On the class of Oe stars:*

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Abstract. We present high-quality spectra of the majority of stars that have been classified as Oe and find that their published spectral types are generally too early, most likely due to infilling of He I lines. As a matter of fact, all stars classified as Oe actually fall inside the range O9–B0 with the important exception of HD 155806 (O7.5 III) and perhaps HD 39680 (difficult to classify, but likely O8.5 V). Observations of a sample of objects with published spectral types in the O9–B0 range previously classified as peculiar or emission-line stars fail to reveal any new Oe star with spectral type earlier than O9.5. Most objects classified as peculiar in “classical” literature show signs of binarity in our spectra, but no spectral anomalies. We conclude that there is likely a real decline in the fraction of Be stars for spectral types earlier than B0, not due to observational bias. The few Oe stars with spectral types earlier than O9.5 deserve detailed investigation in order to provide constraints on the physical reasons of the Be phenomenon.

Key words: stars: emission-line, Be – stars: evolution – early-type

1. Introduction

For a very long time, it has been obvious that there is a strong correlation between fast rotation and the Be phenomenon. Though the exact mechanism behind the Be phenomenon is not known (see Porter & Rivinius 2003 for a recent review), it is a well-known fact that Be stars rotate fast (cf. Townsend et al. 2004). Fast rotation plays a fundamental role in the evolution of massive stars (Maeder & Meynet 2000), as the initial rotational velocity determines the main-sequence lifetime of a star, its post-main-sequence evolution and likely even the nature of its final remnant after supernova explosion (Meynet & Maeder 2000, 2003). It is naturally tempting to think that understanding of the connection between fast rotation and the Be phenomenon may further our knowledge about the effects of rotation on the whole set of massive stars.

Such hope, however, seems to have been consistently frustrated by our profound lack of knowledge of the ultimate causes of the Be phenomenon. As a matter of fact, we are still far from even knowing if Be characteristics, which are seen in a broad variety of stars, are always due to the same physical causes, even if we restrict ourselves to “classical” Be stars, i.e., fast rotating moderately massive stars in which the emission lines are produced in a circumstellar disk of material expelled from the photosphere (cf. Porter & Rivinius 2003).

The main reasons (or perhaps excuses) for our ignorance are the very complexity of the Be phenomenon and the vast range of stellar parameters over which it occurs: a B0 III star is a very different beast from a B9 V star on all accounts, in spite of which, most authors will still expect physical mechanisms behind Be characteristics in one and the other to be the same. Indeed, the completely arbitrary (for Nature) fact that the Be phenomenon is confined to the vicinity of the B spectral type (whose definition, though not arbitrary, certainly does not respond to any fundamental physical reason), makes us forget that the Be phenomenon spans both sides of the divide (rather more meaningful in physical terms) between intermediate-mass and massive stars.

The relevance of this division comes from the fact that massive stars have self-initiating radiative winds and the presence of these winds may have some effect on whatever mechanisms cause the Be phenomenon. As the Be phenomenon tends to become very rare among O-type stars, some thought should be given to the physical causes of this scarcity of Oe stars. Naively, one could think that a fast radiative wind will exert a force on any circumstellar material that will be sufficient to sweep it away and prevent it from forming a disk. Though radiative pressure may certainly be an important factor to prevent the formation of a Be disk, several authors have argued that other effects may be even more determinant in...
explaining the disappearance of the Be phenomenon towards early types. In the evolutionary model proposed by Keller et al. (2001, thoroughly discussed in Section 4), based on model calculations by Meynet & Maeder (2000), the reason why the Be phenomenon does not extend into the O-range is the very different evolution of angular momentum in fast rotators of moderate and high mass.

In order to gain some understanding of the reasons why the Be phenomenon is restricted to the B-type range, an investigation has been conducted in search of O-type stars with Be characteristics. Our aim is assessing the frequency of the Be phenomenon in the O-range and the earliest type at which the Be phenomenon is seen. A similar programme was recently conducted to determine the highest luminosity at which the Be phenomenon was observed (Negueruela 2004, henceforth Paper I).

2. Target selection and Observations

2.1. Oe stars

The extension of the Be phenomenon to the O-type range was first proposed by Conti & Leep (1974), who defined the set of Oe stars as those O stars showing emission in the Balmer lines, but not in He II $\lambda$4686 Å or any N III lines. The reason to exclude stars with He II $\lambda$4686 Å emission is mainly morphological, but expected to have a physical base. He II $\lambda$4686 Å emission in O-type stars is generally believed to be a signature of a strong radiative wind. Together with the presence of He II emission, it is a defining characteristic of the Oe morphology, frequently accompanied by the presence of H$\alpha$ emission. In most cases, these He II $\lambda$4686 Å and H$\alpha$ lines present either P-Cygni or single-peaked shapes. Hence they should be easy to distinguish from emission lines produced in a disk configuration, which are typically double-peaked (though this may not be the case for optically thick lines; see Hummel & Hanuschik 1997). Double-peaked emission lines from He II $\lambda$4686 Å are seen in a few anomalous objects, classified Oef by Conti & Leep (1974). The underlying assumption is that emission lines in Oe stars respond to similar physical mechanisms to those generating emission lines in Be stars. This is supported by their very similar shapes and the lack of an obvious break in the spectral distribution. Most stars with Oe and Oef characteristics are, on the other hand, either supergiants or of very early spectral type, thus presenting an obvious discontinuity with the distribution of Be stars.

