A Search for Luminous Be stars

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Abstract. As Be stars are restricted to luminosity classes III-V, but early B-type stars are believed to evolve into supergiants, it is to be expected that the Be phenomenon disappears at some point in the evolution of a moderately massive star, before it reaches the supergiant phase. As a first stage in an attempt to determine the physical reasons of this cessation, a search of the literature has provided a number of candidates to be Be stars with luminosity classes Ib or II. Spectroscopy has been obtained for candidates in a number of open clusters and associations, as well as several other bright stars in those clusters. Among the objects observed, HD 207329 is the best candidate to be a high-luminosity Be star, as it appears like a fast-rotating supergiant with double-peaked emission lines. The lines of HD 229059, in Berkeley 87, also appear morphologically similar to those of Be stars, but there are reasons to suspect that this object is an interacting binary. At slightly lower luminosities, LS I +56°92 (B4 II) and HD 333452 (O9 II), also appear as intrinsically luminous Be stars. Two Be stars in NGC 6913, HD 229221 and HD 229239, appear to have rather higher intrinsic magnitudes than their spectral type (B0.2 III in both cases) would indicate, being as luminous as luminosity class II objects in the same cluster. HD 344863, in NGC 6823, is also a rather early Be star of moderately high luminosity. The search shows that, though high-luminosity Be stars do exist, they are scarce and, perhaps surprisingly, tend to have early spectral types.

Key words: stars: emission-line, Be – stars: evolution – supergiants –open clusters and associations: general

1. Introduction

In recent years, it has become obvious that rotation plays a fundamental role in the evolution of massive stars (Maeder & Meynet 2000). 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). However, one of the most obvious manifestations of stellar rotation, the Be phenomenon, remains unexplained after more than a century of study (see Porter & Rivinius 2003 for a recent review).

The accepted definition of a Be star is that given by Collins (1987), namely, “a non-supergiant B star whose spectrum has, or had at some time, one or more Balmer lines in emission”. This definition may need some qualification, as the Be phenomenon appears to extend into late O and early A subtypes, and also because some objects (such as Herbig AeBe stars) are generally excluded from the class (see Porter & Rivinius 2003 for a detailed discussion). It is, however, widely accepted for the “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.

The “non-supergiant” part of the definition is generally understood to represent a warning against potential confusion. Many B-type supergiants show relatively strong Hα emission lines, which are not produced in a circumstellar disk. These lines arise in the strong radiatively-driven winds of the supergiants (e.g., Leitherer 1988) and are considered morphologically normal (i.e., not unusual for the spectral type). As a consequence of their different formation mechanisms, Hα emission lines in classical Be stars and supergiants usually have rather different shapes, with the lines in Be stars showing rotational symmetry, while the lines in supergiants typically display P-Cygni profiles (see Fig. 1).

There may, however, be a deeper interpretation to this qualification, as it clearly states that no supergiant star displays the Be phenomenon. As an important fraction of O9-B1 main sequence and giant stars display the Be phenomenon (e.g., Zorec & Briot 1997) and these stars are sufficiently massive to become blue supergiants at a later stage, one would (naively) conclude that the Be phenomenon has to disappear at some point during the post-Main-Sequence (post-MS) evolution of the star.

There are two immediately obvious physical effects to which this cessation of the Be phenomenon could be linked.
On the one hand, the Be phenomenon is known to be related to fast rotation and supergiants do not rotate fast. If the unknown cause of mass loss requires fast rotation, then mass loss could stop as the rotation slows. Because of angular momentum conservation, a star is expected to slow down as it expands (cf. Steele 1999). On the other hand, as the luminosity increases, the star develops a slow radiative wind which could exert a force on the circumstellar disk that would lead to its dissipation. The disk would be swept away by radiation pressure even if suitable conditions for its formation were still present.

In reality, things could not be so simple. The relevant factor in the Be phenomenon is not high rotational velocity itself but its ratio to some critical velocity, which measures the tendency of the star to be centrifugally disrupted (e.g., Porter 1996; Keller et al. 1999; 2001). More complicated evolutionary models can therefore be envisaged in which loss of angular momentum via wind breaking stops the Be phenomenon (cf. Meynet & Maeder 2000; Keller et al. 2001).

