotis, the plates had been taken by McLaughlin, but were measured and reduced by Mrs. Cowley (who faithfully continues his work), with the aid of Mrs. Hendry. Here are the results for all four stars.

PROPERTIES OF ELLIPTICAL RINGS

Star	*P*	*e*	*a*
105 Tauri	11.5	0.20	3.4
HD 20336	4.5	0.25	3.2
25 Orionis	4.8	0.26	3.9
Beta[1] Mon.	13.2	0.32	3.8

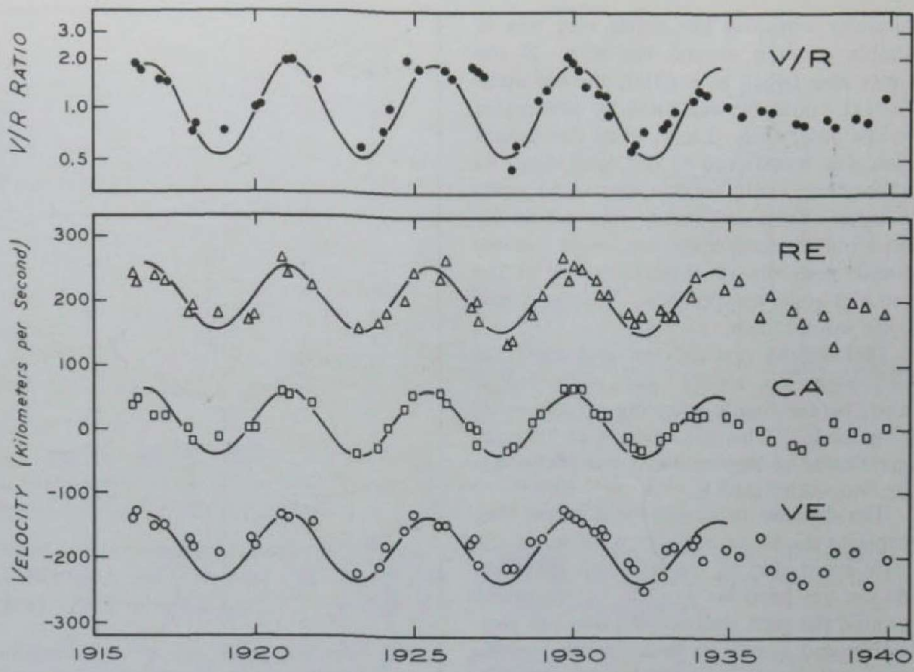
P, orbital period of ring in years; *e*, ring eccentricity; *a*, semimajor axis of ring, in radii of the central star.

In addition, my associate Debbie Brown is now studying Pi Aquarii, which had been observed by McLaughlin and shows a somewhat irregular V/R variation.

FORMATION OF THE RING

Since the angular momentum of an object in Keplerian orbit around a star is proportional to the square root of the orbital radius, ejected matter from the stellar surface does not have enough angular momentum to form a rotating ring that is several stellar radii in size. To form the ring, some extra angular momentum has to be supplied to the ejected matter. What is the mechanism for this?

This problem was extensively studied by Nelson Limber and Michael Marlborough (*Astrophysical Journal, 152,* 181, 1968). They found that ordinary thermal viscosity is too small to transport angular momentum from the rotating star to the ring, and suggested magnetic and turbulent viscosity as the most likely mechanism. Indeed, several astrophysicists have proposed models of rotating rings that depend on magnetic forces.



A comparison of McLaughlin's observations of HD 20336 with the elliptical rotating-ring model: As in the preceding diagram, the radial velocities labeled *RE*, *CA*, and *VE* are for the red emission edge, central absorption, and violet edge of the hydrogen lines. By 1937 the variations had almost ceased. Diagram by Elise Albert and the author.

However, the successful interpretation of V/R variations by the rotating elliptical ring model creates a serious difficulty for the magnetic-energy-transport theory, for an elliptical ring revolving according to Kepler's laws shows clearly that gravitation is the force dominating its motion. Magnetic interaction would probably produce circular or spiral motion, but hardly elliptical. Also, if magnetic transport were important, the star need not rotate rapidly to form a ring; even moderate rotation would suffice. Actually the *Be* phenomenon is always associated with rapid rotation, as we have seen. Consequently, it is unlikely that the stellar magnetic field plays any significant role. Moreover, rings may appear and disappear on a time scale of decades, and this transient behavior would require the stellar magnetic field to appear and disappear on the same time scale.

