THE CONTINUING SAGA OF THE Be STARS: A SUMMARY

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1. INTRODUCTION

This paper, written in summary of IAU Symposium 98 on the Be Stars, contains an outline of the proceedings, organized according to physical parameters of the stars, the circumstellar environment, models explaining the data, and a summary of the outstanding problems. Suggested future observations and needed theoretical work are described.

At the end of a very full week, the participants in IAU Symposium 98 had heard some 70 contributed papers and 7 invited review talks. All of the observed phenomena and a substantial variety of theoretical interpretations were thoroughly discussed, and in the process, many important points of agreement and of controversy were emphasized.

A few important themes appeared repeatedly throughout the week. One was that the Be stars, whatever they are, must not be studied in a vacuum, without consideration at the same time of their astronomical relatives, including especially the Oe stars and the A shell stars, but also other classes of objects, such as O stars with stellar winds and mass-exchange binaries, all of which may have important lessons to teach us about the Be stars.

Another very important theme of the Symposium was that we all must use caution in the interpretation of data; the Be star phenomena are quite complex, and care must be taken not to confuse the issue further by failure to fully recognize observational uncertainties. Vorsicht!

While the Symposium was organized primarily by observing technique, this summary will follow a different course in reviewing the proceedings. Hindsight permits the information to be rearranged according to scientific aims, presenting a more cohesive and coherent

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view. Perhaps the outline of this summary could be taken as a suggested agenda for the next symposium on Be stars.

The review is organized as follows: it begins with a brief overview of the nomenclature and catalogs, followed by sections on properties of the stars; characteristics of the circumstellar envelopes; the evidence for winds, coronae, and mass loss; the astounding variety of information on time variability; models of the Be phenomenon; a discussion of related objects; a summary of the major remaining questions about Be stars; and, finally, an outline of important future research.

The author apologizes in advance for any omission or oversight; it was a very full Symposium, the subject is complex, and the time and space for writing this review are short.

2. NOMENCLATURE AND CATALOGUES

Some discussion took place on the question of what we mean by the term "Be star", and by other words used in describing related phenomena. While it proved difficult to agree on what a Be star is, a general consensus was reached that it is not an OB emission-line supergiant; nor a pre-main sequence Ae or Be star (the so-called Herbig Ae and Be stars); nor a B[e] star, a peculiar Be star associate with nebulosity. At the same time, it was agreed that the Oe and A shell stars probably represent straightforward extensions of the Be phenomena to higher and lower temperatures, and should be included.

Several associated terms, such as "shell star", "extreme Be star", "pole-on", and others were discussed, and it was agreed that even though we may not clearly understand the phenomena to which these terms refer, we should at least agree on what we mean by them.

Substantial discussion on bibliographic organization led to the adoption of an outline proposed by Koubsky, which will be followed by Jaschek in the future in listing papers on Be stars in the Be Star Newsletter. This outline will also be published in the Newsletter.

Active efforts on both the cataloging of Be stars and surveys for new emission-line objects were described. Egret and Jaschek have completed a new general catalog of some 1100 Be stars, which will be available from the Stellar Data Center, and Ducati described a catalog of the emission-line strengths that he has compiled. Survey work for faint new Be stars was discussed by MacConnell and Cardon.

3. PROPERTIES OF THE STARS

Whatever causes the Be phenomenon, it must have something to do, at a very fundamental level, with the stars themselves. The circumstellar envelopes must some how arise from the stars, and it is appropriate that we begin by compiling our information on them. Quite possibly more time could have been devoted to this very important topic.

On the subject of spectral classification, Slettebak in his review outlined the general distribution of spectral types, and in later contributions, Egret and Jaschek, Hubert-Delplace, and others discussed statistical properties of the Be stars as a function of spectral type. An important question came up regarding the effect of rotation on classification, with Slettebak suggesting that high values of v sin i can result in assignment of a star to a later class, by as much as 2 or 3 subclasses. It is evident that spectral classification of Be stars can be very complicated, due not only to rotation, but also to the presence of optically thick circumstellar envelopes, which can completely hide the underlying star, as reported by Plavec et al. and others.