In any case, evidence from young open clusters in the Milky Way and the SMC (e.g., Keller et al. 1999; 2001) supports the idea that fast rotating B stars become Be stars late in their MS life, as the highest fraction of Be stars appears to occur at the MS turn-off and above it. Therefore, whatever the mechanisms involved, if the Be phenomenon occurs preferentially in stars that are close to the end of their MS lives or have already started to move away from the MS and, at the same time, we know that it has already stopped when the star reaches the supergiant stage, it is tempting to conclude that the Be phenomenon is related to some physical conditions occurring only during a fraction of the lifetime of the star. If this is so, some information on the mechanism producing the Be phenomenon can be gained by determining at what phase in the evolution of the star the Be characteristics disappear and what are the physical parameters of the star when this happens.

In this spirit, a programme has been started to identify the highest luminosity at which a star may display the Be phenomenon. If one can identify stars of relatively high luminosity which still display the Be phenomenon, important constraints could be gained on the physical conditions that lead to its development. Some care is necessary here, as Be characteristics are mainly observational, and the assumption that they obey to a single physical mechanism may be misleading. Therefore a careful determination of the stellar parameters of putative high luminosity Be stars via fitting of stellar atmosphere models will be necessary before any conclusion can be reached.

As a first step for such work, in this paper I set out to investigate the existence of high-luminosity Be stars. As Be stars are known to be widespread among luminosity classes III to V, attention is centred on OB stars of luminosity class I or II that may display Be characteristics.

2. Target selection and Observations

A search of SIMBAD was made in order to select objects classified as emission-line stars with spectral types earlier than A0 and luminosity classes I or II. Only objects North of \( \delta = -10^\circ \) were considered because of the telescopes used. Stars with luminosity class Ia were excluded, as many of them appear in lists of emission-line stars, even when their H\( \alpha \) emission lines are morphologically normal for their spectral type; for example, HD 14818 (= MWC 45) or HD 224055 (= MWC 404) in Fig. 1.

A literature search showed that many O-type stars classified as emission-line objects had later been considered morphologically normal Of stars. The same applies to several B stars or luminosity classes Iab and Ib which display P-Cygni emission profiles in H\( \alpha \). Also, it was seen that many stars classified as late-B/A luminosity class II objects in old studies (such as the LS catalogue; Hardorp et al. 1959, and continuations) were later found to be shell stars of much lower luminosity. A shell star is a Be star seen at high inclination, which, in addition to emission lines, presents sharp absorption cores of singly-ionised metals, which at low resolution, may resemble a high-luminosity star (cf. Porter 1996; Hanuschik 1995).

It has also been suggested that some low-mass interacting binaries and post-AGB stars may display spectra very similar to those of supergiants during short periods of time (e.g., Saselov 1986). For these reasons, targets were preferentially selected among objects belonging to open clusters or associations, so as to make sure that they were really massive stars of high luminosity. This selection made also possible to observe other members of these associations to be used as comparison.
Table 1. Log of observations. Objects specifically targeted because they have been referred to in the literature as high-luminosity emission-line stars are marked with a †. Other objects are comparison stars in the same clusters.

