STUDY OF B AND Be STARS BY GAIA

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ABSTRACT

All the Gaia instruments will provide fundamental information about the yet unexplained Be phenomenon. We hope that Gaia itself will provide a clear detection of Be stars among B stars with the help the photometric and spectroscopic instruments. Hipparcos definitely established that Be stars are brighter that B stars of the same spectral type. Parallaxes and extinction provided by Gaia could allow the determination of individual absolute magnitudes of B and Be stars to within a few hundredths of a magnitude, up to several kiloparsecs, and to study absolute magnitudes of Be stars versus fundamental parameters: temperature, emission strength, $v \sin i$.... and age for Be stars in open clusters. Spectroscopic information from Gaia will also be used to characterize Be stars with strong emission: we have already shown how the presence of emission in the lines in the wavelength range of the Gaia RVS, i.e., Paschen lines as well as CaII triplet, is a powerful index of the strength of emission in Be stars, and is correlated to a larger rotational velocity and to an infrared excess.

Key words: Stars: early type; Stars: emission-line, Be; Stars: fundamental parameters.

1. WHAT IS A Be STAR?

According to the ‘classical’ definition, a ‘classical’ Be star is a non-supergiant B star in which, at least once, some emission has been observed in at least one Balmer line. When narrow absorption lines are superimposed on some emission lines, they are called ‘shell’ stars. Be stars were discovered a long time ago (Secchi 1867) and extensively studied since then. However they are not yet satisfactorily understood. Emission is attributed to a circumstellar non-spherical envelope ejected by the star. Be stars have a very high $v \sin i$ and they are the fastest rotators that we know among non-degenerate stars. Shell features are generally observed for Be stars with the largest $v \sin i$, and that is explained by a star seen nearly equatoron. It is important to emphasize that Be stars are not rare objects: they represent 17% of all B stars and up to 34% of all B1 stars (Zorec & Briot 1997). Emission can display very various strengths, from a strong emission affecting quite every observational range, to a hardly detectable emission modifying lightly some Balmer lines, principally the H_α line. On average, emission is stronger for early Be stars and decreases versus the temperature of the star. Emission and shell features show a very strong character of variability. All the characters of emission, or shell, can disappear and possibly re-appear again, with non-regular periods of several years. A Be star can then mimic a B star without any emission. Many other variations have also been observed and very short period variations are attributed to non-radial pulsations in the central star. The formation of the circumstellar envelope in which emission and shell features originate are not yet well explained. The fast rotational velocity certainly plays an important role in the triggering of the ejection of the envelope by the star, but it is generally admitted that this rotational velocity is less than the critical rotational velocity. Some additional process is necessary. Moreover to explain the possible disappearance and reappearance of any emission feature requires some process which added to the rotational velocity would provoke discrete events of matter ejection occurring several times during the life of the star. Non-radial pulsations, magnetic activity, κ effect (Maeder & Meynet 2000) or binarity are the physical mechanisms most often invoked to justify the formation of the circumstellar envelope.

The fundamental question about Be stars is: does the Be phenomenon correspond to special conditions of the formation of the star, or does the Be phenomenon correspond to some evolutionary effect occurring during the life of any main sequence B star, or only for some of them? If the Be phenomenon is an evolutionary effect for all B stars, can the surface rotational velocity be accelerated? As a conclusion: is the Be phenomenon innate or acquired? The Be stars raise many astrophysical problems related to the formation of massive objects, as well as many astrophysical problems related to the physics of massive objects with fast rotation. They also may be important objects contributing to the enrichment of the interstellar medium, by the ejection of matter from the envelope. The high proportion of Be stars among all B stars implies that we cannot neglect these objects and the problems they raise.

Who, or what, will resolve the Be stars enigma ?