Conti & Leep (1974) proposed 7 members for the class of Oe stars and few others have been added since then, suggesting that the frequency of the Be phenomenon is indeed much lower among O-type stars than at B0-B1, where it reaches 10 − 15% of all stars with luminosity classes III-V (Zorec & Briot 1997). Studies of Oe stars have been extremely scant. Frost & Conti (1976) obtained observations of HD 39680, HD 60848 and HD 155806. They showed Balmer emission lines similar to those of Be stars. The first two stars also displayed double-peaked He I emission lines. Frost & Conti (1976) noted that He I $\lambda$4471 Å was filled in by emission and therefore the spectral types obtained using the canonical He II $\lambda$4541/He I $\lambda$4471 ratio would be earlier than really corresponded to the stars. They noted that HD 39680, previously classified O6 V on this account, appeared to have a spectral type around O9. They classified HD 46056, ζ Oph and 68 Cyg as O(e), because emission was seen sporadically and only in H$\alpha$. Their list of Oe stars is reproduced in Table 1.

Andrillat et al. (1982) obtained red and near-infrared spectra of all the objects in Table 1 except 68 Cyg. HD 60848 and HD 155806 showed emission in the Paschen series, similarly to early Be stars, while HD 39680 and ζ Oph did not.

A detailed analysis of photospheric features of X Per when it was not in a Be phase led to its classification as B0 V (Lyubimkov et al. 1998). Hence, this object will not be considered as an Oe star. HD 46056 has only been reported to show some emission infilling in the core of H$\alpha$. Both this object and 68 Cyg have been extensively studied, with no further references to Oe characteristics. Moreover, Underhill & Gilroy (1990) suspected binarity for HD 46056. Therefore these two objects are, at best, very mild members of the class.

2.2. Sample

In order to investigate the extent of the Be phenomenon into the O-star range, we selected a sample of objects chosen according to several criteria. First, we included all stars classified as Oe visible from La Palma. Apart from those in Table 1, we ran a search of SIMBAD selecting emission-line stars of spectral type O. However, many morphologically normal Of stars are listed as emission-line objects and were removed from the sample. Also, a few candidates were rejected because SIMBAD did not provide any reference in the literature from which the classification as emission-line stars could stem (one such example is BD +36°4032, studied in Paper I).

In addition we selected stars with spectral types in the O8-B0 range that had been classified as "p" (peculiar) in the classical works of Morgan et al. (1955, from now on M55) and Hiltner (1956, henceforth H56). With this, we expected to be able to select some other early Be stars and also study the possible existence of objects with peculiar characteristics, perhaps resembling the Oef or Of?p stars (cf. Rauw et al. 2003; Walborn et al. 2003) at later spectral types or the peculiar O9 star BD +53°2790 (Negueruela & Reig 2001). All stars for which we could find in the literature an expla-
nation for the “peculiarity”, such as CNO anomalies, were excluded from the sample.

2.3. Observations

Observations were collected as part of the Isaac Newton Group service programme at the 2.5-m Isaac Newton Telescope (INT), with a few additional spectra obtained during an observer led run at this telescope in July 2003. For all the observations, the Intermediate Dispersion Spectrograph (IDS) was used with the 235-mm camera and a combination of settings (detailed in Table 2). The service observing strategy allowed the observation of stars over a broad range in Right Ascension. Unfortunately it did mean that the whole sample could not be observed. However, the sample observed is not only a large fraction (~ 80%) of the original sample, but certainly large enough to be considered representative.