| Association          | Object      | Date          | Configuration | Spectral Range |
|----------------------|-------------|---------------|---------------|----------------|
| Vul OB1 (NGC 6823)   | HD 344863†  | Jul 1st, 2003 | INT+IDS+R900V | 3500–5850Å     |
|                      |             | Jul 3rd, 2003 | INT+IDS+R900V | 4900–7200Å     |
|                      | HD 344873†  | Jul 2nd, 2003 | INT+IDS+R900V | 3500–5850Å     |
|                      |             | Jul 3rd, 2003 | INT+IDS+R900V | 4900–7200Å     |
| Cyg OB3 (NGC 6871)   | HD 190918   | Jul 31st, 2001| INT+IDS+R900V | 3500–5850Å     |
|                      |             | Jul 3rd, 2003 | INT+IDS+R900V | 4900–7200Å     |
|                      | HD 344873†  | Jul 31st, 2001| INT+IDS+R900V | 3500–5850Å     |
|                      |             | Aug 1st, 2001 | INT+IDS+R900V | 4460–4910Å     |
|                      | HD 227611†  | Jul 18th, 2001| INT+IDS+R900V | 3500–5850Å     |
|                      |             | Jul 31st, 2001| INT+IDS+R900V | 3500–5850Å     |
|                      |             | Aug 1st, 2001 | INT+IDS+R900V | 4460–4910Å     |
|                      | HD 227634   | Jul 31st, 2001| INT+IDS+R900V | 3500–5850Å     |
|                      |             | Aug 1st, 2001 | INT+IDS+R900V | 4460–4910Å     |
|                      | HD 227733†  | Jul 1st, 2001 | INT+IDS+R900V | 3500–5850Å     |
|                      |             | Jul 6th, 2002 | INT+IDS+R900V | 3500–5850Å     |
|                      | HD 190918   | Jul 2nd, 2003 | INT+IDS+R900V | 3500–5850Å     |
|                      |             | Jul 3rd, 2003 | INT+IDS+R900V | 4900–7200Å     |
|                      | HD 227611†  | Jul 18th, 2001| INT+IDS+R900V | 3500–5850Å     |
|                      |             | Jul 31st, 2001| INT+IDS+R900V | 3500–5850Å     |
|                      |             | Aug 1st, 2001 | INT+IDS+R900V | 4460–4910Å     |
|                      | BD +35°3955 | Jul 31st, 2001| INT+IDS+R900V | 3500–5850Å     |
|                      |             | Aug 1st, 2001 | INT+IDS+R900V | 3500–5850Å     |
|                      |             | Jul 6th, 2002 | INT+IDS+R900V | 3500–5850Å     |
|                      | V439 Cyg    | Oct 23rd, 2001| INT+IDS+R900V | 3500–5850Å     |
|                      |             | Oct 22nd, 2001| INT+IDS+R900V | 3500–5850Å     |
|                      | Cyg OB1     | HD 194280†   | Jul 1st, 2003 | INT+IDS+R900V | 3500–5850Å     |
|                      |             | Jul 5th, 2003 | INT+IDS+R900V | 3500–5850Å     |
|                      | Cyg OB1 (NGC 6913) | HD 229221†  | Jul 4th, 2003 | INT+IDS+R900V | 3500–5850Å     |
|                      |             | Jul 6th, 2003 | INT+IDS+R900V | 3500–5850Å     |
|                      | HD 229238   | Jul 3rd, 2003 | INT+IDS+R900V | 3500–5850Å     |
|                      | HD 229239†  | Jul 3rd, 2003 | INT+IDS+R900V | 3500–5850Å     |
|                      |             | Jul 5th, 2003 | INT+IDS+R900V | 3500–5850Å     |
|                      | None        | HD 207329†   | Jul 7th, 2003 | INT+IDS+R900V | 3500–5850Å     |
|                      |             | Jul 7th, 2003 | INT+IDS+R900V | 3500–5850Å     |
|                      | Cam OB3     | LS 1 +56°92† | Jul 23rd, 2002| INT+IDS+R900V | 3500–5850Å     |
|                      |             | Jul 25th, 2002| INT+IDS+R900V | 3500–5850Å     |

Though many of the clusters considered are relatively well studied and spectral classifications exist for some of their members, it was felt necessary to re-observe some of the brightest members in order to provide a consistent framework. As an example, Table 2 lists the spectral types assigned by different authors to the five bright stars defining the core of NGC 6913, which is thought to be a Trapezium-like system. Even though there is a general agreement, there is a lot of variation. Apart from some systematic effects (the intermediate types B0.2 and O9.7 were not defined at the time of the first works), this variation is most likely caused by differences of appreciation by the various authors. As we are concerned here with small differences in luminosity, having all spectral types in a single consistent system will allow us to effectively compare the Be stars with other luminous members.

