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Review

Classical Be Stars

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ABSTRACT. Recent results for classical Be stars are reviewed and links to general astrophysics are presented. Classical Be stars are B-type stars close to the main sequence that exhibit line emission over the photospheric spectrum. The excess is attributed to a circumstellar gaseous component that is commonly accepted to be in the form of an equatorial disk. Since 1988, when the last such review was published, major progress has been made. The geometry and kinematics of the circumstellar environment can be best explained by a rotationally supported relatively thin disk with very little outflow, consistent with interferometric observations. The presence of short-term periodic variability is restricted to the earlier type Be stars. This variation for at least some of these objects has been shown to be due to nonradial pulsation. For at least one star, evidence for a magnetic field has been observed. The mechanisms responsible for the production and dynamics of the circumstellar gas are still not constrained. Observations of nonradial pulsation beating phenomena connected to outbursts point toward a relevance of pulsation, but this mechanism cannot be generalized. Either the evidence that Be stars do not form a homogeneous group with respect to disk formation is growing or the short-term periodic variability is less important than previously thought. The statistics of Be stars investigated in open clusters of the Milky Way and the Magellanic Clouds has reopened the question of the evolutionary status of Be stars. The central B star is a fast rotator, although theoretical developments have revived the question of how high rotational rates are, so the commonly quoted mean value of about 70%–80% of the critical velocity may just be a lower limit. Be stars are in a unique position to make contributions to several important branches of stellar physics, e.g., asymmetric mass-loss processes, stellar angular momentum distribution evolution, astroseismology, and magnetic field evolution.

1. INTRODUCTION

On 1866 August 23, Padre Angelo Secchi, director of the observatory of the Collegio Romano, wrote a letter to the editor of the Astronomische Nachrichten, reporting "une particularité de l'etoile γ Cassiopée." Instead of Balmer line absorption as in Sirius or Vega, it would have "une ligne lumineuse trés-belle et bien plus brilliante que tout le reste du spectre" (Secchi 1867). This was one of the first emission-line stars detected and the first report of a Be star.

1.1. Astrophysical Context

More than 120 years later, Collins (1987) gave the definition of a Be star as "a non-supergiant B star whose spectrum has, or had at some time, one or more Balmer lines in emission," which is still in use today as working definition (see Jaschek, Slettebak, & Jaschek 1981 for the first definition of this sort). However, it was clear then that this definition encompassed more than one type of B stars with emission lines. Definitions have to be readily applicable, and so any further narrowing of the above definition (which may provide a more physical description) may also involve a significant amount of dedicated analysis to classify a particular star, hence rendering the definition practically inapplicable. More recently, the term "classical" Be stars has become increasingly used to exclude Herbig AeBe stars, Algol systems, etc.

What is the broader astrophysical context of Be stars? First, there is the star itself. Be stars are the class of stars that (on average) rotate closest to their critical limit where the centrifugal force balances gravity. Rotation, however, is the biggest unknown in our current understanding of stellar evolution and especially of hot stars (Maeder & Meynet 2000). Why do Be stars rotate so fast? Langer & Heger (1998) discuss the evolution of surface parameters of rotating massive stars during the main sequence (also see Heger & Langer 2000) and find that the outer layers may spin up as a result of the evolution of the angular momentum distribution. A particularly interesting limit is the so-called Ω limit (or "Ω-Γ limit"; Langer 1998;

TABLE 1
SELECTED SPECTRAL PROPERTIES

Group	Observed General Property								
	1*a*	1*b*	1*c*	2	3	4	5	6	7
Classical Be stars	+	−	−	+/−	−	+	−	−	−
Herbig Ae/Be stars	−	+	−	−	−	−	−	−	−
Algol systems	−	+	−	−	−	−	−	−	+
σ Ori E and similar objects	−	−	+	−	−	+	+	+	−
Slowly pulsating B (SPB) stars	−	−	−	+	−	−	−	−	−
β Cephei stars	−	−	−	−	+	−	−	−	−
Bn stars	−	−	−	−	−	+	−	−	−
Helium abnormal and Bp stars	−	−	−	−	−	−	+	+	−

NOTE.—Selected spectral properties and their observed presence in different classes of non-supergiant B-type stars. Circumstellar line emission formed in (1*a*) equatorial decretion disk, (1*b*) accretion disk, (1*c*) corotating clouds. Other properties include (2) low-order line profile variations, (3) radial and/or *p*-mode (short-period) pulsation, (4) rapid rotation, (5) large-scale magnetic field, (6) surface abundance anomalies, (7) binaries. A plus is not to be regarded as sine qua non, but rather expresses a statistically expected property; similarly, a lacking entry is meant only statistically as well. Low-order LPV is common among early-type Be stars only. Adapted and expanded from Baade, Rivinius, & Štefl 2003 with permission.

Maeder 1999) where the star rotates at its critical speed, defined where the effective gravity (taking rotation and optically thin radiation into account) becomes zero. Whether Be stars rotate *at* the critical limit or not remains unclear (see § 2.2), although it is clear that their high rotation places Be stars in the center of discussions of angular momentum evolution (even during pre–main-sequence phases, e.g., see Stępień 2002), making them one of the most significant test beds for rotationally induced instabilities (e.g., Maeder & Meynet 2000 and references therein).

Aside from their important role in massive-star evolution studies, Be stars offer prospects for astroseismology of the hottest objects examined so far, because of the penetrating nature of *g*-mode pulsations—particularly with multiperiodic Be stars (e.g., μ Cen; see § 3.1). Also, hints exist of magnetic fields in a few Be stars that may prompt new research into field generation mechanisms for hot stars in general.

Study of Be star circumstellar environments has produced several models that are starting to be applied to other hot stars that have (implied) nonspherical circumstellar gas, from planetary nebulae to supernova progenitors (e.g., Ignace, Cassinelli, & Bjorkman 1996, 1998). The triggering of large-scale wind inhomogeneities in hot stars may be related to the process(es) leading to the formation of a Be star disk. For all these research fields, solutions to Be star problems may offer new hints to all (hot) stars, and of course vice versa.

Table 1 summarizes some variants of non-supergiant B-type stars. The Be star definition applies to the first four rows. Algols and Herbigs, however, are not commonly regarded as Be stars in the sense of this paper. Similarly, stars such as σ Ori E are not regarded as Be stars. This is an He-strong star, which also shows emission in magnetically bound clouds (not in a disk). We have kept this star separate from other He-abnormal and Bp stars as this form of circumstellar gas is similar to one proposed for the Be phenomenon.

Be X-ray binaries are not mentioned in Table 1, since it is currently believed that the companion has little influence on the Be star and how the disk is produced, but alters only the outer part of the disk (see § 6.3). The table expresses the current understanding of Be stars in physical terms, for which the designation "classical" Be star will be used in the rest of this work. The table is clearly not exhaustive and is not meant to provide a prescription for classification, although it does give common properties of Be stars

1.2. General Observational Characteristics

Before discussing the detailed features of Be stars, it is useful to describe the observational characteristics of an "average" Be star throughout the electromagnetic spectrum.

The photospheric absorption spectra of Be stars have high measured line widths on average, but are normal in terms of gravity, temperature, and abundance (Slettebak 1982). Emission lines of Be stars are typically double peaked, with the peak separation correlated to the observed line width (Struve 1931; Hanuschik 1996, see also Fig. 1).

In emission-line Be stars, the central reversal between the peaks does not reach below the flux level emerging from the stellar photosphere (i.e., no net absorption, in contrast to shell-line Be stars). The most common lines in emission are those of H I, He I, Fe II, and sometimes also Si II and Mg II. In a given Be star, the strength of the emission can be highly variable. It may disappear completely, only to return decades later.

Shell-line Be stars are characterized by narrow absorption cores in addition to the broad photospheric absorption lines (see *o* Aqr in Fig. 1). Hanuschik (1996) proposed clarification of this definition and denoted a Be star as a shell star when the absorption (or the central reversal) reaches below the stellar undisturbed flux. Shell stars have the highest measured photospheric line widths among Be stars, and their emission peaks,

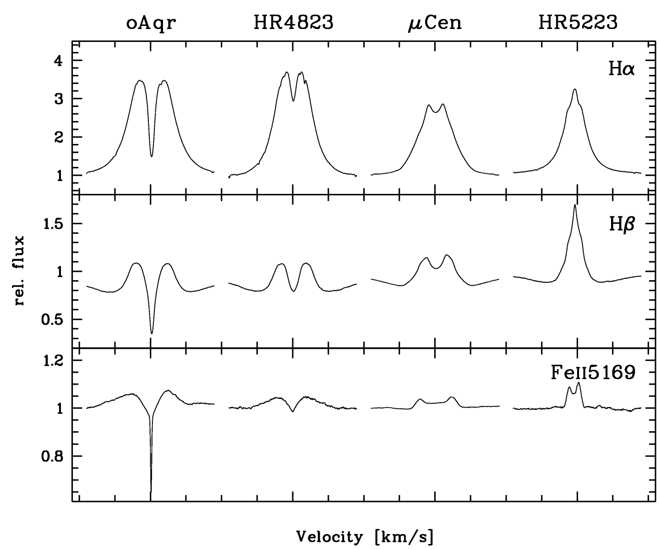

FIG. 1.—Example Be star emission-line profiles, ranging from a shell Be star (*left*) to a single-peak emission Be star (*right*). Along this sequence, photospheric line widths decrease from ≈260 to ≈70 km s^{-1}. The velocity tick marks are spaced by 250 km s^{-1}; larger tick marks indicate the respective zero velocities.

when present, also have the largest separation (Fig. 1). In addition to the ions mentioned above, sharp absorption lines formed by Ti II and Cr II are present, along with other ions one would rather expect in typical BA-supergiant spectra (Jaschek & Jaschek 1987). In the majority of Be stars, both peaks of the emission lines are of equal height. But there is a significant fraction (about $\frac{1}{3}$; see Hanuschik et al. 1996) in which the so-called violet-to-red ratio V/R is cyclically variable with cycle times of years to decades. Be stars may change from stable $V = R$ to V/R variability and back.