The fundamental properties of the stars, such as luminosities, masses, radii, and effective temperatures, were not discussed extensively, except for a number of papers on flux distributions, such as the reviews by Mendoza and Houziaux, and contributions by Divan et al.; by Zorec and co-workers; and by Plavec et al.; and reports on luminosity indicators by Kozok and Zeuge. A particularly important problem was stressed in the reviews by both Marlborough and Poeckert, who pointed out that recent far-ultraviolet data indicate serious errors in the assumed extreme ultraviolet flux distributions of early-type stars. This is significant because models of circumstellar envelope radiative transfer have had to rely on predicted stellar Lyman continuum fluxes, and these now appear to be in error.

Equatorial darkening due to rapid rotation, an idea whose possible importance was brought to the fore at the time of the previous IAU Symposium on Be Stars (in 1975), has now begun to receive the attention it deserves. If sufficiently complete and accurate models of line profiles as a function of rotation and stellar inclination angle can be developed, we will have in our hands the ability to untangle the confusion between projection and true rotation effects that pervades all Be star observations to date. Papers presented by Marlborough (review), by Ruusalepp, and by Sonneborn showed that progress is being made, although simplifying assumptions of the models leave us short of our ultimate goal.

The subject of pulsational instabilities in Be stars was an exciting new ingredient brought forth at the Symposium. While it has been recognized for some time that many of the Be stars lie near the

β Cephei instability region in the H-R diagram, pulsations have not generally been considered as a contributing cause for the Be phenomenon. Papers presented by Baade and by Bolton, in which probable β-Cephei type pulsations in Be stars were reported, force us to consider this possibility seriously. As Prof. Kippenhahn noted in a comment, in a rapidly rotating star, there is a wide range of atmospheric conditions from pole to equator, and it is likely that in some regions in some Be stars, the instabilities associated with stellar pulsations may be encountered.

The evolutionary status of the stars was not widely discussed. The review by Slettebak, and reports by Mermilliod and Endal stressed that the Be stars are on or very near the main sequence, and the latter author discussed the effects of rotation on stellar structure, but clearly this is an area that needs further work.

4. CIRCUMSTELLAR ENVELOPES

The presence and nature of circumstellar envelopes is, of course, the principal characterisitic of Be stars and by far the greatest number of reports at the Symposium had to do with the observational properties of the envelopes. Here again great caution must be exercised, because of the unknown geometry of the circumstellar material, and because of the difficulty in separating effects due to the envelope from those due to the star.

Confusion with stellar emission has the greatest impact on observations of the flux distributions of circumstellar envelopes, because it can be exceedingly difficult to ascertain the intrinsic continuum flux distribution of the underlying star. Things are complicated even more by the problem of determining the interstellar extinction for a star that may have intrinsic reddening due to Paschen continuum emission or an infrared excess.

Despite these difficulties, some clear results were shown. Several authors, including Mendoza and Houziaux in their review papers, referred to the effects of flux redistribution by the circumstellar envelopes, which tend to produce ultraviolet deficiencies (an effect illustrated statistically by Zorec et al.) and infrared excesses through electron scattering processes. The Paschen and Balmer continua and discontinuities were discussed by Divan and co-workers, whose BCD spectrophotometric index was shown to be a good means of distinguishing between the stellar and the circumstellar Balmer jumps; and by Chkhikvadze, who discussed the different properties of the Paschen continuum in Be and shell stars.

The most obvious manifestation of the presence of circumstellar envelopes is to be found in spectroscopic data, which reveal the emission and absorption lines that qualify stars as members in the Be

or shell-star class. The majority of papers in the Symposium dealt with spectroscopic observations of the envelopes, either of emission lines, shell absorption features, or both. Andrillat and Fehrenbach presented illustrations of the fine H_α emission-line profiles obtained electronically at Haute Province, and showed the importance of using high spectral resolution, revealing the presence in several cases of heretofore undetected narrow absorption components. Barker presented results from his own extensive program of Be-star spectroscopy, and Andrillat et al. showed rather conclusively that the Oe stars are similar spectroscopically to the Be stars.

In addition to these survey projects, a large number of analyses of individual stars were presented, too numerous to be mentioned here in any detail. A note of caution was raised, particularly in comments by Doazan, about the danger of analyzing or comparing data obtained at different times.

One of the major themes of the Symposium was the question of non-spherical symmetry of the circumstellar envelopes. Several papers were presented, some based on samplings of numbers of stars, and others based on detailed analyses of individual objects, all supporting or at least consistent with the classical conclusions that line and continuum emission from the envelope are both enhanced in stars seen at low polar inclinations to the line of sight, while shell absorption is enhanced in stars seen nearly equator-on. Coyne, in his review of polarization, and Poeckert, in his subsequent summation of models for Be stars, showed how polarization measurements also mandate an equatorial concentration of the circumstellar material.