Table 2. Dates of observation and configurations of the instrumentation used. All observations have been obtained with the INT+IDS, equipped with the 235-mm camera.

| Observation Date | Set-up               | Wavelength Range (Å) | Dispersion (Å/pixel) |
|------------------|----------------------|-----------------------|-----------------------|
| 2001 Aug 27      | R1200R + Tek#5       | 6275–7120             | 0.8                   |
| 2001 Oct 7       | R1200B + EEV#10      | 3600–5250             | 0.45                  |
| 2002 Jan 26      | R1200R + EEV#10      | 5750–7400             | 0.45                  |
| 2002 May 23      | R1200B+Tek#5         | 3850–4710             | 0.8                   |
|                  | R1200R+Tek#5         | 4100–4940             | 0.8                   |
| 2003 Jul 1-6     | R900V+EEV#13         | 4900–7200             | 0.65                  |

In order to complete the sample of Oe stars, archival observations of HD 39680 and ζ Oph were retrieved from the ING Archive. Spectra of HD 39680 had been obtained on the night of 1997 March 25th with the INT+IDS equipped with the 500-mm camera, R1200B grating and Tek#3 CCD. This setup covers only ~ 400 Å, but three different grating angles had been used in order to span the range λλ 3750-4560Å. The observations of ζ Oph had been obtained on 1997 April 25th, using the INT+IDS equipped with the 235-mm camera, H2400B grating and the Tek#3 CCD. Two grating angles were used to cover the range λλ 3950–4750Å.

In addition, observations of two other stars (HD 155806 and HD 240234) were obtained on 2003 Aug 17th using the 4.2-m William Herschel Telescope (WHT) equipped with the Intermediate Dispersion Spectroscopic and Imaging System (ISIS). The R1200B and R1200R gratings were used in the blue and red arms respectively, which were suited with the EEV#12 and the MARCONI2 CCDs. These spectra have a higher dispersion (~ 0.2 Å/pixel) than the INT ones. HD 240234 had already been observed in the blue with the INT.

3. Results

Spectral classification has been carried out according to the standard criteria outlined by Walborn (1971) by comparison to standard stars (as specified in Paper I) and the grid of standards of Walborn & Fitzpatrick (1990). We have been careful, though, to take into account the fact that He I lines are generally filled in by emission components in Be stars (see Steele et al. 1999 for a more thorough discussion). On the other hand, all spectral types derived are based on the assumption that Be stars do not suffer infilling of the He II lines. The disks of Be stars, where the lines are produced, are rather cooler than the stellar photospheres, $T_{\text{disk}} \approx 0.5 T_{\text{eff}}$ (Millar et al. 2000), and they will not reach the temperatures needed for the production of He II emission. Moreover, Conti & Leep (1974) based their definition of the Oe class on the fact that no He II emission was present, as opposed to Of or Oef stars, where emission lines are believed to arise due to different physical mechanisms. We now discuss our classification of the individual objects.
3.1. BD +59°2829

Known as a Be star since the work of Merrill & Burwell (1933), BD +59°2829 was classified B0 IV by M55. It lies in the region traditionally assigned to Cas OB5.

Our spectra show that this star is still in the Be phase, displaying very strong narrow Balmer lines, weak He I emission lines and quite heavy metallic line emission (see Fig. 1).

He II 4686Å is only very weakly present, suggesting B0.7, while the very moderate strength of C III 4650Å and the Si IV 4089,4116Å doublet makes it a main sequence star. We therefore adopt B0.7 Ve.

3.2. BD +61°105

Given as an emission line star in the LS catalogue – LS I +62°118, OB^+(h,le) – BD +61°105 was classified O9 V by M55. There is no sign of emission components in our spectra (the blue spectrum is displayed in Fig. 3), but the strength of the Si IV 4089,4116Å doublet and He II λ4686 ~ C III λ4650 support a luminosity class IV leading us to our final classification of O9 IV.

3.3. LS I +63°94

Listed as a Be star by Merrill & Burwell (1949), LS I +63°94 is given as B0 III by H56. Our spectrum displays Hα strongly in emission and double-peaked Hβ and red He I lines, however no Fe II emission lines are obvious.

The blue spectrum of LS I +63°94 is shown in Fig. 2. No He II lines are visible in the spectrum, but C III/II 4650Å is prominent. The spectral type is B1 III.

3.4. BD +60°180

Known as a Be star since the work of Merrill & Burwell (1933), BD +60°180 was classified B0IV by M55. In our spectra, it shows moderately strong double peaked Hα and Hβ emission. In the higher Balmer lines and He I lines, only the dominant blue peak is seen. Double-peaked Fe II lines are rather strong in the green region and heavily veil the blue spectrum (see Fig. 2).

The general aspect of the spectrum shows that it is considerably later than previously assumed. The Si II 4128Å doublet is rather strong and Mg II 4481Å is a prominent line, while O II 4650Å is rather weak and less prominent than N II 4640Å. The spectral type is around B2.5 IIIe.

3.5. BD +54°395

Classified B0IV by M55, this star lies relatively far away from the Galactic plane (b = −6°4) and suffers from little reddening. We find nothing anomalous in its spectrum, which is indeed extremely similar to the B0.2 V standard τ Sco. Using this luminosity class and the photometry of H56, we find a distance modulus DM = 12.8 which is compatible with the Perseus Arm.