In the ultraviolet regime, Be stars in an emission-line phase with line widths larger than about 150–200 km s^{-1} show signs of enhanced wind in the resonance lines of Si IV and C IV compared to normal B stars of the same spectral type (Grady, Bjorkman, & Snow 1987; Grady et al. 1989). At variance, the UV spectra of Be stars in shell phases are dominated by narrow shell lines, similar to the visual domain (Doazan et al. 1991).

The ultraviolet spectral energy distribution of a B emission-line star does not differ significantly from that of a non-Be star, but the Paschen continuum can be brighter than expected. Shell stars, on the other hand, show highly veiled ultraviolet spectra (Doazan et al. 1991), and their Paschen continua are typically dimmer. Depending on the amount of circumstellar matter, the spectra of both types of Be stars become dominated by free-free and free-bound emission from the disk in the near- to mid-infrared region.

In the far-IR, the observed spectral energy distribution index a ($S_\nu \propto \nu^a$) changes from $a = 0.6$ to $a > 1$ in the radio regime, indicating some structural change far away from the central star (Waters et al. 1991; Waters & Marlborough 1994). Some Be stars may also show dust signatures in the far-IR and radio, but this is probably a remnant from earlier phases of stellar evolution and not related to the current Be nature of the star (Miroshnichenko & Bjorkman 2000).

Almost all Be stars emit polarized continuous light (e.g., Wood, Bjorkman, & Bjorkman 1997; Bjorkman 2000b). The amount of polarization, which can be as high as 2%, is variable, and in a given star scales with the emission-line strength, although time lags have been observed in some cases (Poeckert, Bastien, & Landstreet 1979). Polarization strength may vary also with other quantities, such as the V/R ratio (McDavid et al. 2000), while the polarization angles are constant (Wood et al. 1997). Observations of spectral line polarization have mostly yielded null results (Shorlin et al. 2002) placing an upper limit of ~kG on the magnetic field.

Nearby Be stars are prime targets for interferometric studies. The first studies have already shown Be stars to be surrounded by flattened envelopes (Dougherty & Taylor 1992). Shell stars have higher axial ratios than emission-line stars (Quirrenbach et al. 1993, 1994), and the polarization angles are always perpendicular to the major axis of the envelope (Quirrenbach et al. 1997). Most recently, Domiciano de Souza et al. (2003) have presented the first measurement of rotational flattening of a rotating star itself for the Be star Achernar.

Compared to other main-sequence B type stars, the majority of supposedly single Be stars exhibits a qualitatively similar but somewhat higher X-ray luminosity (Cohen, Cassinelli, & Macfarlane 1997; Cohen 2000).

In addition, there are Be stars in binaries with substantial X-ray luminosity. Their main characteristics are strong X-ray brightenings, increasing the flux by a factor of 10 or more, repeating on timescales of weeks to years (Coe 2000).

1.3. Overview of Previous Work

The first viable model was proposed by Struve (1931), who suggested that Be stars were rapid rotators forming an equatorial mass-loss disk. For a detailed discussion of Struve's (1931) initial idea and the following models, we refer to Slettebak (1988) and Underhill & Doazan (1982), who reviewed these historical works of Be star research and observational efforts in detail. More information about the evolution of Be star research can also be found in older conference proceedings, e.g., Slettebak (1976), Jaschek & Groth (1982), and Slettebak & Snow (1987). To reflect the change of relevance of some topics, and also to provide a concise discussion, we restrict ourselves to results obtained since these reviews.

There is now a consensus that a classical Be star is a rapidly rotating B-type star that produces a disk in its equatorial plane. This disk is *not* related to the natal disk the star had during its accretion phases. However, the formation process of the disk seems not to be as straightforward as Struve suggested. Although Be stars do rotate rapidly, it is widely quoted that they do so only at about 70%–80% of their critical limit (unfortunately, this result seems not to be as firm as one would wish; see § 2.2). Thus, a significant part of the research focused on the mechanism producing the disk, in addition to rotation. The wide interest in this "Be phenomenon" is illustrated by the number of meetings since the last review: IAU Colloquium 175 was dedicated to "The Be Phenomenon in Early-type Stars" (Smith, Henrichs, & Fabregat 2000), and there have been numerous other meetings with significant contributions from Be star researchers, such as IAU Symposium 162 "Pulsation, Rotation, and Mass Loss in Early-type Stars" (Balona, Henrichs, & Le Contel 1994), the ESO workshops on rapid variability (Baade 1991) and cyclical variability (Kaper & Fullerton 1998), IAU Colloquium 169 on "Variable and Non-Spherical Stellar Winds in Luminous Hot Stars" (Wolf, Stahl, & Fullerton 1998), and most recently IAU Symposium 215 on "Stellar Rotation" (Maeder & Eenens 2003).

In the past years, an increasing amount of original data, i.e., reduced but not further processed, has been published in machine-readable form. Such data enable researchers to build on previous efforts to a much higher extent than if only the processed results had been published. It must be appreciated that this includes not only data from surveys and space missions, such as *IUE* or *Hipparcos*, but also data that have been obtained by single investigators or research groups without a commitment for publication.

Extended data sets have been published in the *Journal of Astronomical Data* on CD-ROM, while other catalogs are available on-line through the VizieR service. We are confident that this good habit will be fostered and expanded by more such publications in the near future.

In the following, we will summarize the knowledge about the star itself, especially the evolutionary status and the rotational rates of Be stars (§ 2) and the rapid variability of the photospheric and close circumstellar regions (§ 3). Then, the statistical and dynamical properties of the disk are reviewed (§ 4), followed by a discussion of the physical processes currently favored to play a role in the formation and evolution of the disk (§ 5). Finally, the implications of binarity on Be stars and their disks (§ 6) are described before concluding remarks are given (§ 7).

2. THE STAR

The underlying star is a spectral-type B star. While the Be phenomenon can be observed in some late O stars and early A stars, it is mainly confined to the B star range.

Jaschek & Jaschek (1983) identified 12% of all B-type stars as Be stars from the Bright Star Catalogue; subsequent work (Zorec & Briot 1997) has shown that the mean frequency of Be stars is 17%, although this figure is dependent on spectral type (e.g., the frequency may be as high as 34% for B1e stars). Most authors agree that the highest fraction of Be stars appears around spectral type B1e–B2e. Using narrow-band Hα and broadband photometric observations, studies by Grebel, Richtler, & de Boer (1992), Grebel (1997), and Keller, Wood, & Bessell (1999) have been successful in identifying Be stars in several Magellanic Cloud clusters (a technique corroborated by Hummel et al. 1999). These census studies have found a large scatter in the ratio of Be to B stars (from 10% to 34%). Using these fractions, Maeder, Grebel, & Mermilliod (1999) suggest that there may be a higher fraction of Be stars in low-metallicity clusters, possibly pointing to a metallicity influence in determining whether a star becomes (or is) a Be star. However, the current statistics does not allow a firm conclusion to be reached. A well-known problem in all census studies is that Be stars are variable and may lose their disk (and hence emission) completely (see § 4.4) and be classified as normal B-type stars. Therefore, census studies will provide a lower limit to the fraction of Be stars within a sample.

2.1. Evolutionary Status

Their observational definition places Be stars on, or just off, the main sequence. Are Be stars "born," or do they evolve from B to Be stars (i.e., is the ratio of Be to B stars a function of evolution)? Mermilliod (1982) pointed out that the Be fraction was maximum for clusters with main-sequence turn-offs in the range O9–B3 and falls for older clusters. This trend has also been observed in Grebel's (1997) results and has often been seen as evidence for an evolutionary trend of the Be fraction, although it may simply reflect the fact that the relative fraction of Be stars for early spectral types is higher than for later types, and hence may not be an evolutionary trend at all. Fabregat & Torrejón (2000) claim that there is an evolutionary trend and that the Be phenomenon occurs in the latter half of a B star's main-sequence lifetime and is completely absent in clusters younger than 10 Myr. Similar results were presented by Keller, Bessell, & Dacosta (2000) for the Magellanic Clouds. On the other side, Galactic field Be stars are equally present in all luminosity classes (V–III), instead of enhanced in the more evolved ones (Zorec & Briot 1997), providing evidence of no evolutionary trend.

The claim and counterclaim of the detection of an evolutionary effect on the Be star fraction makes a definitive statement somewhat premature at present. This is a topic that clearly needs more work in the future to make progress.

2.2. Rotational Rates of Be Stars

Rotation was identified early in the study of Be stars as an important feature of the central star, and which may be a significant contributor to the generation of the circumstellar medium (e.g., Struve 1931). Photospheric absorption lines display line widths expressed in velocity units of several hundred km s^{-1}. Slettebak (1982) published a large set of line widths along with spectral types for Be stars—an influential study, as it was a relatively large, (and importantly) homogeneous set of observations. These line-width velocity measurements are taken to represent the rotational velocity of the star v multiplied by the sine of the inclination of the pole to the line of sight, or $v \sin i$. We must be careful in this identification, though, as there is not necessarily a linear mapping between the two. It is commonly assumed that the observed photospheric line broadening measured in velocity units (via line-width measurements, Fourier analysis of lines, or spectral synthesis) is the real $v \sin i$ of the star. However, Collins & Truax (1995) illustrate the effects of high rotation on observational derivation of $v \sin i$: they find that stars with rotation values above ~80% of critical speeds are likely to produce underestimates of the true rotation speed of the star (also see Stoeckley 1968). This is partly due to the gravitational darkening caused by rotation. With the equatorial belts less prominent because of this darkening, the largest component in the photospheric line broadening arises from an intermediate latitude, thereby producing a line width *narrower* than that from a uniformly bright stellar disk. Hence, for high rotation, this yields an underestimate of a star's $v \sin i$.

