The B[e] Phenomenon: Forty Years of Studies
ASP Conference Series, Vol. 508
A. Miroshnichenko, S. Zharikov, D. Korčáková, and M. Wolf, eds.

Introduction to the B[e] Phenomenon

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Abstract. In this contribution we introduce the topic of this workshop with a brief history of studies of objects with the B[e] phenomenon, including its discovery and evolution of our understanding of the phenomenon. We will also review the most prominent results on selected objects published prior to the previous B[e] star conference in 2005. These include the discovery of B[e] supergiants in the Magellanic Clouds, detection of maser and laser lines in the spectrum of MWC 349A, studies of η Carinae, and a few more. This talk is planned to set up the stage for discussion of more recent results that will be presented at the conference.

1. Earlier Results and Problems

The B[e] phenomenon is easy to define; a star with spectral type B and forbidden emission lines in its spectrum. Although it is a straightforward description which is simple to grasp, the history of stars with the B[e] phenomenon is much older than the phrase itself, while understanding the objects themselves has proved to be a major challenge. In the sections below, we will give a very brief overview of this history and set the stage for the rest of the conference. In preparing for this paper, we drew heavily on the Lamers et al. (1998) paper and the overview papers presented by Swings (2006), Miroshnichenko (2006), and Zickgraf (2006) at the Vlieland conference in 2005.

It is fair to say that the prototype B[e] star is the object HD 45677 (FS CMa). About 40 years after the advent of astronomical spectroscopy, it was found to exhibit hydrogen emission back in the 19^{th} century by Fleming (1898) (see also Pickering et al. 1898), when it appeared alongside a number of other emission line stars. As typical in those days, no spectra were actually shown in the paper. Thirty years later, Merrill (1925, 1928) identified several singly ionized forbidden iron lines, and in 1928 he reported a remarkable finding. The hydrogen "Hβ and Hγ lines are double", whereas "The chief interest" was that the newly detected, forbidden, iron lines "do not share the structure of the hydrogen lines, but are narrow, single lines". So, almost a hundred years ago the typical spectral characteristics of what would later become the class of stars with the B[e] phenomenon were already described. Also, we note that in this article, published 30 years after Fleming's original discovery, no figures presenting the spectra appeared either. The explanation for the double peaked profiles, which were also seen in the more common Be stars came only a few years later in the seminal paper by Struve (1931) who demonstrated, using model spectra, that the double peaked lines are due to rotating disks.

We now fast-forward another 40 years to the early seventies, when new technologies allowed observations at infrared wavelengths to be undertaken. Naturally HD 45677 was one of the first objects to be observed and published about. Low et al. (1970) presented a large infrared excess emission over and above the stellar photospheric emission and attributed this to a cool companion. Not soon thereafter, Swings & Allen (1971) pointed out that HD 45677 had not displayed any radial velocity variations for half a century and suggested that instead of a companion, a dusty shell could be responsible for the excess infrared emission. This notion was later refined and proposed to be due to a dusty ring-like structure by Coyne & Vrba (1976) based on the observed linear polarization. The polarization was due to light scattered and polarized by the circumstellar dust grains distributed in an aspherical structure. Infrared excess emission is a common property of, and proved crucial in finding, B[e] stars in both the Galaxy and the Magellanic Clouds, of which more later.

Around this time, one of the first attempts to explain the various line profiles was made. Whereas the doubly peaked hydrogen lines were long assumed to be due to a rotating disk, the single peaked forbidden lines possibly needed a different explanation. Swings (1973) published two-dimensional spectra recorded on photographic plates, which clearly show the single-peaked forbidden lines and double hydrogen and permitted iron lines. These data were interpreted using distinctly different emitting regions, the forbidden lines came from an extended envelope which could be rotating, but in that case the lines would seem single because of the low rotational speeds. In turn, the double peaked lines originated in a rotating ring. The first steps to the classical hybrid model were made. The evolutionary status of the star was still unclear however.

In parallel, more objects similar to HD 45667 began to be found. It was especially the combined presence of forbidden emission lines and dust excess emission that allowed these objects to be discovered. Allen & Swings (1976) completed a survey of ~700 B–type stars with optical spectroscopy and near-IR photometry and selected 65 stars, which showed both forbidden emission lines (e.g., [O I], [Fe II]) and a strong IR excess radiation at $\lambda = 2\mu$m. The first group name suggested by the discoverers was "peculiar Be stars".