3.6. BD +61°370

Even though it is noted as an emission-line star in the LS catalogue – LS I +61°256, OB^+(le) – BD +61°370 was simply classified O9 V by H56. Our spectrum, displayed in Fig. 3, fully confirms the classification and no anomalies are noted.
3.7. HD 12856 = BD +56°429

Within the theoretical boundaries of Per OB1, HD 12856 was given as a Be star by Merrill & Burwell (1933) and classified B0pe by M55. Our spectrum confirms that it is still in the Be phase, displaying double-peaked Balmer-line emission (Hα is single-peaked) and moderately strong metallic emission lines. He II 4686 Å is only very weakly present, while C III 4650 Å is very strong. The spectral type is hence close to B0.5. The luminosity class is difficult to establish, but the strength of C III 4650 Å supports III, though S IV 4089 Å appears a little too weak.

Using the photometry of H56, we find DM = 12.1 for B0.5III and DM = 11.6 for B0.5IV, which is close to modern determinations of the distance to h and χ Per.

3.9. HD 16832 = BD +56°703

HD 16832 was classified B0p by M55, though later given as O9.5 II by Walborn (1976), who did not find any CNO anomaly in its spectrum. Our spectrum, shown in Fig. 4, supports Walborn’s classification, though the luminosity could actually be as low as III. We find no anomalies. From the photometry of H56, we find a DM = 12.3 even for O9.5III, suggesting that – as is generally the case of the O-type stars assigned to Per OB1 – HD 16832 is not physically associated with h and χ Per (cf. Walborn 2002 for a discussion of this issue).

3.10. HD 39680 = BD +13°1026

Listed as a Be star by Merrill & Burwell (1949), HD 39680 is one of the original Oe stars in the list of Conti & Leep (1974). Frost & Conti (1976) argued that the O6 V?inpe var classification given by Walborn (1973) was due to the infilling of He I 4471 Å, and commented that the spectral type of HD 39680 based on the strength of the He II lines should be close to O9. Weak wind features in its UV spectrum support a later type (Walborn & Panek 1984). At b = −5°9, this object is slightly outside the Galactic plane.
Our spectrum (see Fig. 5) fully supports the conclusions of Frost & Conti (1976). As a matter of fact, He I 4471Å is a double-peaked emission feature, something extremely unusual in a Be star. All the Balmer lines display similarly double-peaked emission. An exact spectral type cannot be derived because of the infilling of all He I lines, but O8.5 Ve looks most likely and the star is certainly not earlier than O8, based on the strength of the Si IV lines and the presence of He I 4009Å. All N III lines are relatively strong, suggesting a moderate N-enhancement.

3.11. HD 254755 = BD +22°1273

A likely member of Gem OB1, HD 254755 was classified O9 V?p by M55. Schild & Berthet (1986) suggested that it was an N-enhanced object, but its spectrum looks absolutely normal in this respect (see Fig. 3). In the red spectrum, both Hα and He I 6678Å are asymmetric, perhaps suggesting binarity.

3.12. HD 255055 = BD +23°1304

HD 255055, a likely member of Gem OB1, was classified O9 V?p by M55 and O9 Ve? by Crawford et al. (1955). The star is immersed in diffuse nebulosity and shows very narrow Hβ and Hγ emission lines (not clearly seen in the spectrum shown in Fig. 4, which has been smoothed for display). As we could not obtain an Hα spectrum, we cannot decide whether the lines arise from the nebulosity or the star itself. Otherwise, its spectrum is very similar to the O9.5 V standard HD 34078, except for slightly weaker C III features.

3.13. HD 256035 = BD +22°1303

Another likely member of Gem OB1, HD 256035 was classified O9 V?p by M55. Its spectrum, shown in Fig. 3, is indeed peculiar and difficult to classify. All the lines are broad. The strength of the He II lines supports the O9 spectral type, but the Si IV lines appear too weak and the C III lines, too strong. Both Hα and He I 6678Å appear split, which, together with the weakness of all the features in the blue spectrum, is highly suggestive of a spectroscopic binary.

Using the photometry of Haug (1970), we find $DM = 11.0$, which is in very good accord with the distance to Gem OB1 ($DM = 10.9$; Humphreys 1978) for a single star.

3.14. HD 45314 = BD +14°1296

A likely member of Mon OB1, HD 45314 was first given as a Be star by Merrill et al. (1925). Classified O9?pe by M55, it is one of the objects making up the original list of Oe stars by Conti & Leep (1974). The spectrum of HD 45314, shown in Fig. 1, displays extremely heavy emission veiling and few features suitable for classification are visible. Based on the
Fig. 5. The spectrum of HD 39680 (top) compared to the O6.5 V star HD 42088, observed with the same setup. He I 4471 Å is clearly in emission, something seldom seen in Be stars. Very clearly HD 39680 is rather later than HD 42088 and a spectral type O8.5 V seems justified.