New forms of evidence were presented, from all parts of the electromagnetic spectrum, for dense, relatively cool disks around Be stars. The arguments for this include infrared data, shown by Persi et al. to be consistant with an expanding disk; by Rappaport, who in his review of X-ray emission from binary companions of Be stars showed that the X-ray fluxes in some cases are best explained by assuming the presence of a thick equatorial disk with low expansion velocity; and by Poeckert, who illustrated very successful models in which Be stars have disks sufficiently dense and cool to contain neutral gas. Further evidence supporting this picture emerged from the contrasting mass-loss rates reported from infrared data by Persi et al. and from ultraviolet line profile analysis by Snow, which can only be reconciled if the observed regions are entirely distinct from each other, one being a high-density, low-velocity region, and the other being a low-density, very hot, rapidly-expanding zone.

Metz, in contrast, argued that polarization could arise by scattering the non-spherically symmetric flux distribution from a rapidly-rotating star through a spherically symmetric shell; and Doazan,

Stalio, and Thomas presented arguments in support of a spherically symmetric geometry to account for all the observed phenomena.

5. WINDS, CORONAE, AND MASS LOSS

At the last Symposium, six years before this one, the first direct evidence for the general existence of mass loss from Be stars was just becoming available, (even though the idea, and lots of indirect evidence for it, has a much longer history). At this meeting mass loss was treated as an established phenomenon, and the discussions centered more on its nature, its relationship to the stationary material in the circumstellar envelopes, and the rates of mass loss.

Marlborough reviewed the ultraviolet spectroscopic evidence for winds, Snow showed that nearly all Be stars in his survey of nearly 20 have ultraviolet wind indicators, and several authors, notably Peters, Paterson-Beeckmans, and Hirata, added reports on winds in individual stars.

The important question of whether non-thermal heating is present was discussed in the review of Marlborough and in contributions by Doazan et al., by Henrichs, and by Peters, all of whom showed that many Be star winds are characterized by highly-ionized species, such as CIV and NV, which cannot be produced in radiative equilibrium with the stellar photospheres. Unfortunately, no information was available on the presence or absence of soft X-ray emission from Be stars, a universal indicator of coronal gas in the winds from O stars and B supergiants.

The mass-loss rates were summarized by Snow, who added values derived from nearly 20 stars observed in the ultraviolet. His results, the survey of lower limits on mass-loss rates by Franco et al., and the values reported for individual stars by Hirata and by de Freitas Pacheco, all were in strong contrast with the rates inferred from infrared excess emission by Persi et al., a discrepancy that probably can be explained by concluding that the ultraviolet absorption and infrared emission form in different locations.

6. TIME VARIABILITY

Awareness of time variability in Be stars no doubt reached an all-time record level during this Symposium. Most authors of observational papers were quick to point out either the presence or the possibility of variations, and if they did not, almost invariably someone in the audience rectified the omission.

A great amount of effort has gone into establishing the frequency of occurrence and the timescale of variability. This is difficult

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business, especially in cases where historical data from the literature are used. Because of uncertainties in the data and the incompleteness of the time coverage, it is often possible to find variations or periods of variation that may not actually be well-founded.

Photometric variability was summarized in a statistical sense in the review of Mendoza and the papers by Jerzykiewicz, Ponomareva, Feinstein, and others. Studies of individual stars, either photometrically or spectroscopically, were reported by numerous authors. It is especially useful to combine, where possible, photometric and spectroscopic data in attempting to interpret variations, and this was done by Hubert-Delplace, Ballereau, and Doazan and co-workers, as well as by Daminelli Neto and de Freitas Pacheco.

The question of timescales, and especially of periodicity, is an important one. Changes over characteristic times of decades, often in the form of extended emission-line episodes, were well documented, and in many cases these appear to represent some sort of cyclical behavior. True periodicity has been found in a number of Be stars, many of which are binaries. Harmanec reviewed the subject of binary phenomena in Be stars, Peters added results on a number of systems, and Bossi, Koubsky, and Galkina each reported on binary behavior in individual cases. The best-established examples are those that are well-observed over several orbital cycles by a consistent and uniform technique, but Pastori et al. were able to find evidence for long-period orbital motions in a few cases, using historical literature data.