At this time various classes of early type stars with emission lines were known, each having their own designations in the literature. In 1976 an IAU Symposium No. 70 on "Be and Shell type stars" was held and during the general discussion Conti (1976) proposed to create order in the chaos by suggesting definitions for Be stars, B[e] stars, Herbig Ae stars, emission line supergiants (such as B5Ie), Oe stars and reserving the small letter "p" only for (peculiar) stars that did not fit any of the other categories. It would seem that these definitions have stood the test of time, except perhaps those for the Herbig Ae/Be stars, which he suggested to collectively call Ae stars as "most were A–type anyway". In the meantime, many Herbig Be stars have been found and this may be the only definition from Conti's contribution that did not last so long. Let us quote Conti's definition for the B[e] stars here, as there may have been some confusion as to what constitutes a spectral type B[e] or not: *"...those B-type stars which show forbidden emission lines and I would suggest that we classify these as B with a small e in brackets B[e], following the notation for forbidden lines."* Thus, clearly, the original definition for B[e] designation is purely based on the spectroscopic characteristics, as can be expected from a spectral classification. Although many B[e] objects have an infrared excess for example, its presence is not a defining *spectral* characteristic. It may also be clear that the stars with the B[e] phenomenon are different from the Be stars.

Initially studies of the phenomenon were not intense, because the list of objects with the described above properties was heterogeneous. Progress in understanding of various manifestations of the phenomenon was possible mostly due to studies of individual objects as members of other groups. A major step in the understanding of the B[e] phenomenon was made in the eighties by Zickgraf et al. (1985) who presented an in-depth photometric and spectroscopic study of the LMC B[e] supergiant R126. This time, the spectroscopic data were still taken on photographic plates, but 1D traces were used to measure the spectra and to plot them in the manner we are nowadays used to. A new element in the study was the use of ultraviolet IUE spectra, which covered high ionization lines in emission, many of whom showed broad P Cygni type absorptions. These authors proposed the two-component model which was visualized in a figure that has become a classic: A rotating disk traced by the doubly peaked emission lines and singly peaked forbidden lines further out, and, significantly, a strong stellar wind emanating from the poles, as traced by the highly ionized lines.

The second major step forward was made a year later, also by Zickgraf et al. (1986), who searched for, and found, a large number of similar B[e] stars in the Magellanic Clouds. They first selected objects with near-infrared excess and then followed these up with optical spectroscopy. A sample of 8 such objects were presented and, for the first time, a very well informed interpretation of the evolutionary nature of these objects could be made because of the known distances to the stars. Their high luminosities and resulting positions in the HR diagram leave little doubt for an evolved, post-main-sequence nature of the objects. Curiously, although their position in the HR diagram is comfortably between the, much better studied - but equally numerous, Luminous Blue Variables and the Wolf-Rayet stars (see Oudmaijer et al. 2009), surprisingly little is known about their precise evolutionary state. Zickgraf et al. (1986) surmised that large rotational speeds, leading to the disks, may have an important role to play in their appearance. Later, Gummersbach, Zickgraf, & Wolf (1995) extended the sample to lower luminosites in the Magellanic Clouds. Apart from the LMC and SMC objects for which the luminosities could be determined, the situation for Galactic objects continued to be less clear.

2. Not so Early Days

The main results obtained in the first 20 years of studies of B[e] stars, as counted from Conti's definition, were summarized at the first conference on the phenomenon held in Paris (Hubert & Jaschek 1998). A major outcome of the conference was that a well-defined and documented description of the B[e] phenomenon was agreed upon.

One of the reasons for this initiative was that the B[e] phenomenon was often confused with the Be phenomenon. The latter is defined as the presence of Balmer emission in the spectra of B–type normal dwarfs and giants (Balona 2000). Also, Be stars show no signs of circumstellar dust in their spectra. The *SIMBAD* database does not have a category for objects with the B[e] phenomenon leading to the following problems: (1) some objects from the original list are called Be stars (e.g., FS CMa = HD 45677), and (2) some Be stars are occasionally called B[e] stars. The confusion between Be and B[e] has not completely gone away, so let us therefore list the main criteria to assign a B[e] nature to an object here as well. These are nowadays due to Zickgraf (1998), who modernized Conti's original definition and reiterated the classification (criteria as quoted in Lamers et al. 1998):