3.15. HD 46847 = BD +02°1302

A likely member of Mon OB2, HD 46847 was classified B0 III?p by M55. According to the WDS catalogue, it is a very close visual binary, with a second component 1.0 mag fainter than the primary. There is no evidence, however, of double lines in our spectrum, shown in Fig. 7.

If the spectrum corresponds to a single star, the condition He II λ4541 = Si III λ4552 defines O9.7. As He II 4686 Å is weaker than C III 4650 Å, a luminosity class IV or III is suggested, with the moderate strength of Si IV 4089 Å supporting the former, which we therefore adopt.

3.16. HD 50891 = BD –03°1643

This Be star, first listed by Merrill & Burwell (1949), was classified B0?pe by M55. It is still in the Be phase and displays moderately strong single-peaked Balmer emission lines. The absence of any He II lines in its spectrum makes it later than B0, while the prominent C III/O II 4650 Å line means it cannot be much later. We therefore adopt the most likely class of B1 IIIe.

3.17. HD 60848 = BD +17°1623

First given as a Be star by Merrill & Burwell (1933) and in the original list of Oe stars, HD 60848 = BN Gem is a well studied object with numerous references to double-peaked emission lines. Hα, Hβ and He I 6678 Å display this shape in our spectra (see Figures 4 and 8).

Very far away from the Galactic plane (b = +17°5), HD 60848 is indeed an interesting object. It was classified O8 V?pevar by M55, and hence considered a prototypical Oe star, but is given as B0 by Munch & Zirin (1961). Our spectrum, shown in Fig. 4, can hardly justify the O8 classification. He II 4686 Å is the only prominent He II line, and it is not stronger than C III 4650 Å. The Si IV lines do not support a high luminosity and the adopted spectral type is O9.5 IVe.

As was the case of HD 39680 (Frost & Conti 1976), the early classification of HD 60848 must have been due to infilling of He I 4471 Å.

3.18. ζ Oph = BD –10°4350

This 2nd magnitude star has been extremely well studied in all wavelength ranges. Classified as an O9.5 V star by M55, it was given as O9 V (e) by Conti & Leep (1974). ζ Oph is a mild Be star with relatively short periods of activity followed by long time-spans of quiescence (cf. Kambe et al. 1993).
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Fig. 6. The spectrum of HD 45314 close to Hα is shown as representative of stars with strong Be characteristics. Hα is asymmetric, but the double-peaked structure is lost due to radiative transfer effects in this optically thick line. Weak features at $\lambda 6492$ Å and $\lambda 6584$ Å could be due to N II, though the possibility that they are Ti II and Zr II respectively cannot be ruled out.

The spectrum shown in Fig. 9 is typical of a very fast rotator, which makes its spectral classification difficult. As He II $\lambda 4686 < \lambda 4650$, it cannot be O9, unless it is of high luminosity. As there appears to be a rather prominent O II 4640 Å line blended into the C III line and the Si III triplet is still present, we favour a spectral type O9.5 IV, which is in good agreement with the atmospheric parameters derived by Herrero et al. (1992).

3.19. HD 155806 = CPD $-33^\circ 4282$

The prototypical Oe star, HD 155806 was first reported as a Be star by Merrill et al. (1925). It was classified as O8 Ve by Hiltner et al. (1969) and O7.5 IIIe by Conti & Leep (1974), and it has been repeatedly included in different works on Be and O stars. Hanuschik et al. (1996) reported a complex multi-peaked structure in Hα, while Walborn (1980) reported Fe II emission lines in the yellow region of the spectrum.

In our red spectrum, Hα is an asymmetric double-peaked structure, while He I 6678 Å shows weak double-peaked emission (see Fig. 8). In the blue, we observe no Fe II emission lines, but C II 4267 Å and Mg II 4481 Å show double-peaked emission (see Fig. 10). These lines are not normally seen in emission in later Be stars. In addition, He I 4713 Å also shows double-peaked emission and there are weak selective N III emission lines, typical of a mild O((f)) star. Note that the presence of these N III lines is not consistent with the definition of Oe star given by Conti & Leep (1974). They are, however, morphologically normal for a O7.5 III spectral type. Based on the strength of metallic features (and specifically Si IV 4089 Å), we adopt O7.5 IIIe, though He II 4686 Å is rather strong and hence the luminosity is on the low side. Indeed Walborn (1973) classified it O7.5 V[n]e.

HD 155806 is therefore the earliest known Be star showing both emission lines typically seen in Be stars and others which are not typical of Be stars of later types.
Fig. 9. The spectrum of ζ Oph (bottom) is compared to that of the MK O9.5 V standard HD 34078 artificially spun up to a rotational velocity $v \sin i = 400 \text{ km s}^{-1}$, estimated by Herrero et al. (1992) for ζ Oph. The metallic lines appear slightly stronger in ζ Oph, while the He II lines are slightly weaker, suggesting luminosity class IV.