To escape from these difficulties, I abandon the continuous processes that most theoreticians prefer to assume, because the sudden appearance and disappearance of emission in *Be* stars clearly shows that the process of ring formation is not continuous.

I propose the following scenario for the *Be* phenomenon. Consider the mass ejected from the star's equatorial regions. Its *average* angular momentum per particle is not great enough to form a rotating ring, but there is no reason why *all* the ejected material should go to the ring. Instead, let us envisage a situation in which most of the material either escapes into space or falls back onto the star.

After all, there are a large number of particles in the ejected matter, and we can expect a broad statistical distribution of angular momentum among the different particles. Those with small angular momenta and large kinetic energies escape; those with small angular momenta and small kinetic energies fall back; and only a few with the right amount of angular momentum can orbit the star and form a ring. On this view, the ring is produced without the aid of any special transport mechanism.

Further ejection of matter may modify or destroy an existing ring, or form a new one. Also, a ring may dissipate slowly. The observed lifetimes of the rings support our conjecture that the ejection is not a continuous flow but sporadic, with large quantities of material leaving the star at intervals of years or decades.

Why is matter expelled from the star? If there were no radially outward velocity component, a ring could be formed only by the slow gravitational contraction of a rotating sphere (as in Laplace's old theory of the origin of the solar system). That would take millions of years, and so cannot apply for the *Be* stars. Hence the ejected matter must have a radially outward motion in addition to the tangential motion imparted by rotation. In other words, ring formation is due only partly and not solely to stellar rotation.

To discover what the other factor is, let us examine the percentage of emission

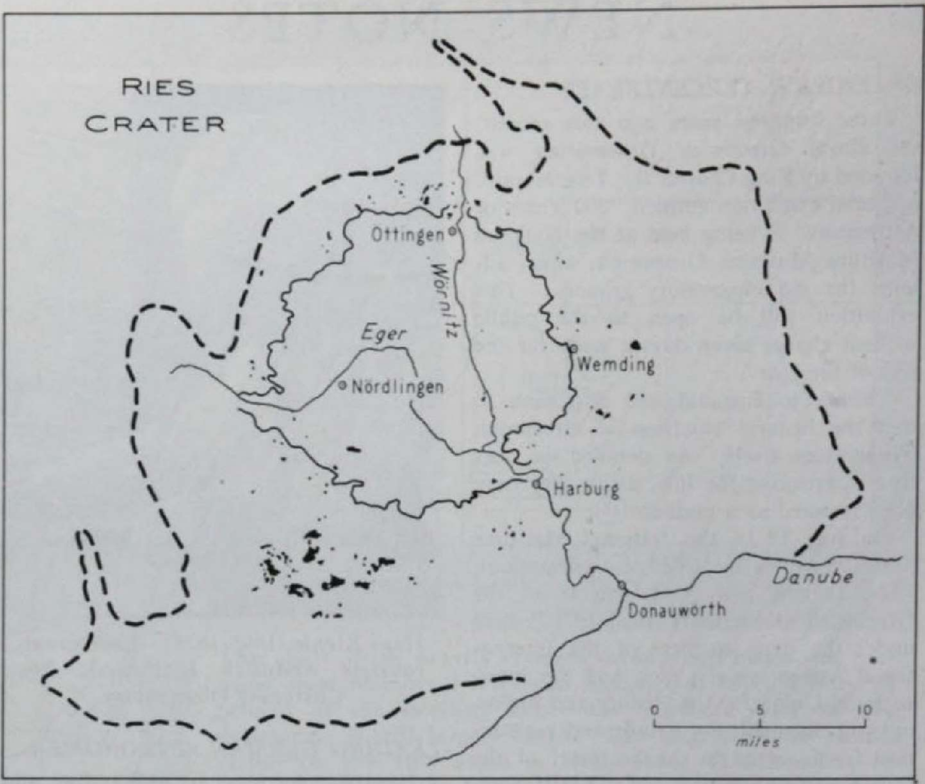
(*Continued on page 367*)

may have been the origin of alemonite and suevite with their high silica content.