The fundamental distribution of the rotational speeds of Be stars is of great interest as it places constraints on models of disk formation. However, the distribution of rotational velocities is convolved with inclination to the line of sight. This is a well-understood historical problem (e.g., Chandrasekhar & Münch 1950), and several numerical attempts to deconvolve the Be star $v \sin i$ distribution have been made (e.g., Lucy 1974; Balona 1975; Chen & Huang 1987). Porter (1996) adopted a slightly different approach of first dividing all $v \sin i$ values by the critical rotation rate of the star derived from spectral types. Then, by assuming that the Be-shell stars are edge-on Be stars, Porter used their distribution as the intrinsic distribution of all Be stars. The results of all these studies was that Be stars do *not* rotate at their critical rotation rates. Instead, the distribution peaks at values of 70%–80% of the critical rate with a rather small intrinsic width of the distribution. This is an interesting finding: clearly, the mean rotation is high in Be star samples, pointing to it making it an important contribution in the differentiation between normal B and Be stars. The caveat here is that observation of some stars yields rotation rates much lower than this mean value (even accounting for the inclination), making the issue less well determined. On the other hand, the studies above assume that the velocity from the photospheric line widths is an accurate estimator of the $v \sin i$ of the star, which (as described above) may be doubtful for the fastest rotating stars.

As a sample, it seems that the mean rotation rate of Be stars is 70%–80% of the critical value; while there are some examples of slower rotators, many of them may actually be rotating at critical rates. An example is the B3 Ve star α Eri, which has been subject to the very first measurement of an axial ratio of a rapid rotator. The interferometrically determined axial ratio is 1.56 ± 0.05 as a lower limit (Domiciano de Souza et al. 2003), which is just consistent with the maximum value of 1.5 applicable to a rigid body rotating at its critical limit.

3. THE SHORT-TERM VARIATION OF Be STARS

The common definition term of Be stars as objects that "have, or had at one time … Balmer lines in emission" (Collins 1987) already includes an enigmatic feature of Be stars: their variability. Long-term and gradual variations of the circumstellar emission and absorption lines are in fact common to all classical Be stars (see § 4.4). In addition, however, there is also more rapid variability (e.g., Oudmaijer & Drew 1997). The timescales range from minutes to a few days, sometimes present in the same object simultaneously. These timescales, and the spectral lines in which such variations are observed, favor either the photosphere proper or the immediate circumstellar environment as their formation region. Since rotation alone may not be sufficient to produce the disk (Slettebak 1987), the short-term variations became a prime candidate to identify the additional mechanism required for a rapidly rotating B star to become a Be star.

Short-term variations were readily found in most early-type Be stars (e.g., Baade 1982, 1984; Penrod 1986; Porri & Stalio 1988), but similar searches for Be stars later than about B5 were not successful (Baade 1989a, 1989b, and references therein). The latest type Be stars for which significant line profile variability (LPV) is reported are o And (Hill et al. 1989; Sareyan et al. 1998), κ Dra (Hill, Walker, & Yang 1991), and θ CrB (Hubert et al. 1990), all of spectral type B6. The UV wind variability in early-type Be stars is (at least partially) also modulated with the LPV periods (Peters & Gies 2000).

Photometric studies confirm this trend: of the 32 early-type and 18 late-type Be stars Cuypers, Balona, & Marang (1989) and Balona, Cuypers, & Marang (1992) have investigated, 90% of those up to B5 are variable, while only 28% of type B6 and later showed significant short-term variations (see also Stagg 1987).

Short-periodic variations were also found photometrically in the Small Magellanic Cloud (e.g., Balona 1992, for NGC 330). From these, Baade et al. (2002) selected the stars they expected to show the strongest spectroscopic signature, but obtained a null result. If this is confirmed, the paradigm that photometric and spectroscopic short-term periodic variations are two sides of the same coin needs to be reconsidered.

The advent of cross-dispersed echelle spectrographs, providing large wavelength coverage at high resolution and signal-to-noise ratio, boosted the study of short-term variability. Among the most important to name for Be star research are the MuSiCoS campaigns (e.g., Hubert et al. 1997; Neiner et al. 2002), HEROS (e.g., Štefl & Rivinius 2000), and more recently also GIRAFFE (e.g., Balona 2002) and FEROS (e.g., Štefl et al. 2003a).

3.1. Pulsation

Baade (1982) attributed the short-periodic LPV on timescales between 0.5 and 2 days to nonradial pulsation (NRP). However, Balona (1990, 1995) argued on statistical grounds that the periods were better explained by stellar rotation and attributed the LPV to stellar spots, and later to corotating clouds.

In order to resolve this issue, most investigators concentrated on a few well-observed objects. The most important in this list are ω CMa (Balona, Aerts, & Štefl 1999; Maintz et al. 2003), μ Cen (Rivinius et al. 1998b, 2001b; Balona et al. 2001a), ω Ori (Balona et al. 2001b; Neiner et al. 2002), and η Cen (Štefl et al. 1995; Balona 1999; Janot-Pacheco et al. 1999; Levenhagen et al. 2003). All these objects have been investigated by several groups, partly coming to different conclusions.

The proponents of both pulsation and starspot hypotheses above agreed that the detection of *true* photospheric multiperiodicity would decide the issue in favor of NRP (Baade & Balona 1994). However, the emphasis on "true" hints at the problem: while any discretely sampled signal can be explained with multiple frequencies, the actual physical presence of such frequencies in the star is much harder to show (see Aerts 2000 for a review).

Multiperiodicity was found in μ Cen (six photospheric periods; Rivinius et al. 1998b) and recently probably also in η Cen (two photospheric periods; Rivinius, Baade, & Štefl 2003). Comparison of the line-emission outburst times of μ Cen with the beating pattern of the multiperiodicity indicates that the multimode pulsation is playing at least a triggering role in the mass transfer from star to disk, even enabling prediction of such events (Rivinius et al. 1998c; see Fig. 2). This finding may prove to be the "smoking gun" for the disk formation in μ Cen, but most (early-type) Be stars seem not to have such closely spaced mode groups.

Townsend (1997) published a modeling code applicable to NRP in rapidly rotating stars in general, i.e., not only to Be stars, the BRUCE/KYLIE package. This code has become one of the most widely used tool in modeling the appearance of pulsating and/or rotating early-type stars.

With BRUCE/KYLIE, the short-periodic LPV could be modeled with a superior quality to NRP with mode parameters $l = m = +2$ (Fig. 3 for ω CMa, taken from Maintz et al. 2003) in comparison with any other attempt so far. Similarly, (multimode) modeling reproduced the periodic part of the variability of μ Cen in all details (Rivinius et al. 2001b). The derived pulsational modes were again $l = m = +2$ for the longer period group and $l = m = +3$ for the shorter periods.

On the basis of archival HEROS and FEROS data of further Be stars, Rivinius et al. (2003) showed that in at least 80% of early-type Be stars, the periodic LPV can be explained by this pulsation mode ($l = m = +2$), and a few more might pulsate in different modes. Support for NRP also comes from other wavelength ranges: Smith (2001), investigating archival *IUE* data, finds the UV spectrophotometric variability of six stars indicative for pulsation, eight stars do not allow for clear conclusions, and only three stars behave as though they possess circumstellar clouds.

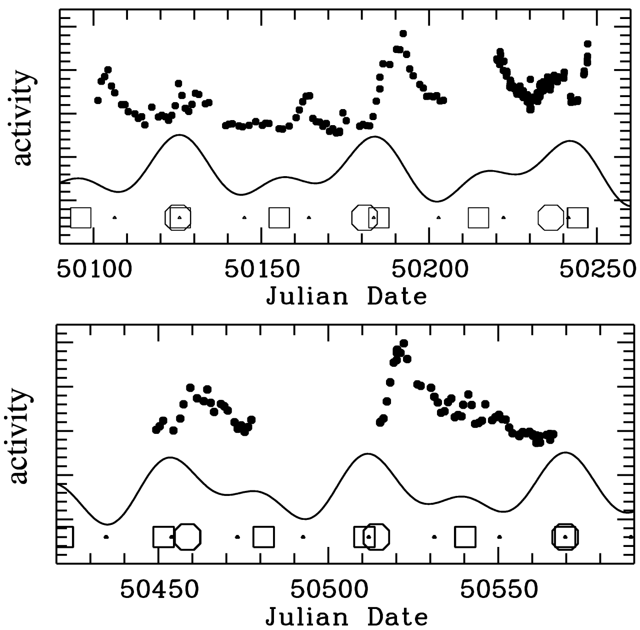

FIG. 2.—Circumstellar activity (*points*) of μ Cen (taken from Hδ absorption wing strength in 1996 [*upper panel*] and 1997 [*lower panel*]) compared to the combined amplitude of the multiperiodicity (*solid line*). The symbols mark times when two strong modes have phase difference zero (from Rivinius et al. 1998c, reproduced with permission).

3.2. Rotational Modulation

Rotational modulation was first proposed to be due to ordinary starspots, i.e., regions of lower temperature than the surrounding photosphere. In order to explain the spectroscopic variability, however, one would have to assume starspots too large and cool to be consistent with the observed photometric amplitudes (Balona 1995).

Therefore, later hypotheses favored rotational modulation arising from the circumstellar environment. The easiest way to maintain such rotational modulation is provided by an oblique magnetic field. At first, this appears attractive in that angular momentum is supplied to the expelled material—a criterion that appears to be required from the observations (see § 4.3)—but numerical simulations of such a situation do not produce a structure capable of accounting for the observations (§ 5.3).