3.20. BD $-08^\circ 4634$

Classified O9? V?p by M55, BD $-08^\circ 4634$ has never been listed as an emission-line object. Our spectrum, however, reveals weak double-peaked Hα emission, with a deep central reversal going below the continuum level. This shape is typical of Be shell stars, though the low quality of our spectrum does not allow us to ascertain whether this object is a Be shell star. Our blue spectrum is not of a very high quality either, but the photospheric lines are rather sharp. He II 4686 Å is weak and the Si III triplet is rather strong. The spectral type is likely B0.2 III, but Nitrogen is moderately enhanced, giving a final classification of BN0.2IIIe.

3.21. HD 228548 = BD $+39^\circ 4098$

Known as a Be star since Merrill & Burwell (1933), HD 228548 was classified B0pe by M55. It still displays strong single-peaked Balmer-line emission and metallic veiling. He i lines show partial infilling, except for He i 4713 Å, which is in emission.

No He II lines are seen on the spectrum, but C III 4650 Å is strong, suggesting that the spectral type is close to B1. The Si III triplet is completely lost in the emission forest, which would indicate that the luminosity is low. Therefore we adopt B1 Ve, though a slightly earlier classification is possible.

3.22. BD +36°4145

Given as an emission line star in the LS catalogue – LS II +37°99, OB(ce,le) –, BD +36°4145 was classified O9 V by M55. There is no evidence of emission in our spectra. The classification spectrum, shown in Fig. 3, is rather similar to the O9 V standard 10 Lac, but the He II lines are clearly stronger, suggesting O8.5 V.

3.23. BD +42°3835

BD +42°3835 was classified O9p by M55 and later given as O9 III? by Garmany & Vacca (1991). We observe no obvious peculiarities in what appears to be a rather luminous star. Its spectrum is actually extremely similar to that of HD 16832 (see Fig. 4), and we adopt the same spectral type.

3.24. BD +45°3260

This star, classified as O9 V by M55, was included in this work because of a very discrepant classification as B3 II by Fehrenbach (1961). Our spectrum, seen in Fig. 10, is incompatible with both classifications. He II 4541 Å is comparable to He I 4471 Å and selective N III lines are in emission, but He II 4686 Å is relatively strong. The spectral type is hence O7.5 III((f)).

3.25. LS III +58°38

This little studied star was classified O9p by Georgelin et al. (1973) and later given as O9 III? by Garmany & Vacca (1991). Though the red spectrum appears normal, in the blue spectrum all lines are clearly double even at this moderate resolution (see Fig. 3). In both spectral components He II 4686 Å is stronger than C III 4650 Å and one of the components seems to have rather strong He II 4541 Å. LS III +58°38 is hence a double-lined spectroscopic binary. The spectral types of the components are likely to be O8 and O9 approximately.

3.26. LS III +57°88

First listed as a Be star by Merrill & Burwell (1943), LS III +57°88 was classified B0? III?pe by H56. It is still in a very strong Be phase, presenting very heavy metallic emission.

Our spectrum (see Fig. 1) shows that He II 4686 Å is weakly present, but the Si IV lines are lost in the broad wings of Hα. Though an exact spectral type cannot be given, B0.5 Ve is most likely.
3.27. HD 240234 = BD +59°2677
Catalogued as a Be star by Merrill & Burwell (1949), HD 240234 was classified O7e by Mayer & Macák (1973). In our red spectrum, Hα is rather strongly in emission and there are many weak double-peaked emission lines corresponding to He I and Fe II.

The blue spectrum (shown in Fig. 7) is affected by a moderately strong emission line forest. Both Si IV 4089Å and C III 4650Å are very strong, He II 4686Å is slightly weaker and He II 4200Å is clearly seen. Considering the condition He II λ4541 ≃ Si III λ4552, we take O9.7 IIIe. We note that Si III 4552Å could actually be suffering from blanketing by some emission line, but the strength of the He II lines does not allow a classification later than B0 III, so this object is most likely an Oe star, though a very late one.

3.28. BD +61°2408
Classified B0 III? by H56, BD +61°2408 was observed by Crampton & Fisher (1974), who noted double lines in its spectrum. In our spectrum, Hα and He I λ6678, 7065Å are all clearly split. The secondary component, however, is rather weak compared to the primary.

In the blue, all three He II lines are present, but He II 4686Å is not very strong. As the Si IV lines are far too weak to justify the B0 III classification, we adopt B0.2 IV.

3.29. HD 224599 = BD +59°2801
HD 224599 lies within the traditional limits of Cas OB5 and is listed as an emission-line star in the LS catalogue – LS I+59°25, OBce,h. It was classified B0.5? V?nnp by M55. In our spectrum, Hα is a narrow emission line of moderate intensity, while Hβ and He I λ6678, 7065Å display weak asymmetric double-peaked emission lines.