- Strong Balmer emission lines
- Low excitation permitted lines of predominantly low ionization metals in the optical spectrum, e.g., Fe II
- Forbidden emission lines of [Fe II] and [O I] in the optical spectrum
- A strong near or mid-infrared excess due to hot circumstellar dust

With the refined criteria in hand, Lamers et al. (1998) determined that around half of the original objects belonged to four stellar groups with an arguably known evolutionary status. These groups are

i) sgB[e] stars, supergiants, massive and evolved

ii) HAeB[e] stars, Herbig Ae/Be stars, pre-main-sequence

iii) cPNB[e] stars, compact Planetary Nebulae, low-mass evolved

iv) SymB[e] stars, symbiotic binaries

At the same time, they found it difficult to classify the other half, because these objects either exhibited properties of more than one group or were not studied well enough to determine their fundamental parameters. Lamers et al. (1998) suggested to call the latter unclassified (unclB[e]) and use the term "objects with the B[e] phenomenon" rather than "B[e] stars" for the entire list. The main reason for the new term was realization that the phenomenon is caused by conditions in the circumstellar environments and not by the age or nature of the underlying stars.

The second conference on objects with the B[e] phenomenon (Kraus & Miroshnichenko 2006) became the next milestone in this area of astrophysics. It took place in 2005, almost 30 years after Conti's original definition and ten years after the first such conference. It may therefore not come as a surprise that we are here now in 2016 celebrating 40 years of studies of the B[e] phenomenon! The Vlieland conference showed that the phenomenon is more widespread than appeared earlier. It turned out that many Herbig Ae/Be stars exhibit forbidden lines, more objects were studied in detail, and a number of newly found objects were presented. Based on the conference results, Miroshnichenko (2007) summarized the history of studies of the B[e] phenomenon for the first 30 years and proposed to recognize a new subgroup of FS CMa separated from the list of unclB[e] objects. The subgroup name was chosen after the prototype B[e] object, FS CMa, proposed by Swings (2006). A summary on the growing number of objects with the B[e] phenomenon in the Milky Way is presented in Table 1.

We should probably stress that the new subgroup has not replaced the unclB[e] subgroup but rather rejected some hypotheses about the objects' nature. In particular, Miroshnichenko (2007) showed that FS CMa type objects are not HAeB[e] stars, sgB[e], or cPNB[e]. They are also definitely not symbiotic binaries, because the B–type star dominates the optical spectrum even in those with detected lines of a cool companion (see Miroshnichenko & Zharikov 2015). Most FS CMa objects have very strong emission-line spectra, in which the H_α line equivalent widths are on average over an order of magnitude stronger than those of classical Be stars of the same spectral type (Miroshnichenko 2008). More information about the binary nature of the FS CMa type objects is given in the review by Miroshnichenko (this volume).

Table 1. Temporal growth of the number of objects with the B[e] phenomenon

Subgroup	Original	Current
HAeB[e]	6	≥ 100
sgB[e]	7	∼ 15
cPNB[e]	13	≥ 100
symB[e]	6	∼ 30
unclB[e]	32[a]	∼ 80[b]

Column 1 lists short names of the subgroups of objects, column 2 shows numbers of objects in the original list published by Allen & Swings (1976), and column 3 shows estimated numbers of currently recognized objects in each subgroup.
[a] – this number includes 23 FS CMa type objects and 9 with an unknown nature by the time the paper by Miroshnichenko (2007) was published.
[b] – this number includes 70 FS CMa type objects and 7 with an unknown nature by now.

3. Recent Results on Individual Objects

In this section, several results on individual objects are presented to underline the significance of the B[e] phenomenon.

Perhaps the most famous object from the original list is η Carinae. It has an extremely strong emission-line spectrum, exhibited a major outburst in the 1840's, and is currently considered a member of the Luminous Blue Variables group (see more in, e.g., Humphreys & Davidson 1994). A hint for its binarity has been found nearly 20 years ago in a periodical behavior of the He I $\lambda 1.083 \mu$m emission line strength (Damineli 1996). Currently this one of the most massive objects in the Milky Way, a binary with a 5.5–year orbital period, is under a constant attention from many research teams.