Although LPV periods in general seem not to be rotational (see above), there are exceptions: Sareyan et al. (2002) give arguments in favor of a rotational modulation in o And, and in fact this is one of the stars for which an $l = m = +2$ pulsational mode is not applicable (Rivinius et al. 2003). ζ Tau may fall as well into this category (Balona & Kaye 1999; Smith 2001).

Neiner et al. (2002) attribute the main LPV period of ω Ori (1.03 days) to NRP. In addition, however, a sinusoidal variation of the longitudinal magnetic field component was observed by

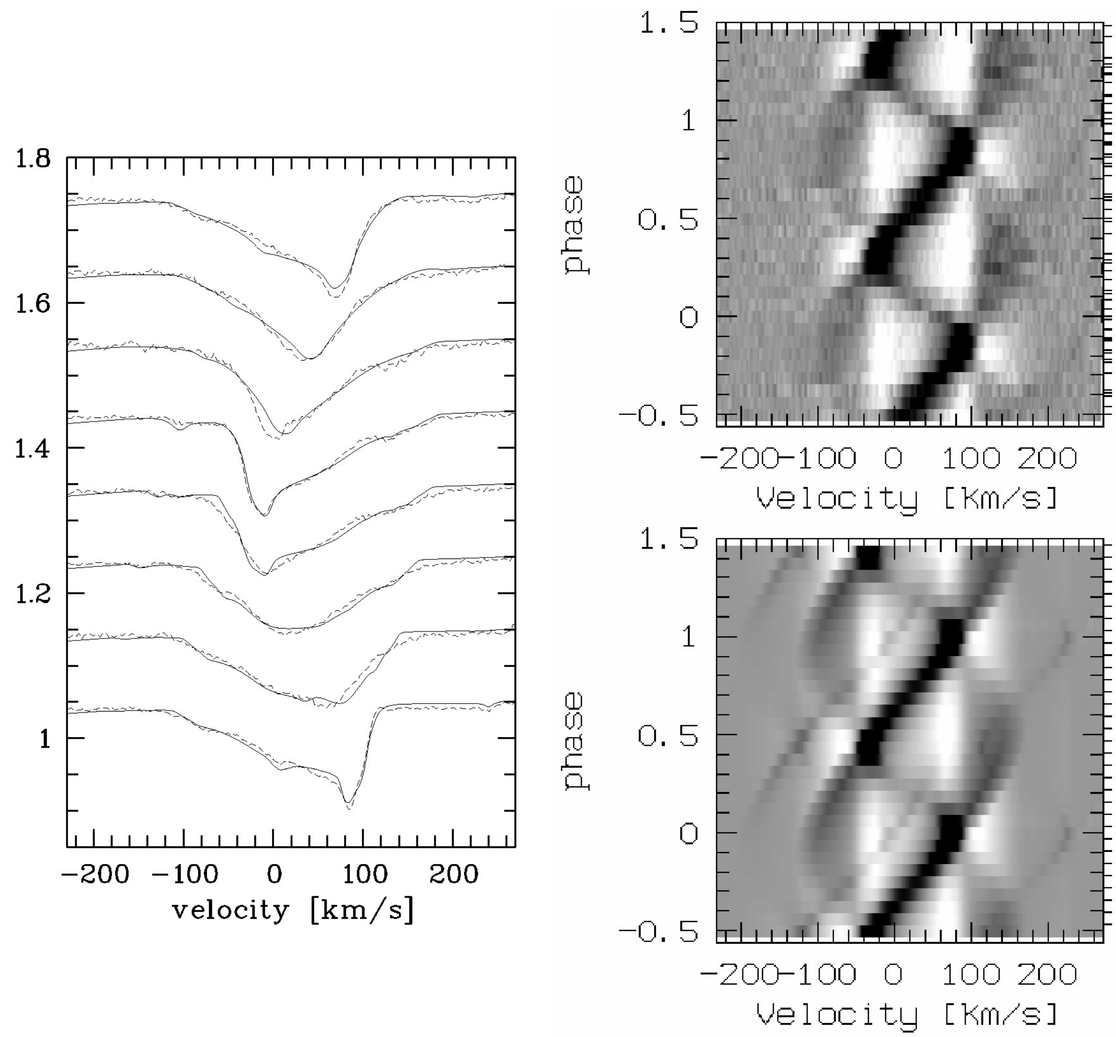

FIG. 3.—Observed short-term periodic line profile variability of Mg II 4481 of ω CMa, modeled as NRP in the absolute profiles (*left*) and residual gray-scale representation (*right*, with the top panel as the data and the lower panel as the model) (from Maintz et al. 2003, reproduced with permission).

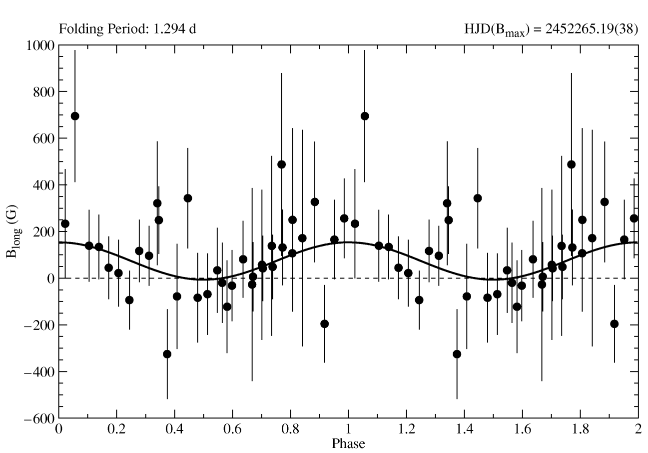

FIG. 4.—Magnetic field of ω Ori as measured by Neiner et al. (2003), reproduced with permission.

Neiner et al. (2003) with a period of ≈1.29 days (see Fig. 4). Assuming an oblique dipole, they derive a polar field strength of 530 ± 200 G. This is likely to become the first detection of a magnetic field in a classical Be star, but at the time of writing the efforts for independent confirmation were ongoing (A. M. Hubert 2003, private communication).

Searches for magnetic fields in other Be stars have so far returned null results (most recently Shorlin et al. 2002), but in general the detection limit is still higher than the field strengths actually required for some models of magnetically induced disk formation.

3.3. Transient Features and X-Ray Flares

On even shorter timescales, transient features are observable in some stars. Peters (1986) describes a blueshifted absorption feature forming in less than 10 minutes, and Penrod (1986) reports such features for a number of stars, with a typical life-

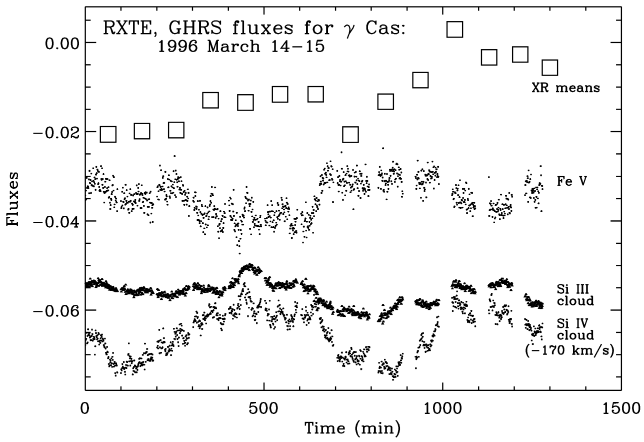

FIG. 5.—X-ray (orbit bins) and UV flux (Fe V λ1413, Si III λ1417, and Si IV λ1403) in γ Cas, leading to the picture of a disk dynamo and magnetic flaring (see § 3.3; figure from Smith 2000, reproduced with permission).

time of an hour. Apparently, such absorptions are seen only when the star-to-disk mass transfer is active (Rivinius et al. 1998a).

Within the limits of the stellar photospheric line width, Smith (1989) found various kinds of line transients in λ Eri and later also in other objects (Smith et al. 1996), including γ Cas. Although not as widespread as periodic LPV, such transients are present in quite a few Be stars, again mostly early-type ones. Multiwavelength campaigns on λ Eri (X-ray, UV, and optical; Smith et al. 1997) and γ Cas (X-ray and UV; Smith, Robinson, & Corbet 1998 and later papers of that series) led to the picture of magnetic flaring. For γ Cas, Robinson, Smith, & Henry (2002) propose a magnetic field threading from the star through the disk: the combination of an azimuthal field and a dense disk sets up a magnetic dynamo in the disk that in turn produces cyclic flux changes (Fig. 5). In this scenario, the differential rotation between star and disk causes magnetic stresses that may eject high-velocity plasmoids (similar to coronal mass ejections), some of which impact on the stellar surface and may account for the hard X-ray flares.

4. DISK PROPERTIES

4.1. Geometrical Distribution

While it has been accepted for many years that Be stars have circumstellar gas, its geometry and kinematics have remained a hotly contested subject. Recently, a consensus has been emerging about the geometric distribution of the gas. It has long been suspected that the circumstellar gas is in the form of a disk (Struve 1931). Polarization studies (e.g., McLean & Brown 1978) have indicated that the circumstellar gas is not spherically symmetric.

A major step forward was made in 1992 with the first interferometric observations of a Be star by Dougherty & Taylor (1992). This radio study of ψ Per using the VLA confirmed that the geometry of the emitting circumstellar region was not spherically symmetric: ψ Per's radio emission has an axial ratio of less than 2. More recently, optical interferometry has begun to produce results for Be stars, particularly from the (several) groups at Mount Wilson and Observatoire de la Côte d'Azur. The results from these groups have confirmed the aspherical geometry of the circumstellar emission (Quirrenbach et al. 1994, 1997; Stee 1995; and see Fig. 6). Indeed, for those stars that have had the position angle of the disk measured, it lies normally to the continuum polarization angle (Quirrenbach et al. 1997), as expected for scattering models (e.g., Brown & McLean 1977; Wood et al. 1996a, 1996b). Also, the available axial ratio determinations of the envelopes agree well with the inclination estimates from the emission shape.