As shown in Fig. 2, He II 4686Å is barely noticeable, indicating a spectral type B0.7. At this spectral type, the strong Si III and C III lines clearly indicate a luminosity class III. Using the photometry of H56 and our spectral type, we find $DM = 12.4$, which is consistent with the Perseus Arm in this direction.

4. Discussion

4.1. Variability and reliability
Variability is a well known characteristic of the Be phenomenon and indeed several surveys (e.g., Steele et al. 1999; Negueruela 2004) have found that stars classified as emission-line objects did not display any sign of emission at the time of the observations. It is therefore a matter of importance to be able to rely on bibliographic data in order to assess the likelihood that a star catalogued as an emission-line object has indeed displayed emission lines at some time.

In this respect, it is suggestive, though likely not statistically significant, to note that the 12 stars in our sample included in the Mount Wilson Catalogue (MWC, Merrill & Burwell 1933 and continuations) do display emission lines in our spectra, while 3 out of 4 objects given as emission-line stars in the LS catalogue and not included in the MWC were found not to display any emission. As a matter of fact, the only object displaying emission not in the MWC (HD 224599) seems to be intermittently in the Be phase, as M55 did not classify it as an emission-line object.

Before the description of the class of B[e] stars (Conti 1976), it was customary to use the Bpe designation for emission-line stars displaying forbidden lines (cf. Underhill & Doazan 1982). However, among the our sample, it appears that objects classified by M55 and H56 as “pe” tend to be peculiar only in the sense that the presence of very strong emission lines makes their spectral classification difficult. A representative spectrum is shown in Fig. 6: all lines are double-peaked and correspond to permitted transitions of singly ionised metals. Objects marked as “p” but not displaying emission lines tend to appear as spectroscopic binaries at higher resolution. No truly “peculiar” object has turned up from in sample.

4.2. The Oe stars
The list of Oe stars presented by Conti & Leep (1974) showed a good spread in spectral types. However, Frost & Conti (1976) already cautioned that the spectral classifications were insecure and likely to be affected by line infilling in He I 4471Å. This has been shown by our modern spectra to be the case for all the Oe stars catalogued, except HD 155806.

All the stars classified as B0pe have also received later classifications here. This is in contrast to the result obtained by Steele et al. (1999) for a sample of Be stars spanning the B0-B9 range. There the majority of objects, especially those of late spectral types, were found to have earlier spectral types than given in the literature. Both effects can be readily explained by infilling of He I lines affecting the spectral types derived from old low-resolution spectograms.

With the new classifications, all the known Oe stars, with the exception of HD 155806 and likely HD 39860, have spectral types in the O9-B0 range. Their spectral types are so close to the B spectral type that they may just be seen as the tail of the distribution of Be stars. Only HD 39680 and HD 155806 seem to display characteristics not shared by later-type Be stars that might be attributed to higher temperatures (He I 4471Å and C II 4267Å in emission, respectively).

The number of Be stars with spectral types earlier than O9.5 is very small. To the best of our knowledge, there are four catalogued stars reported by several independent sources to be emission-line stars and have “modern” spectral types earlier than O9.5: the two stars discussed in the previous paragraph, HD 344863 (O9 III), discussed in Paper I and not in a Be phase at present, and HD 17520, in IC 1848, classified O9 V by Conti & Leep (1974) and O8 V by Walborn (1971), which entered a Be phase around 1985 (Walter 1992). In addition, BQ Cam and LS 437, the optical counterparts to the X-ray pulsars V 0332+53 and X 0726−260, have spectral types O9 V or slightly earlier (Negueruela 1998). However, these two latter stars are certain to have been sped up to high rotational velocities because of extensive mass transfer, and their
representativity is hence arguable. Moreover, these two stars are much fainter than the ones included in our (and other) sample(s) and are thus drawn from a much larger volume. They should not be included in counts based, like the present one, on catalogues of bright stars.

Such scarcity is most likely not due to selection effects, though the number of O-type stars is certainly rather low to allow good statistics. In the recent O-type star catalogue of Ma´ ız-Apell´ aniz et al. (2004), which is complete to though the number of O-type stars is certainly rather low to allow good statistics. In the recent O-type star catalogue of Ma´ ız-Apell´ aniz et al. (2004), which is complete to $V = 8$ and includes many stars fainter than this, there are $\approx 80$ stars with spectral types in the $O7.5$-$O9$ range and luminosity classes III–V. Of these, 3 are Oe stars (HD 344863 is not included). Though we are certainly in the area of very small number statistics, the fraction of Oe stars appears to be rather lower than that of Be stars. Moreover, no Oe stars are known with spectral type earlier than O7.5.