Another unique object from the original list is MWC 349A (see Báez-Rubio & Martín-Pintado and Manset et al., this volume). It is an optically faint star ($V \sim 13$ mag) attenuated by ∼10 mag of interstellar extinction located in the outskirts of the Cyg OB2 association. In addition to an extremely strong optical emission-line spectrum (the H_α equivalent width ≥ 700 Å), it is the only known source laser and maser emission lines in the IR and radio spectral regions associated with a star (Strelnitski et al. 2013). It is definitely a massive star with although uncertain evolutionary status. It has been suggested to be either a pre-main-sequence Herbig Be star or a B[e] supergiant. The former case is unusual, because such massive (∼30 $M_\odot$) stars evolve very fast (see, e.g., Palla & Stahler 1993). It can also be a component of a $2\farcs4$ visual binary system, in which the secondary component is also a hot massive star.

Most objects with the B[e] phenomenon are located in the Galactic disk, although a few can be found at high Galactic latitudes. An extremely puzzling one is FBS 0022–021 (see Zharikov et al., this volume). It was discovered over 30 years ago as an extra-galactic candidate object, but its radial velocity (~ -50 km s^{-1}) suggests that it belongs to the Milky Way. A strong emission-line spectrum, comparable to that of the two above mentioned objects, an unusually high galactic latitude of $-64°$, and a low optical brightness ($V \sim 15$ mag) do not allow a definite conclusion on its nature and evolutionary status.

Here are a few more objects from the original list that have attracted interest long ago, but a good progress in their understanding has been achieved only recently.

- CI Cam = MWC 84. It has a very strong emission-line spectrum with sharp lines and the He II 4686 Å line, whose position varies regularly with a period of 19.4 days. In 1998 it exhibited an outburst, which was detected in all spectral regions, from γ rays to radio (see Goranskij et al., this volume).
- HD 62623 = 3 Pup is one of the two A[e] Galactic supergiants, a $V = 4$ mag star, the brightest objects showing the B[e] phenomenon. Its binarity has been suspected but unconfirmed.
- HD 94878 = GG Car shows a 31.03-day photometric and spectroscopic period, however no spectral lines from the secondary has been detected. Its distance and luminosity are still uncertain.
- MWC 137 is a V=12 mag object with a very strong emission-line spectrum. The Balmer and He I emission lines have profiles, which can be understood as triple-peaked. The object has been classified as a Planetary Nebula, a HAeBe star, and a B[e] supergiant. The latter suggestion is most likely correct (see Mehner et al. and Manset et al., this volume).
- Finally, the prototype of the class, FS CMa / HD 45677 has been studied extensively over the last decades, often using the latest and most modern techniques. Just to name a few: optical interferometry (Kluska et al. 2014), spectropolarimetry (Schulte-Ladbeck et al. 1992; Patel et al. 2006), spectroscopy (Sitko et al. 1994; Israelian & Musaev 1997; Muratorio et al. 2006), spectro-astrometry (Baines et al. 2006), and many more. The nature of the object is still not fully understood, but the studies seem to be converging towards a pre-main-sequence nature for this object.

4. Some Unsolved Problems

Studies of objects with the B[e] phenomenon revealed a complicated structure of their environments and yet uncertain stellar content. Analysis of this information allows to recognize several problems that need to be addressed. They include the following issues:

- Mass loss mechanisms. Are they similar those in Be stars if the object is single? What is the role of mass transfer in close binaries? Can any of the B[e] objects be explained as a result of mergers accompanied with an explosion (see de la Fuente, this volume)?

- Binary fraction. Most known Galactic sgB[e] exist in binary systems (Wang et al. 2012). SymB[e] are binaries by nature. Nearly one third of known FS CMa type objects show signs of binarity (Miroshnichenko & Zharikov 2015). Is the B[e] phenomenon at least in evolved stars caused solely by non-conservative binary evolution?

- Why are there many Be stars and only a few objects with the B[e] phenomenon located within 1 kpc from the Sun? How to model circumstellar envelopes of B[e] stars?

5. Conclusions

The above discussion of the recent results in studies of B[e] objects leads to some conclusions which can be summarized as follows. The B[e] phenomenon is a remarkable manifestation of a hot star radiation processed by a large amount of circumstellar matter distributed in an extended area. Investigation of B[e] objects expands our knowledge of stellar evolution and triggers exciting discoveries. The number of B[e] objects in all subgroups constantly grows as well as their variety. Even those discovered long ago keep presenting new puzzles testing our understanding of physical processes that take place in stars and their environments. Complexity and dynamics of many B[e] objects requires frequent attention with various observing techniques and sophisticated modeling tools.

Acknowledgments. A. S. M. acknowledges support from the College of Arts and Sciences Advancement Council and the Department of Physics and Astronomy of the University of North Carolina at Greensboro.

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