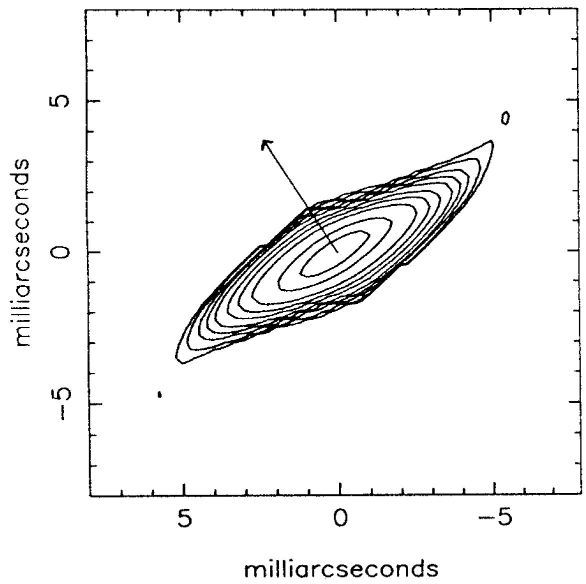

FIG. 6.—Reconstructed Hα intensity map of ζ Tauri, showing the high axial ratio of the circumstellar environment of this shell star. The polarization angle (denoted by the arrow) is perpendicular to the plane of the disk (from Quirrenbach et al. 1993, reproduced with permission).

Several attempts have been made at determining the opening angle of the disk directly from the data: values of 5° and 13° from the statistical studies of Be-shell stars were determined by Porter (1996) and Hanuschik (1996), respectively, and an upper limit of 20° was determined from interferometric observations and spectropolarimetry by Quirrenbach et al. (1997), while Wood et al. (1997) calculate an opening angle of 2°.5 for ζ Tauri from polarization (this technique is sensitive to the inner regions only, which, if the disk flares, may account for the apparent inconsistency with the statistical studies that probe larger disk radii). Hanuschik also finds that the disk flares at large radii; i.e., the opening angle is an increasing function of radius. Yudin (2001) concludes from his statistical analysis that the half-opening angles lie in the range 10°–40°.

In summary, interferometric studies have confirmed that the geometry of the circumstellar gas is disklike and that statistical estimates of opening angles point to a relatively thin disk. The polarization angle is perpendicular to the outer disk plane, which also strongly suggests a disk structure in the inner parts (since these densest regions affect the polarization most), and the observed variation properties are modeled best with a homologous structure from the near-photospheric regions outward (Rivinius et al. 2001a).

4.2. Density and Temperature Structure

The IR continuum excesses of Be stars are interpreted as free-free and free-bound emission of the disk (Gehrz, Hackwell, & Jones 1974). The emission has been used to constrain some global properties of the disk: both empirical and theoretically derived models find a power-law parameterization of the disk density field $\rho \propto r^{-n}$ (Waters 1986; Okazaki 2001), with some models also allowing the density to fall off exponentially with height above the equatorial plane (e.g., Marlborough 1969; Poeckert & Marlborough 1978). These models attempt to model the *steady* disk: models of disks forming and dissipating (see § 4.4.3) are rare and have not been fully explored.

Model fits to IR data (especially those from *IRAS*; Waters 1986) yield values of the index n to be typically $2 < n < 4$, although the exact value depends on the geometrical model for the disk (e.g., flaring or slab disks). Power-law density profiles are also implemented in line-profile studies of the disk kinematics, which also find values of n in this range (see below). Radio continuum observations (e.g., Dougherty, Taylor, & Waters 1991) probe the outer parts of the disk and derive higher values of the power-law index, $n \geq 4$, perhaps indicative of flaring disks, truncation, or cooling at large radii (Taylor et al. 1987).

The temperature structure is difficult to determine from the IR continuum excesses (e.g., Waters 1986). Examination of disk heating and cooling within a pure hydrogen disk by Millar & Marlborough (1998, 1999) of two popular models (the disk model of Waters 1986 and the Poeckert & Marlborough 1978 model) indicates that the midplane disk temperature is approximately constant with radius. Extra line cooling will be present for more complex compositions including metals, which may enable the temperature to decrease with radius.

4.3. Kinematics

The kinematics of the circumstellar gas has received much attention. Doppler shifts within the disk may reveal the velocity structure of the disk via the line profile. Line profiles may be either single peaked or double peaked and may be asymmetric (e.g., see the atlas by Hanuschik et al. 1996), although the most common profile is double peaked and symmetric across the line center (see Fig. 1). An asymmetry may reverse in time such that the violet and red parts of the line may be dominant at different times (termed *V/R* variation). This variety of profiles and behaviors makes the line profiles difficult to interpret, and it is remarkable that good fits to observations have been obtained for around 25 years using relatively simple models (e.g., Poeckert & Marlborough 1978; Hummel 1994; Hummel & Vrancken 2000, to name a few). In order to model a line profile, both the kinematics and the surface emission (or density profile) of the disk are required. Many studies have assumed the disk kinematics and have determined disk density parameters from best-fit models of the observations. Choice of kinematics has ranged from a Keplerian disk with little or no outflow $(v_r, v_\theta, v_\phi) = (\sim 0, \sim 0, v_{\phi,0}/q^{1/2})$, where $v_{\phi,0}$ is the inner-disk rotation speed and q is the distance to the rotational axis (the radius in cylindrical coordinates; see e.g., Hanuschik 1995), to an angular momentum–conserving dense-wind structure with a β radial velocity law $(v_r, v_\theta, v_\phi) = (v_{r,0}[1 - R_*/r]^\beta, \sim 0, v_{\phi,0}/q)$, where $v_{r,0}$ is the inner-disk velocity and R_* is the stellar radius (see, e.g., Poeckert & Marlborough 1978).

Unambiguous observational determination of the kinematics is difficult. Using a rotational velocity of $v_\phi \propto R^{-j}$, Hummel & Vrancken (2000) illustrate that it is possible (for optically thin lines) to produce indistinguishable line profiles using either a Keplerian disk or an angular momentum–conserving disk by using different density structures for the disk. For nonnegligible optical depths, the degeneracy is broken, and they find that their best-fitting models have an average rotational parameter $j < 0.65$, which is consistent with a Keplerian disk, although not definite proof.

Line profiles from "edge-on" Be shell stars are excellent diagnostics of radial outflow. These lines involve absorption of the photospheric flux throughout the whole disk, and hence provide information on the radial velocity structure. Observations of central quasi-emission peaks in shell lines were analyzed by Rivinius et al. (1999) and contrasted with theoretical profiles of Hanuschik (1995). Curiously, these features are not derived from emission but may be explained by absorption processes within a Keplerian disk with no detectable radial flow. Indeed, significant radial motions within the disk would produce (time-independent) asymmetric lines with larger red components than blue (i.e., $V > R$) and blue absorption that increasingly resembles classical P Cygni profiles for higher radial velocities (Waters & Marlborough 1992). As these profiles are not observed, the radial velocity is observationally constrained to upper limits. Examination of Doppler shifts in optically thin shell lines of Fe II provide no evidence for radial motions within the disk (Hanuschik 2000).

All of the kinematic evidence seems to point to a disk velocity field dominated by rotation, with little or no radial flow, at least in the regions where the kinematic signatures of emission and absorption are significant (i.e., within a few stellar radii).

4.4. Global Disk Variations

4.4.1. Cyclic V/R Changes

For the typical double-peaked emission lines, the heights of the blue- and redshifted peaks are designated as V and R, respectively. Long-term cyclic changes in the ratio V/R are observed in many stars, taking from a few years up to decades to complete the cycle (see list in Okazaki 1997).

Many observers have published *V*/*R* values over the past decades, but one should be aware that the definitions applied may differ somewhat, depending on whether or not the underlying continuum has been subtracted before calculating the ratio and which line was observed. The morphology of such cycles has been described by, e.g., Hanuschik et al. (1995), using high-resolution data. They found the emission-line behavior to be consistent with a one-armed density wave in the disk, precessing around the central star (see below). Telting et al. (1994), using observations by Cowley & Gugula (1973), concluded the direction of precession to be prograde, i.e., in the sense of rotation. This has been confirmed by interferometric measurements of ζ Tau, where the photocenter of the Hα emission is seen to move around the central star (Vakili et al. 1998). Similar observations were published by Berio et al. (1999) for γ Cas.

McDavid et al. (2000), modeling polarimetric data, required a spiral structure, rather than a plainly radial "arm," to explain phase lags in 48 Lib between Hα observations (scanning the outer parts of the disk) and polarimetric measurements (affected most by the dense inner parts of the disk). Early observations of phase lags between the *V*/*R* cycles of individual lines of up to several months (see references in Baade 1985) also imply some spiral structure of the density wave in at least some stars.