2. ABSOLUTE MAGNITUDE OF B AND Be STARS

2.1. Past and Present Situation

The location of Be stars in the HR diagram is a key to understand the Be process because it gives some information about the evolutionary path, the luminosity of the central star and characteristics of the central envelope. Since Merrill (1933), many studies have investigated the absolute magnitudes of Be stars compared to those of B stars (references are given in Zorec & Briot 1991). However, B stars, and moreover Be stars, are scarce in the solar neighbourhood. This implies that only very few, inaccurate ground-based parallax measurements are available for B stars and practically none for Be stars. Before the Hipparcos mission, absolute magnitudes of Be stars were only determined by various indirect methods: membership of binaries, open clusters or associations, or by statistical means based on their spatial and kinematics distributions. Because of the poor quality and the small size of the samples studied, the results obtained were contradictory. There was nevertheless a consensus of considering Be stars brighter, by about 0.5 up to 1 mag, than B stars without emission. The advent of the Hipparcos satellite changed the situation. For the first time, we obtain trigonometric parallaxes of a significant sample of Be stars and a large sample of B star (Briot et al. (1997), Briot & Robichon (2000)). A first result is that B stars are fainter than previous estimations by about 0.5 magnitude on average. We then observe that on average Be stars are brighter than B stars of the same spectral type and this over-luminosity increases with the spectral type. We interpreted this result by the fact that the rotational velocity of late Be stars is nearer the critical rotational velocity than in the case of early Be stars. A similar result about absolute magnitudes of Be stars was found later (Wegner 2000).

2.2. The Hoped-for Benefits from Gaia

2.2.1. Detection of emission

Huge progress in the knowledge of B and Be stars could be made with Gaia if the emission in Be stars is detected from the Gaia instruments themselves. The RVS instrument will probably detect emission in strong Be stars (as defined below) but probably not in weak ones and it has anyway a limiting magnitude smaller than the other instruments. Therefore, in order to perform systematic and statistically significant study, the photometric system of Gaia must to be able to detect emission and recognize Be stars among B stars. To do so, whatever the choice of the photometric system, it is to include a dedicated filter around the H_α spectral region in order to detect the emission in Be stars (Kolka et al. 2005).

2.2.2. Absolute magnitudes

Very accurate determinations of parallaxes for a very large sample of B and Be stars will be obtained. About 150 000 O and B stars lie in a radius of 3 kpc around the Sun. These stars, assuming a mean absorption of 0.7 mag/kpc, will have a relative precision on their parallaxe better than 3%. The error on the absolute magnitude coming from the error on the parallaxe will be smaller than 6%. Gaia will then allow us to break free from the usual statistical biases (Malmquist, Lutz & Kelker). The main source of error will probably come from the determination of interstellar absorption. From Jordi et al. (2004), the precision on A_v should be better than 0.1 magnitude for these stars. However it is quite unclear where this number comes from and whether it is reliable for Be stars which have intrinsic reddening. Moreover, the scientific targets of the photometric systems design do not include emission line objects (Jordi et al. 2004). As several photometric systems are currently studied, it is difficult to know now what will be the performance of the final photometric systems for Be stars in terms of determination of some fundamental parameters: $T_\mathrm{eff}, A_\mathrm{v}$, etc. Fortunately, even if the photometric system is not well suited for Be stars, good work can be done in open clusters (and probably also in OB associations). In clusters, a lot of parameters will be determined using cooler members: A_v, [Fe/H] and age, as well as the parallaxes will be improved. Within 3 kpc around the Sun, about 1000 clusters will contain about 10 000 B stars (out of which up to 30% can be Be stars). For these clusters, the precisions will be only a few hundredth of dex for [Fe/H] and few hundredth of magnitudes for A_v.