A fascinating new interpretation of periodicity was offered by Baade and by Bolton, each of whom reported on stars whose periodic behavior can best be explained in terms of non-radial pulsations, with the surface wave travelling around the star in the direction opposite of rotation. These reports opened the possibility of an entirely new class of theories regarding the origin of the Be phenomenon.

In very many cases, however, the observed variations undoubtedly reflect changes in the circumstellar envelope that are quite distinct from orbital or pulsational behavior. Often spectroscopic changes are accompanied by photometric variations, and the relationship of the two was discussed by numerous authors, including Dachs and Hirata, who in separate papers commented on the general relationship; Hubert-Delplace, who with different co-authors has studied variation episodes in a few stars; and by Hirata, who has also analyzed in detail the changes in the circumstellar envelopes of a few individual stars. Variations in polarization have also been found, as summarized by Coyne, and Poeckert in his review showed that these may be precursors of the onset of new shell episodes, and hence should be watched for more closely.

It has become clear that the rates of mass loss also vary, and Doazan et al. and Henrichs reported on short-term fluctuations in high-velocity winds. Stellar wind variations can also be inferred from observations of changes in infrared excess fluxes, as reported by Persi et al. and from variations in X-ray emission from mass-accreting secondary stars, as noted in the review of Rappaport. Guarnieri et al. reported one case where an optical change in a Be star was followed in 8 days by an X-ray flare-up in its compact secondary companion; perhaps the time delay represents the wind flow time from the Be star to the orbital radius of the secondary.

7. MODELS

The question of interpreting all the assorted data on Be stars, to develop a physical picture, is obviously very complex. The problems are enhanced by the unknown inclination angles and by the time variability, which together make it very difficult to isolate general properties (if any exist!) of the Be phenomenon.

There are two distinct questions one can ask: (1) what physical picture can account for the observed properties of Be stars; and (2) what is the underlying cause of the Be phenomenon? The reviews of Coyne and Poeckert both illustrated a general class of interpretations of polarization data, in which a disk structure is invoked to provide the asymmetry needed to explaining the observed polarization. Poeckert further described a physical picture in which the disk may contain the neutral gas responsible for both Balmer emission and shell absorption lines, although the location of the highly-ionized material that produces the ultraviolet spectroscopic wind indicators remains unknown.

The presence of distinct velocity components in the highly-ionized species, with the simultaneous existence of low-velocity Balmer emission and shell lines, was interpreted by Doazan, Stalio, and Thomas as being due to a spherically symmetric envelope with acceleration in a coronal zone near the star and a deceleration zone well away from the star, where a high-density "balloon" builds up until it disperses, accounting for the well-observed shell episodes in some Be stars. Barker pointed out the potential influence of magnetic fields on mass outflow from rotating stars, illustrating that fields much too small to detect can have important effects, which depend strongly on the wind velocity law.

On the question of the underlying cause of the Be phenomenon, Harmanec in his review described three alternatives: rotation, expansion (stellar wind), and mass exchange in binary systems; and the papers of Baade and of Bolton suggested a fourth: pulsational instability. None of these has been developed into a comprehensive model, although it is clear that at least some Be stars are binaries,

with mass exchange in some cases. Individual systems were described by Harmanec, Peters, Molaro et al., Selvelli et al., and Plavec et al. On the other hand, the case for non-radial pulsations in some objects seems well-established, it is clear that most or all Be stars have winds, and it was demonstrated by Endal that rapid rotation may lead naturally to the formation of a circumstellar envelope. Perhaps elements of all four hypotheses are correct under different circumstances, or perhaps other, as yet unidentified, factors are responsible for Be stars.

8. RELATED OBJECTS

Several classes of objects not included in the standard definition of Be stars were discussed. These included the peculiar Be stars (designated B[e], with forbidden FeII emission lines) described by Swings; the so-called Herbig Ae and Be stars, pre-main sequence emission-line objects discussed by Finkenzellar and by Baschek et al.; the famous binary β Lyrae, whose properties were described by Mendoza and by Bahyl; and extreme B supergiant emission-line stars, such as the clone of P Cygni discussed by Stahl et al. and the variable supergiant described by Wolf et al.

Other objects not classified as Be stars may be more closely related than those just mentioned. The Oe and A shell stars have already been discussed, as probably extensions of the Be phenomenon to hotter and cooler spectral types. It was stressed by Henrichs and by Snow that the Be stars must also bear some relationship to O stars in general, because of the similarities of their stellar winds. The Be star winds seem to represent an extrapolation of the winds of O stars to objects of lower luminosity.