Theoretical explanations for these *V*/*R* variations have concentrated on one-armed density waves (i.e., $m = 1$ modes, with m equal to the azimuthal wavenumber). These are the only global modes in a near-Keplerian disk (suggested by Kato 1983 and applied to Be stars by Okazaki 1991). In Okazaki's model, the $m = 1$ mode arises as the velocity distribution within the disk deviates slightly from Keplerian, which generates pressure perturbations and produces slightly elliptical orbits. However, the model produced infinite oscillation periods. Papaloizou, Savonije, & Henrichs (1992) expanded the model and illustrated that the elliptic particle orbits precess under the action of a gravitational field containing a quadrupole component that is created by the rotating star itself (which was not included in Okazaki's model). A recent alternative to producing precession of elliptical orbits, described by Gayley, Ignace, & Owocki (2001), uses the radiative force of optically thick lines within the disk (Okazaki 1997 included the effects of optically thin line radiation to the model). Where the elliptic orbits crowd, a density enhancement appears. The precession of the whole pattern then occurs, with the pattern speed producing a period of a few to 10 years for typical B star parameters. When the dense part is on the approaching side of the disk, the *V* peak will be higher, while *R* is enhanced when the periastron passes the receding side.

Radiative transfer modeling of one-armed density waves (e.g., Hummel & Hanuschik 1997) reproduces the *V*/*R* variation seen in the line profiles, showing that the kinematic structure of one-armed oscillations is consistent with observation.

For these one-armed density waves to build up to observational magnitudes, it is clear that the disk gas must orbit the star several times. Therefore, it imposes a strict criterion on the velocity field within the disk: the rotational velocity must be *much* larger than any radial outflow (consistent with other results; see § 4.3).

4.4.2. Transitions between Emission Line and Shell Appearance

Since emission-line and shell Be stars are explained by inclination differences, transitions between both flavors are hardly expected. Also, the constancy of the measured polarization angles propose a constant disk angle. Mild changes might be understood as due to varying radii (Hanuschik 1996) of a flaring disk, but in a few cases extraordinary variations were seen. These so-called spectacular variations were observed in γ Cas (e.g., Merrill & Wilson 1941), Pleione (e.g., Gulliver 1977; Cramer et al. 1995), and 59 Cyg (e.g., Barker 1982). How might these variations be caused? Hummel (1998) proposed that they are explained by misaligned stellar equatorial and disk orbital planes. The intersecting node line then would precess around the star, so that the disk is seen edge-on in front of the star at times but more face-on during other observations. Hummel (1998) could not explain how this misalignment would develop, although Porter (1998) proposed that radiative warping of Be disks may be a possible mechanism. It should also be noted that both 59 Cyg and γ Cas were confirmed as binaries only recently (Rivinius & Štefl 2000; Harmanec et al. 2000) (which is, however, not required to induce warping, as spiral galaxies' disks show).

4.4.3. Be and Normal B Star Phases

The strongest variability of the circumstellar environment of Be stars is the complete loss of the disk and its eventual rebuilding (Fig. 7).

When a Be star is building up line emission, the Paschen continuum will brighten by up to 0.5 mag in *V*, while at the same time $B-V$ becomes redder and $U-B$ becomes bluer. In shell stars, however, the Paschen continuum dims by $\Delta V =$ 0.3 mag compared to normal B stars, while both $B-V$ and $U-B$ redden (Harmanec 1983). This behavior can be understood as a consequence of scattering in the disk (Poeckert & Marlborough 1978).

θ CrB showed a strong shell spectrum before 1980, but lost the shell signature in summer 1980, turning into a normal B star in the visual domain. Ultraviolet shell lines disappeared until late 1981, and enhanced ultraviolet wind lines finally vanished in early 1982. After that, only transiently enhanced wind lines were seen from time to time (Doazan et al. 1984, 1986a, 1986b, 1987). Similar observations of o And (Gulliver, Bolton, & Poeckert 1980) and ν Pup (Rivinius et al. 1999) show a very narrow absorption core in Hα becoming weaker and finally disappearing. Following the arguments of Hanuschik (1995), such narrow shell lines originate far away from the central star, and so the observations may indicate that the disk is slowly dissipated outward and does not reaccrete onto the stellar surface.

From this, one could infer that the enhanced wind seen in

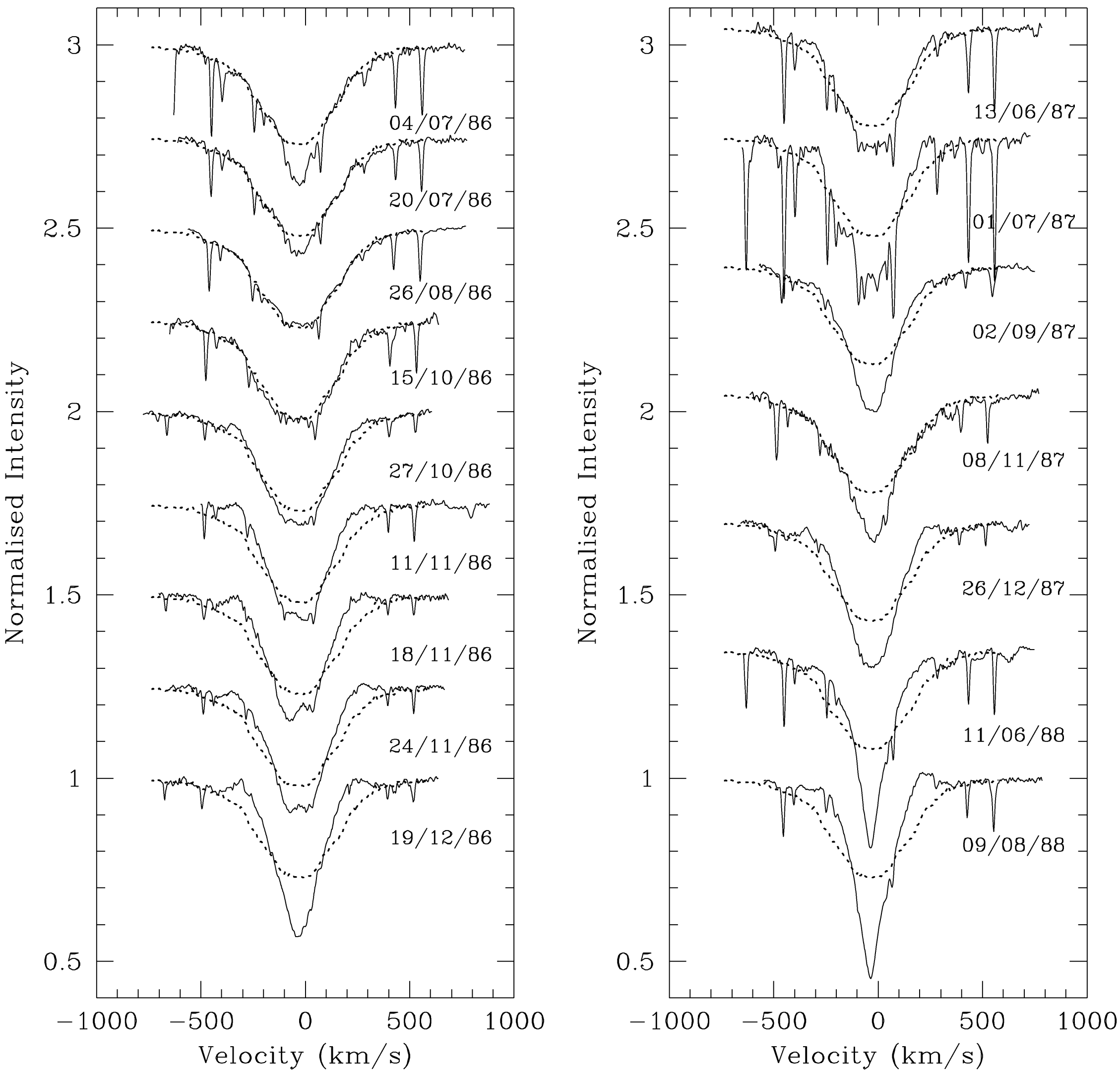

FIG. 7.—Disk loss and rebuild phase as observed in *o* And (from Clark et al. 2003, reproduced with permission).

many Be stars originates in the disk (Rivinius et al. 2001a), a process that may be achieved by ablating gas from the disk surface via radiation driving (Gayley, Owocki, & Cranmer 1999). Telting & Kaper (1994) came to this conclusion from the appearance of strong discrete absorption components (DACs) in the wind of γ Cas. These DACs are seen only at certain phases of the *V*/*R* cycle, when the dense part of the global wave is on the approaching side of the disk.

o And has meanwhile repeated several cycles of absent, weak, and strong disk (Fig. 7; Peters 1988; Clark, Tarasov, & Panko 2003, and references therein), and θ CrB has also restarted some circumstellar activity after 20 years of quiescence.

An alternative to dissipating the disk through radiation-driven ablation is to entrain the disk gas in the fast wind through Kelvin-Helmholtz instabilities in the shear layer between disk and wind (Bjorkman 2000a). However, both ablation and entrainment are continuous processes, so if they are acting then the disk needs to be constantly replenished while the star remains in the Be phase.

5. DISK FORMATION MECHANISMS

Whatever the dominant mechanism is for ejecting gas from the photosphere, it must generate a region in the star's equatorial plane dense enough to account for the continuum and line observations, and it appears from kinematics to have to be able to supply angular momentum to the disk.