Absolute magnitudes of B and Be stars will then be studied as a function of:

- effective temperature
  Physical conditions of all B and Be stars i.e., temperature, mass etc differ strongly with the spectral type. As seen above, the emission is stronger on average for early B spectral type stars (see, for example Briot 1971, or Briot & Zorec 1981). However the result that we obtained about absolute magnitudes from Hipparcos observations show another trend: the luminosity of late Be stars is very different from the luminosity of the B stars of the same spectral type, whereas only weak emission characteristics can be detected in late Be stars.
- strength of emission
  A very surprising result of Hipparcos observations was that the width of the Be sequence does not seem larger than the B sequence whereas emission characteristics of Be stars are very inhomogeneous. It would be very important to determine whether the over-luminosity of Be stars as compared with B stars is correlated with the importance of the emission factor.
- inclination of the Be star along the line of sight
  The inclination of the star is likely a very important factor for the absolute magnitude of the Be stars, for at least four reasons, the first two reasons being due

to the physics of the central star and the last two ones being due to the physics of the circumstellar envelope:

- In the case of stars with a very fast rotation like Be stars, there is a gravitational darkening in the equatorial region as explained by the von Zeipel theorem (1924).
- Recent observations by interferometry of the bright Be star Achernar during a non-emission phase show that the fast rotating star itself is an apparent oblate star (Domiciano de Souza et al. 2003).
- It is known that the circumstellar envelope of a Be star is not spherically symmetrical but it has a ellipsoidal shape, flattened along the polar axis, so as the envelope appears larger as seen more or less pole-on.
- As seen above, the presence of narrow absorption lines superimposed on emission lines frequently observed for Be stars with a very high $v \sin i$, i.e., 'shell' character, is attributed to the presence of an absorbing envelope around the equatorial regions of the star, and this absorbing envelope will weaken the luminosity of shell stars.

These four factors affect the absolute magnitude in the same sense, weakening the luminosity of a Be star seen more or less by the equatorial regions. A similar preliminary result was obtained for B2e stars from Hipparcos observations (Briot et al. 1997).

- Rotational velocity
  As seen above, Be stars are very fast rotators. The fast rotation of massive stars modifies their evolutionary tracks, as extensively explained in Meynet & Maeder (2000) for example, and then the location of these stars in the HR diagram is modified as well.

It is important to recall that Be stars show photometric variations in very various time scales. A fundamental information to obtain is: how the luminosity of the Be stars varies when the emission and/or the shell characteristics vary, and even disappear or appear again? Some results have been obtained up to now, but they concern only scarce studies and did not allow to exhibit firm correlations between variations of emission and luminosity. Only a systematic study consisting in a simultaneous detection of the emission (H_α line) and photometric observations, could provide such a result.

2.2.3. Locations of B and Be stars

As seen above, it is not yet established whether the Be phenomenon corresponds to a specific phase during the life of the star, or if Be stars are special objects since their formation. It is then very important to know the conditions of formation of these objects, to determine if they are different for B and for Be stars. Gaia will allow to determine the positions of B and Be stars in the Galaxy. As young stars, they are very near their birth place. The location of field B and field Be stars will be determined:
– with respect to the spiral arms
– with respect to the depth of the galactic plane
– with respect to the galactic centre.

We will also determine the location of B and Be stars inside clusters, so as to compare frequencies of B and Be stars in internal or external regions of the cluster. This would provide information about the process of formation of very fast rotating stars.

Moreover, the high luminosity of B and Be stars imply that they can be seen at large distances and used as galactic candles to study the galactic structure. Then a precise determination of their absolute magnitude is necessary.

Knowing the absolute magnitudes of B and Be stars, we could make new determinations of the proportion of Be stars among B stars, as a function of the spectral type, avoiding samples defining by a limiting magnitude, but defining samples from the volumes really occupied on the one hand by the B stars and on the other hand by the Be stars. We could also determine and compare the mass functions and the luminosity functions of the B and of the Be stars.