The study of meteorite craters is fairly new, attention having been directed to Barringer Crater in Arizona at the beginning of this century. At first, only single craters were discussed. The discovery of the Henbury craters (see page 287 of last month) in 1930 offered the first example of a crater group. By 1955 about 75 craters in 50 localities were known, whereas today the corresponding numbers are about 1,000 and 216.*

That is, emphasis has now shifted from single craters to crater clusters. This change is not solely due to the discoveries in Central Europe, since new groupings have been found in many parts of the world. For example, the crater landscape of Quillagua in Chile consists of at least four clusters containing a total of about 100 individual craters. It can hardly be doubted that crater clusters are the rule and isolated craters the exceptions.

Clearly, impact structures are more common on earth than most astronomers believed a few years ago. During its early history, our planet was probably covered by craters much as the moon, Mercury, Venus, Mars, and the Martian satellites are today. Most of the terrestrial craters have been destroyed by erosion, and the surviving examples often can be established only by modern methods of investigation. As these techniques improve, and especially as understanding grows of the geological and mineralogical effects of impact, there should be a spectacular increase in the number of known meteorite craters.



The thin inner line is the Ries crater rim; the thick outer line is the limit of breccia. Suevite patches are black in W. von Engelhardt's map.

*The author has prepared a manuscript *Catalogue of 216 Terrestrial Meteorite Craters Discovered up to 1974.* Astronomers or geologists requiring a copy should address Sternwarte Pulsnitz, 8514 Pulsnitz, German Democratic Republic.

INTERPRETATION OF THE Be STARS

(*Continued from page 362*)

stars of different spectral type, as given by Slettebak. We note first that few or no *A*-type stars (apart from members of close binaries) have emission rings, even though many rotate rapidly. As we go to hotter and hotter stars, the percentage rises steadily to a maximum at *B*2 and then declines, becoming very small for *O* stars.

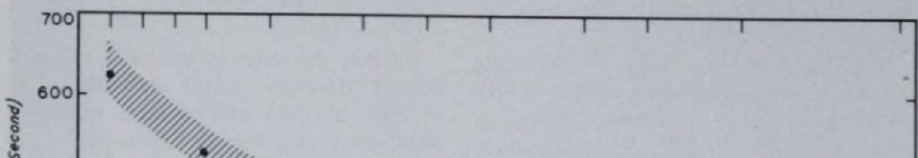
STARS WITH RINGS

Spectrum	*Percent*	*Spectrum*	*Percent*
*A*5-*F*0	0	*B*2	13
*B*9-*A*3	<1	*B*1	10
*B*8	1	*B*0	8
*B*5	5	*O*	few
*B*3	10		

From this behavior, I made the tentative suggestion that the radially outward velocity, let us call it v_2, that assists in ring formation increases with stellar temperature. Thus, in the late *A*-type stars v_2 is small or even zero, perhaps, and rapid rotation alone is insufficient to eject matter. But as v_2 increases, the resultant of it and the rotational velocity v can lift matter above the star's surface to produce a ring. However, when v_2 becomes too large, the resultant exceeds the escape velocity from the star and the ejected matter is lost into space instead of forming a ring. This is the case with the *O* stars.

The cause of this temperature-sensitive radially outward velocity component is very likely the pressure of the star's radiation, as Leon Lucy and Philip Solomon have proposed.

According to this theory of ring formation, it is not necessary for the star to be spinning so rapidly that it is rotationally unstable. And in fact, Slettebak has shown that at each spectral class from *B*0 to *F*5 the maximum observed velocity of stellar rotation is always less than the breakup velocity. This confirms our expectation that something more than rapid rotation is needed to give a star a ring.



This diagram by A. Slettebak shows that even the fastest-rotating *B*, *A*, and *F* stars are not spinning rapidly enough for rotational instability to set in. However, the difference between the two strips is least for the early *B* stars, the very ones in which the occurrence of rings is greatest.