5.1. Gas Ejection Close to the Star

There are several suggested candidates to eject gas from the photosphere. An obvious choice is a radiatively driven wind: hot stars ($T_{\rm eff} > 10^4$ K) can sustain a flow driven by line absorption and scattering of stellar photons (e.g., Castor, Abbott, & Klein 1975). These winds accelerate the gas through the

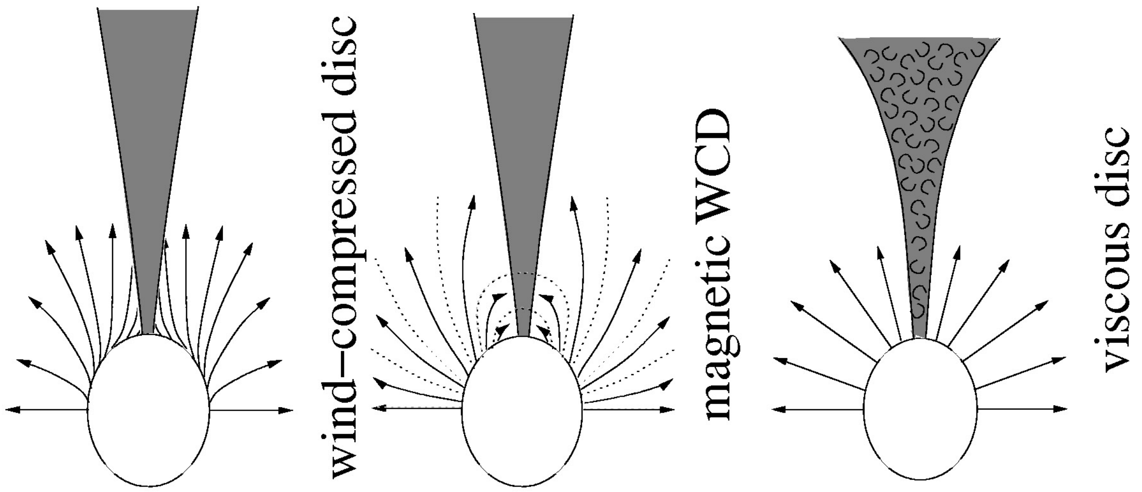

FIG. 8.—Wind streamlines and disk formation for three disk models (see § 5). The wind-compressed disk (WCD) requires only high rotation plus a wind; the wind streamlines are partly channeled along the magnetic field in the magnetic WCD to produce a disk; the viscous disk is turbulent, and the wind is not a significant part of the generation of the disk.

sonic point close to the star and achieve terminal velocities of ~1000 km s^{-1} and mass-loss rates of 10^{-8} to 10^{-10} $M_{\odot}$ yr^{-1} (Snow 1981, 1982; Grady et al. 1987).

Another way to eject gas is via photospheric pulsation (e.g., see convincing evidence for a disk-pulsation link in Rivinius et al. 1998c, 2001b, and Fig. 2). As the stellar photosphere oscillates, lower effective gravities are encountered. While it is very unlikely that pulsations will have amplitudes large enough to simply "throw" material into space, they may lower the gravity enough for the radiation-driving parameters to change sufficiently to produce a locally enhanced mass loss (in a similar way to that producing corotating interaction regions for hot stars; see Cranmer & Owocki 1996). Pulsations may induce turbulent motions at the photosphere and lead to angular momentum deposition in these regions (e.g., Osaki 1986) producing super-Keplerian speeds in the photospheric regions that will lift gas off the star. Subphotospheric processes may produce outbursts of material (e.g., Kroll 1995; Kroll & Hanuschik 1997), and magnetically driven mass loss has also been proposed (Underhill 1987, and the series of papers by Smith et al. 1994, 1997, etc.).

5.2. Wind-Compressed Disks

In the familiar case of spherically symmetric flow for nonrotating OB star line-driven winds, once a stream of gas is expelled by the photosphere, it is acted upon by gravity and radiation and flows along radial streamlines. Bjorkman & Cassinelli (1993) introduced a model in which the rotation of the (radiation-driven) wind produced flow toward the equator. The wind streamline stays in its orbital plane: if rotation were large enough, the streamline would cross the equatorial plane. Complimentary streamlines from opposing hemispheres would intercept each other at the equatorial plane and would result in the formation of a shock. This shock produces a dense (post-shock) region representing the disk that is confined to the equatorial plane by the oppositely directed ram pressure of the wind from both hemispheres (see Fig. 8). This is the wind-compressed disk (WCD) model. Initial numerical work (Owocki, Cranmer, & Blondin 1994) largely confirmed this paradigm. A disk was generated with density contrasts (equatorial-to-polar density ratio) increasing from a few to ~100, depending on the stellar rotation velocity. The azimuthal velocity was close to angular momentum conserving ($v_{\phi} \propto 1/R$), while the radial velocity was found to have a stagnation point at a few stellar radii with reaccretion of the disk close to the star (with inflow velocities of 10 to hundreds of km s^{-1}), while the outer regions accelerate to terminal velocities of a few hundred km s^{-1}.

Later, Cranmer & Owocki (1995) examined the nonradial components of the line-driving force that arises as the force is directed toward the largest *velocity gradient*, which in a rotating wind is not simply radial. Inclusion of the nonradial line-driving force reduces the effect of wind compression to zero, and when gravity darkening is also taken into account, then polar enhanced winds result (Owocki, Cranmer, & Gayley 1996; Petrenz & Puls 2000), which is exactly the opposite of the original WCD predictions! Indeed, the nonradial line forces also may spin down the wind by 30%–40%, making disk formation less likely (Gayley & Owocki 2000). While ruled out from dynamical arguments, wind-compressed disks also fail, as they cannot reproduce the observed IR excess (Porter 1997) and do not produce a kinematic structure that agrees with observations.

5.3. Magnetically Compressed Disks

Recently, the spirit of the WCD model has been revived with the addition of magnetic fields. While the envelopes of B stars do not contain convective cells large enough to generate a significant magnetic field via dynamo action, it may be possible to do so near the boundaries of their convective cores (Cassinelli & MacGregor 2000; Charbonneau & MacGregor 2001). Buoyancy of the magnetic flux tubes forces them to the surface of the star. It is also possible that a remnant primordial field may be present (Moss 1989) as the magnetic decay time is similar to the stars' main-sequence lifetimes. The magnetic field strengths that are required to significantly affect the wind flow are on the order of hundreds of gauss for B star winds. Unfortunately, this is close to (but below) the typical threshold of observation using Zeeman splitting of lines (e.g., Borra & Landstreet 1980; Mathys 1998), hence the scarcity of measured fields (measurements using the sensitive Hanle effect, e.g., Ignace, Nordsieck, & Cassinelli 1997, would aid in this aspect). Recent detections of magnetic fields in hot stars with strengths large enough to be dynamically important (Henrichs et al. 2000; Donati et al. 2001) have questioned the traditional assumption of zero magnetic fields.

Cassinelli et al. (2002) calculate the effect of a dipolar stellar magnetic field on the wind flow. Crudely, for regions where the magnetic energy dominates over the kinetic energy density (sub-Alfvenic velocities), the flow streamlines follow the magnetic field lines. For the closed magnetic loops near the equator, this forces the gas to flow toward the equatorial plane from both hemispheres, and the resultant shocked region makes up the disk (see Fig. 8). This magnetically confined disk model is similar to the one developed by Babel & Montmerle (1997a, 1997b) for Ap stars (and applied to θ^1 Ori C). For sub-Alfvenic speeds, the magnetic field also adds angular momentum to the wind, forcing the flow into essentially solid-body rotation. For higher wind velocities, the rotational velocity drops off as in a simple angular momentum conserving disk, predicting nonmonotonic rotational velocity of the disk. A similar "toy" model to this was shown to produce sufficient IR continuum excess to account for the observations (Porter 1997), although the resultant line profiles have yet to be determined (Cassinelli et al. 2002 calculated Hα equivalent widths).

Ud Doula & Owocki (2002) have performed numerical magnetohydrodynamic simulations of wind flow with dipolar magnetic fields that illustrate features of a magnetic WCD (MWCD). Nonrotating models appear to confirm the expectations of the earlier semianalytical models, although producing significant time-dependent behavior with stagnation of radial flow and reaccretion of the inner parts of the disk. However, simulations including stellar rotation (Owocki & ud Doula 2003), which should be directly relevant to Be stars, do not produce the sort of magnetically torqued disk capable of explaining the observations, casting considerable doubt that MWCD is the solution to Be star disks.

5.4. Viscous Disks

An alternative to compression disks are viscous disks (Lee, Osaki, & Saio 1991; Okazaki 2001; Porter 1999). The dynamics of these disks operate in a similar fashion to accretion disks (e.g., Pringle 1981), except that gas and angular momentum are added to the inner regions and then are diffused outward under the action of turbulent (presumably) magnetohydrodynamic viscosity. In its simplest form, the equatorial regions of the stellar atmosphere are spun up to slightly super-Keplerian rotation speeds, for example, by pulsation. If this gas is continually supplied with angular momentum, then it will be lifted from the stellar surface and continue to move farther away from the star. Hence, a disk may be built up with rotational speeds very close to Keplerian and subsonic radial velocities.

Using the "alpha" prescription for viscosity (Shakura & Sunyaev 1973), Okazaki (2001) considered the structure of time-independent, isothermal viscous disks. He showed that the rotation velocities were indeed close to Keplerian, and radial velocities increase linearly with radius (Mach numbers of the radial flow at the inner edge are 10^{-3} to 10^{-5}, depending on the model parameters). Beyond the radius where the radial Mach number becomes significant (at ~hundreds of R_*), gas is advected outward faster than it may transfer angular momentum, and so the outer parts of the disk become angular momentum conserving ($v_\phi \propto 1/R$).

The disk density decreases as a power law in radius $\rho \propto R^{-3.5}$ and is also assumed to be in hydrostatic equilibrium perpendicular to the equatorial plane (hence density decreases exponentially with height). The scale height ("thickness") of the disk increases with radius as $H \propto R^{3/2}$, so the disk flares (apparently in accordance with observational results from Hanuschik 1996). The gross properties of these viscous disk suit excellently the observational requirements (see § 4, explanation of *V/R* variability, central quasi-emission peaks, no strong outflow, disk flaring, etc.). However, the density decreases too rapidly with radius to account for the IR excess and the line profiles for most stars; observational derivations of the power-law index are commonly lower than the predicted $n = 3.5$ although its range is $2 < n < 4$, so some stars are consistent with the model (see also Porter 1999). When the assumption of isothermality is relaxed, the resultant density structures flatten somewhat (i.e., n decreases) and are then able to reproduce the observed continuum emission (Porter 2003).