3. SPECTROSCOPIC STUDY OF Be STARS BY GAIA

3.1. Paschen Lines

The wavelength range of the Gaia satellite spectrograph (RVS) includes Paschen lines from P13 to P16, as well as the infrared calcium triplet. The lines P13 (λ 8665), P15 (λ 8545), P16 (λ 8502) are blended with the CaII triplet at $\lambda\lambda$ 8562, 8542 and 8498. The line P14 is not blended with any other important line. Some emission can be seen in these Paschen lines in the case of early spectral type Be stars with a strong emission (Briot 1977). In the Gaia case, the occurrence of emission in Paschen line could be determined preferably from P14, because of the blends of lines P13, P15 and P16. We have used the presence of emission in Paschen lines of this wavelength range as a criterion to classify the Be stars according to the intensity of emissive phenomenon (Briot & Zorec 1981; Briot 1986). This parameter coincides quite perfectly with two other criteria in other wavelengths ranges, namely the presence of FeII emission lines, and an infrared excess which can be attributed to free-free radiation. This classification can be defined as following:

- The Be stars in the first category show some emission in the Paschen lines of the wavelength studied here, some FeII emission lines, and an infrared excess which can be attributed to free-free radiation. These stars are classified 'F' by Allen (1973) according to their infrared excess. They show a strong emission in the Balmer lines (Briot 1977). Their spectral types are from B0 to B5. We call these stars: 'Strong Be stars'.

- The Be stars in the second category do not show FeII emission lines, have no detectable emission in the Paschen lines located in the wavelength range studied here, and show a weak or no infrared excess. These stars, classified 'X' by Allen (1973), according to their infrared excess, have weaker emission in the Balmer lines (Briot 1977). We call these stars: 'Weak Be stars'.

When we know only one of these criteria, we can classify the Be star according to the emission intensity. We demonstrated that the 'strong' Be stars have a larger rotational velocity than the 'weak' Be stars in the same spectral type range, i.e., B0–B5, and have the same rotational velocity than the 'weak' Be stars of later spectral type, i.e., B6–B9 (Briot 1986).

3.2. The CaII triplet in Be stars

The Ca II triplet appears sometimes in emission in some 'strong Be stars'. In this case, the infrared excess of the star is larger than for stars in which the Ca II triplet appears only in absorption (Briot (1981); result confirmed later by Jaschek et al. (1988)).

4. DEFINITION OF A PRELIMINARY OBSERVATIONAL PROGRAMME

In order to detect emission line stars observed by Gaia, we will launch a Gaia preparatory observation programme so as to study a representative sample of Be stars, i.e., which would contain Be stars of various spectral types and various strength of emission. Observations will be spectroscopic and photometric as well. Spectroscopic observations will be made both in the visible and specially the H_α line, and in the same wavelength range as the RVS spectrograph. This would allow us to study Paschen lines and lines of the CaII triplet, not only for Be stars with a strong emission, for which we know that the emission in Paschen lines is striking, but also for Be stars with a very much weaker emission in Balmer lines. We will establish whether some emission, even very weak, can be detected in Paschen lines of Be stars with weak emission. Photometric observations will correspond to test the H_α photometric band used by Gaia. Actually, we know that if a weak emission is seen in only one line, this line is H_α. Our aim is to identify Be stars also from this Gaia photometric band.

5. CONCLUSION

It is obvious that Gaia will be an outstanding way to improve our knowledge of Be stars. But if there is no possibility for Gaia to systematically detect emission in Be stars (i.e., if there is no H_α filter in the MBP instrument), any study will be reduced. In this case, we could measure absolute magnitudes, locations and variations with a yet unattained accuracy for a sample of B stars larger than everything which could be studied up to now; but any study of Be stars would need a further ground-based observational programme of emission detection. On the contrary, if the detection of a possible emission can be made from Gaia observations, the totality of the 150 000 B stars observed could be studied in terms of Be stars and B stars without emission. Gaia will also allow us to study photometric variations of Be stars as a function of the variation of the strength of the emission, and in this case again we need simultaneous detection of emission, which can be done if H_α photometric observations are possible.

We know, as said above (Briot 1971) that the presence of emission in the CaII triplet is correlated to the continuous infrared excess. This correlation is so far unexplained, and a more detailed and more accurate study will provide information about physical conditions in circumstellar envelopes of Be stars.

These intriguing objects, the Be stars, will hopefully be finally understood, so giving fundamental clues for the formation and evolution of massive stars.

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