It seems then that observations strongly indicate a real decline in the fraction of Be stars for spectral types earlier than B0. Such decline is, in principle, in agreement with arguments presented by Meynet & Maeder (2000; see also Keller et al. 2001). Assuming a direct connection between fast rotation and the Be phenomenon, these authors examine the evolution of the ratio $\Omega/\Omega_{\text{crit}}$ (surface angular velocity as a fraction of the critical breakup velocity) during the lifetime of a star. In their models of fast-rotating stars, objects with $M_\ast \approx 15 M_\odot$ evolve in such a way that $\Omega/\Omega_{\text{crit}}$ increases during the lifetime of the star. Objects with $M_\ast \gtrsim 15 M_\odot$ display the opposite behaviour because of angular momentum loss associated with their winds.

Keller et al. (2001) go on to argue that the higher fraction of Be stars to non-emission B stars observed close to the main-sequence turn-off in some young open clusters supports the idea that most Be stars develop their emission characteristics late in their lifetime, as their ratio $\Omega/\Omega_{\text{crit}}$ approaches unity. In this view, the scarcity of Oe stars would be a simple consequence of the fact that the $\Omega/\Omega_{\text{crit}}$ ratio decreases for stars with masses in the O-type range. The only Oe stars would be those that are born with rotational velocities close to the critical value.

Though such arguments may well be qualitatively valid, it is clear that observations do not support the details of the picture presented by Keller et al. (2001). In the latest models of rotating stars by Meynet & Maeder (2003), stars of $20 - 25 M_\odot$ start their lives with $T_{\text{eff}} = 32000 - 35000 K$, corresponding to spectral types O9–V and evolve towards higher luminosities and lower $T_{\text{eff}}$, entering the B spectral range after 5 and 5.5 Myr respectively. At this point they would likely have spectral types B0IV and B0III respectively. The B0–I III range is therefore populated by stars of ZAMS mass in the $20 - 25 M_\odot$ range on their way to the end of their H core-burning phase, in good agreement with the mass calibration of Vacca et al. (1996).

If the scenario outlined above was correct, stars of $\approx 20 M_\odot$ would only be seen as Be stars if they happened to be born with $\Omega$ close to the critical value, and only for a short phase close to the ZAMS. The number of Be stars among evolved $20 M_\odot$ stars would be very small or zero. The observational evidence points exactly in the opposite direction: Be stars are rather more frequent among B0–1 III stars than among O8–9 V stars (cf. Paper I and here). As the decrease in the number of Be stars for spectral types earlier than O9.5 seems to generally support the scheme of Meynet & Maeder (2000), possible explanations for this disagreement could be that either 1) the relation between stellar mass and spectral type needs to be shifted to lower masses or 2), more likely, the discontinuity in behaviour predicted by the models to occur at $15 M_\odot$ actually happens at higher masses. This would be a consequence of the treatment of angular momentum transport by the models. As a matter of fact, the more modern models by Meynet & Maeder (2003) show a completely different behaviour for moderately massive stars. Instead of decreasing through the whole MS lifetime, the $\Omega/\Omega_{\text{crit}}$ ratio for stars in the $15 - 25 M_\odot$ range actually grows quite strongly some time before the end of the H-burning phase. This results in a peak approaching $\Omega/\Omega_{\text{crit}} = 1$ during the second half of the H-burning lifetime. This prediction is in much better agreement with observations, as it supports a high Be fraction among early B-type giants.

4.3. Outlook

The very scarcity of Oe stars makes them extremely interesting objects. The fact is that very few stars with spectral type around O8 V display Be characteristics. Determination of the physical parameters of these objects may therefore give us some clue about what “extra” factor turns them into emission-line stars.

In any case, the searches carried out in Paper I and this work very clearly imply that the Be phenomenon is confined to a limited, if broad, range of stellar parameters. High temperature stars do not display the Be phenomenon, and high luminosity stars do not either. If the results presented here are to be taken at face value, it may even be thought that stars of $20 - 25 M_\odot$ acquire Be characteristics when they come into the range (in $T_{\text{eff}}$ and $L_\ast$) of Be stars and then lose them again as they move out towards high luminosities. Whether this is telling us something important remains to be seen.

5. Conclusions

We have searched for new Oe stars by observing a sample of early Be stars and objects classified as Op and B0p. We find that Oe stars are indeed very rare. Moreover almost all known Oe stars have spectral types O9.5 or later, with only 4 stars known to have earlier spectral types. The earliest spectral type is that of HD 155806, O7.5 III. The much higher fraction of Be stars among B0-1 giants than among O8-9 V stars, which are supposed to be their progenitors, strongly argues for an increase of the $\Omega/\Omega_{\text{crit}}$ ratio during the MS lifetime of stars with $M_\ast \approx 20 M_\odot$. Careful determination of the stellar parameters of the few Oe stars known may cast some light on the physical conditions leading to the Be phenomenon.

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