The simplest model of the viscous disk spins up the equatorial regions of the star to super-Keplerian velocities. Therefore, a vital component of this model is the critical rotation of the star, which is difficult to confirm observationally (see § 2.2). The largest unknown in the model is *how* to supply the angular momentum to the disk (see the discussion of Owocki 2003). Pulsation is one mechanism (see § 3.1). Another mechanism is to eject gas through "explosive" events. Kroll & Hanuschik (1997) described smooth particle hydrodynamical simulations where gas bursts in all directions (in to 2π sr) away from the photosphere. As some of the gas is thrown in the direction of the stellar rotation, that gas effectively gains some angular momentum and may orbit the star, while the part of the gas thrown retrograde to the rotation falls back to the star almost immediately. These simulations are instructive in that they show that a symmetrical ejection can lead to some gas attaining enough angular momentum to orbit the star; i.e., it is not essential in this scenario for any directionality in the outburst. For all its apparent successes in describing Be star observations, the viscous disk model still lacks a good description of the vital angular momentum input.

6. Be STARS IN BINARIES

Kříž & Harmanec (1975) proposed that Be stars were mass-transferring binaries with undetected companions. The infrared data obtained since then, however, do not support the presence of cool giants around Be stars, and the identification of some Be stars as post–mass-transfer systems (see § 6.3) also excludes ongoing mass transfer as general explanation.

Still, binarity is an important aspect of Be stars because (1) in confirmed Be binaries, such as Be X-ray binaries, the companions impose additional constraints on model parameters and can be used as probes; (2) the tidal forces may help the stellar matter to leave the Be star and form a disk; and (3) a companion might have *had* an influence on the Be star as a result of previous mass transfer, i.e., spinning it up.

It should be kept in mind that the current census of Be star binaries does not significantly exceed $\frac{1}{3}$, typical also for non-Be stars. Despite individual cases, this does not support a general relevance of binarity for Be stars.

6.1. Wide Systems

For a number of Be star binaries, either they are optically resolved or the companion is a close binary itself, so a radial velocity curve is observed, which does not reflect the motion of the Be star. In such systems, the distance between the Be star and the known companions safely excludes any interaction.

Examples are *o* And (Hill et al. 1988) and 66 Oph (Štefl et al. 2003b). In both, the non-Be companions are slow rotators with measured rotational velocities of up to a few tens of km s^{-1} only. This might be an interesting constraint for explaining the initial angular momentum distribution of such stars, but unless further companions are found, these systems do not support an understanding of the Be phenomenon as a consequence of binarity.

6.2. Closer Systems

This can be different for closer systems. Assuming circular orbits, we use the term "closer systems" for orbital periods of about a year and less. But for the current purpose, a system such as δ Sco may count as a "close system" too, since the high eccentricity leads to nonnegligible tidal interaction around periastron even though the orbital period is more than 10 yr.

δ Sco was reported as a Be star by Coté & van Kerkwijk (1993), observed shortly after the periastron in the early 1990s. During the following periastron in 2000, the amateur astronomer S. Otero, performing unaided eye photometry, recorded a sudden brightening. Subsequent spectroscopy showed δ Sco to be in a fully developed Be emission-line phase (Fabregat, Reig, & Otero 2000). However, a mass *transfer* during periastron is unlikely on the grounds of the determined parameters (Miroshnichenko et al. 2001).

Harmanec et al. (2002) have suggested that, because of the reduced gravity along the connecting line of the binary components, the rotation can become supercritical locally, so material lifts off from the Be star into the disk through this "rotationally modified Lagrangian point." However, this requires the star to rotate at 99% of its critical rotation in the corotating frame (corresponding to almost 100% in the inertial frame). In fact, such a model is very similar to the suggestion by Struve (1931): at such high rotational rates, a Be star disk may form without a companion (Owocki 2003).

6.3. Be Stars with Compact Companions

6.3.1. Be X-Ray Binaries

It is possible that Be stars exist in binaries that harbor white dwarfs, neutron stars, or black holes. However, only systems with neutron stars have been unambiguously confirmed observationally. Beside the low quiescent flux (which is still higher than other Be stars), the X-ray emission of such binaries can be transiently enhanced by a factor of 10 and more. These enhancements are attributed to either periastron passages of the compact companion (Type I outbursts) or changes in the disk's outer boundary conditions possibly producing disk warping (at any phase, Type II outbursts; see, e.g., Negueruela et al. 2001).

Corbet (1984) found the orbital period to correlate well with the spin period of the neutron star and expanded this to a diagnostic distinguishing Be X-ray binaries from other types of high-mass X-ray binaries (Coe 2000).

The Be star is hardly affected in such a system: while the disks' radii have an effective upper size, probably determined by the binary parameters (Reig, Fabregat, & Coe 1997; Zamanov et al. 2001), they are otherwise not significantly different from single Be star disks. Using the viscous disk model, Negueruela & Okazaki (2001) discuss how the disk is truncated and how Type I and II outbursts may be generated (Okazaki & Negueruela 2001). Smoothed-particle hydrodynamic simulations have recently confirmed the disk truncation process (Okazaki et al. 2002)

6.3.2. Post–Mass-Transfer Systems

Another scenario for B stars to become Be stars, suggested by Pols et al. (1991), proposes the rapid rotation of Be stars as consequence of binary evolution spin-up, and hence Be stars would have evolved companions. Because of their unobtrusive appearance, such companions are hard to detect, leaving sufficient leeway for undetected companions. The detection is easier in the equator-on case because of periodic shell phases caused by the companion's radiation heating the outer disk, for example in ϕ Per (Gies et al. 1998 and references therein).

Berger & Gies (2001) found a somewhat higher fraction of runaway Be stars than runaway normal B stars, concluding that the binary fraction in the progenitor population must have been higher as well. Gies (2000) argues that if the Be phenomenon were unrelated to binarity, Be+B and even Be+Be systems should be generated, but no such binaries are known in the period range of up to 10 yr, and at least in the wider systems an inhibition of disk formation is not expected. But this lack of observed Be+Be and Be+B stars might be simply a natural outcome of incomplete sampling.

7. CONCLUSIONS

The years since the last review by Slettebak (1988) have seen significant progress in our understanding of Be stars. One facet expressed at that time has became clear again: although detailed investigations of individual objects are absolutely necessary for progress, Be stars do not form a sufficiently homogeneous class to generalize findings from such detailed studies. The reverse, unfortunately, is equally important for Be stars: a single deviant case is not sufficient to disprove a hypothesis in general.

7.1. The Disk

Interferometric observations have literally broken the dam toward physical understanding of the circumstellar environment. The geometry of Be star circumstellar environments is now generally accepted to be disklike. For the very innermost regions, this has not yet been confirmed observationally (although polarimetry provides excellent evidence), but for the outer regions the asphericity has been resolved interferometrically. The disk appears to be most consistent with (close to) Keplerian rotation and only minor outflow in the line-forming regions.

The standard WCD model has failed to produce a disk that can account for the observations, and early simulations of magnetically induced wind compression models look likely to fail also. Crucially, the star does not need to rotate at its critical velocity to produce these MWCDs (and so may explain relatively slowly rotating Be stars), although the disk variability (both global loss and regeneration and *V/R* cycles) are difficult to account for by such models. Viscous disks appear to have the correct observational characteristics (especially for cooling disks), and line *V/R* variability seems to be generated in these disks naturally. However, the physics behind the angular momentum input is still obscure: without it, the model is still in search of an origin.

7.2. Clues toward the Be Phenomenon

Extended-range high-resolution spectroscopy has answered many questions, although it has asked as many new ones. Low-order profile variability, identified with nonradial pulsation, is present in most, i.e., in about 80%–90%, of the earliest type Be stars, but this fraction drops beyond B2 to almost zero around B6. Although fewer, a significant number of Be stars show transient variability indicative for magnetic flaring, but again this is less common for the later type objects. Only a few Be stars have rotationally modulated variability. If and how all these variations are related to the mass loss leading to disk formation is unknown. The absence of any such variability in late-type Be stars possibly points to a different mass-loss mechanism for them, or that the variability is only a minor ingredient for the Be phenomenon and is not as important as thought previously.

7.3. Open Questions

Despite the progress, many questions remain. The following list is only a subjective selection, but we feel them to be the most promising ones to answer, and the ones that probably would have largest impact also on other fields of stellar astrophysics.

Evolutionary status.—Whether or not the Be star frequency rises toward the end of the main sequence lifetime is still not answered unambiguously.

Stellar rotation.—Statistically, it is clear that Be stars rotate rapidly, with a canonical value of 70%–80%. On one hand, this value might in fact be a lower limit only (for the statistical peak), but on the other hand are there Be stars rotating significantly slower; and if so, how many? What fraction of Be stars has been spun-up from moderate rotation by binary evolution?

Presence and origin of magnetic fields.—Although the spectroscopic line profile variability is possibly not connected to magnetism, this does not exclude the presence of magnetic fields in Be stars. ω Ori is likely to have a magnetic field, with a period differing from the LPV period by about 30%. Are such fields fossil or self-generated?

Mass and angular momentum transfer.—Of the many processes proposed, some seem present in a significant fraction of Be stars—e.g., nonradial pulsation appears in many early-type Be stars—but are likely to be energetically insufficient to produce the disk by themselves. Others such as magnetic fields are observed only exceptionally, and their existence has not yet been put on a firm theoretical basis. However, if the rotational rates do have to be revised toward critical rotation, this would alter the picture significantly. The identification of the mass-transfer process has the potential to invigorate many new interesting investigations (as did the wind-compressed disk hypothesis).

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