9. SUMMARY OF PROBLEMS

A number of particularly important general problems emerged from the discussions at this Symposium. Underlying all of them is the basic question of the cause of the Be phenomenon, a question still entirely without a satisfactory answer. The list of possible mechanisms grew to four during the Symposium, with the addition of pulsational instabilities to the older ideas of rotation, expansion, and binary mass exchange, and there is no completely-developed theory showing how any of them can account for all the properties of the stars.

The question of the evolutionary status of the stars is intimately related to the origin of the Be characteristics, and probably has not received the attention it deserves.

Time variability is an unavoidable complication, that probably should be viewed more as a fundamental property, one that is closely linked to the basis of the phenomenon. If the cause of the variations were understood, quite possibly so would the cause of the Be phenomenon itself.

A more specific problem is presented by the geometry of the circumstellar environment, and this became a general theme of the Symposium. Be stars show a bewildering assortment of properties, requiring an assortment of circumstellar regimes, and the difficulties of fitting them all together into one coherent picture are immense. Somehow we must reconcile the simultaneous presence of Balmer emission, stationary shell absorption, polarization, infrared excess emission, and high-velocity winds with high ionization.

Related to the problem of geometry is the difficulty in ascertaining the inclination angles and true rotational velocities of the stars. The development of a reliable technique for doing this would be enormously helpful in the development of a proper geometrical description of the circumstellar material, and would also be important in elucidating the role of rotation in general. A glimmer of hope has been offered by analyses of equatorial darkening such as those presented at this Symposium, although it appears that further refinement is needed.

9. WHERE DO WE GO FROM HERE?

It is appropriate to complete this summary with an outline of important research that should be pursued in the ongoing effort to understand the Be stars.

On the observational side, two general strategies were discussed, and are being implemented. One is to carry out extensive observing campaigns, both photometric (as described by Harmanec) and spectroscopic (discussed by Barker). Such campaigns provide archival data, allowing future observers to trace the historical behavior of individual objects; they provide sufficient time coverage to allow searches for long-term periodic behavior (if the data are of uniform quality); and they can help ensure that new episodes of activity will be noticed at an early date, so that more intensive observations can be carried out.

The second general approach is to select individual objects for detailed scrutiny, in hopes of developing physical insight into the geometry and the time variability of the Be phenomenon. Such studies are especially important if good time coverage is obtained, particularly if many parts of the electromagnetic spectrum are observed, preferably over the same time intervals. From such observing programs, it may be possible to unravel the physical basis for the time

variations, and hence gather information on the fundamental cause. One particularly extensive program, involving a number of observers and a range of instruments (including IUE and several observatories on the ground) has been described by Doazan et al., who are intensively studying the star 59 Cygni. This object has been varying in spectacular fashion, on rather short timescales, and there is hope that significant new understanding will emerge from the study.

More specific observational questions should be mentioned. While some data probably exist on the presence or absence of soft X-ray emission from Be stars, the information was not forthcoming during the week of the Symposium. Such data could help establish the existence of coronal gas in the circumstellar envelopes of Be stars, something suspected from the high ionization that is observed in the winds and from the apparent similiarity of the Be star winds to those of the O stars.

The question of magnetic fields in Be stars is entirely an open one, and very difficult to pursue observationally, but the attempts must continue. Magnetic fields may play an essential role in governing the circumstellar environment. No model of the Be stars can really be complete until the presence and strength of magnetic fields can be included.

On the theoretical side, several areas of needed work can be indentified. The entire question of non-radial pulsations in Be stars is new, and needs to be pursued; it was clear that more detailed calculations of stellar structure with rotation are needed: improvements are needed in the theory of equatorial darkening in rotating stars; and the entire subject of stellar winds requires further analysis, since the origin of these winds, which might have a lot to do with the cause of the Be phenomena, is itself unknown.

Perhaps some of the fundamental questions will ultimately be answered by a direct probe of the circumstellar environment around a Be star. Discussions of an unmanned mission to a nearby star are already under way; it may be possible to conceive of such a journey to a Be star in the future. Maybe in the year 2066, when astronomers gather on the occasion of the two-hundredth anniversary of the discovery of Be stars for IAU Symposium 523, as suggested in Slettebak's review, this probe will be on its way. Perhaps in 2166, when the three-hundredth anniversary occurs, the data will be in, and at last it will not be necessary to conclude that more observations are needed.