Table 2. Spectral types assigned to the five bright members forming the core of NGC 6913 by different authors. References are R51: Roman (1951); M53: Morgan et al. (1953); M95: Massey et al. (1995); WH00: Wang & Hu (2000); Here: this work.

| Object          | R51   | M53   | M95  | WH00 | Here  |
|-----------------|-------|-------|------|------|-------|
| HD 229221       | B0II?e| B0III | B0II | B0II | B0II |
| HD 229227       | B0III | B0II  | B0.2I| B0II | O9.7I |
| HD 229234       | O9II  | O9.5I | O9II | O7II | O9II  |
| HD 229238       | B0.5I | B0.5Ib| B0I  | B0I  | B0.2I |
| HD 229239       | B0.5Ie| B0.5Iab| B0IV | B0I  | B0.2I |

Observations for this project have been carried out with several telescopes, mostly as poor-weather backup for other
Fig. 2. Typical Hα emission lines in Be stars. BD +35°3956, discussed in Section 3.1.1, is a weak Be star, and the emission line clearly displays the double peaks due to Keplerian broadening. In Be stars with stronger emission, like VES 152 (another Be star in the field of NGC 6871), the emission line is optically thick and the double-peaked structure can only be appreciated at relatively high resolution if the inclination to the line of sight is moderate or low.

projects, taking advantage of the brightness of targets. Most of the observations were obtained during a run on 2003 July 1st–7th at the 2.5-m Isaac Newton Telescope (INT) at La Palma, Spain. The telescope was equipped with the Intermediate Dispersion Spectrograph (IDS) and the 235-mm camera. The R900V grating and EEV#13 camera were used, resulting in a nominal dispersion of \( \approx 0.65 \text{Å/pixel} \). Further INT observations had been obtained on 2002 July 23rd–25th, using a similar configuration, but this time with the R1200Y grating and Tek#4 camera, which gives a dispersion of \( \approx 0.8 \text{Å/pixel} \).

Observations of stars in NGC 6871 were obtained as backup of several runs at the Observatoire de Haute Provence (OHP) during 2001 and 2002. The brightest stars were observed with the Aurélie spectrograph on the 1.52-m telescope during a run on 2001 July 31st–August 2nd. The spectrograph was equipped with grating #3 (600 l mm\(^{-1}\)) and the Horizon2000 2048 × 1024 EEV CCD camera, resulting in a dispersion of 0.22Å/pixel (resolving power of approximately 7000). Other stars were observed with the 1.93-m telescope equipped with the long-slit spectrograph Carelec and the EEV CCD.

The complete list of observations, with details of the configurations used, is shown in Table I. Spectral classification in the MK system is based on comparison with standard stars. The standards used here are those from Steele et al. (1999), which were observed with the INT + IDS + R1200B + EEV#12, resulting in a dispersion of \( \approx 0.5 \text{Å/pixel} \), i.e., slightly higher than with the R900V grating used for most of our observations. They have been complemented with spectra of \( \iota \) Ori (O9 III), \( \upsilon \) Ori (B0 V), HD 48434 (B0 III) and \( \iota \) CMa (B3 II) taken with the ESO 1.52-m telescope at La Silla Observatory, Chile, equipped with the Boller & Chivens spectrograph, fitted with the #32 holographic grating and the Loral #38 camera. This configuration also gives a nominal resolution of \( \approx 0.5 \text{Å/pixel} \).

The set of standards has been complemented by interpolation based on the grid provided by Walborn & Fitzpatrick (1990). Within the spectral range considered, the spectral type is mainly determined by the ratios of Si III and Si IV lines, while luminosities are deduced from the ratios between these lines and the He I lines (Walborn 1971).

3. Results

3.1. NGC 6823

This relatively young cluster in the Vul OB1 association contains the O7 V(\( f \)) star HD 344784 and the B0.5 Ia supergiant HD 344776. Two cluster outliers, believed to belong to the association, have been suggested as high-luminosity Be stars.

3.1.1. HD 344873

This star was originally classified as B0 II by Morgan et al. (1953), though its luminosity was considered uncertain by Walborn (1971), who gave it as B0 III?((n)). Massey et al. (1995) classified it as B0 III. HD 344873 is listed in Wakerling’s (1970) catalogue of emission-line stars, as it appears as OB+ h, r (Hα in emission) in the LS catalogue (LS II +23°43). In Fig. 3 the spectrum of HD 344873 appears compared to that of the B0 III standard HD 48434. The two spectra are very similar, though the Si III and specially the O II lines in HD 344783 are clearly weaker. This is suggestive of an earlier spectral type and, making use of the condition He II \( \lambda 4541 \text{Å} \approx \text{Si III } \lambda 4552 \text{Å} \), we can consider a classification O9.7 II as the spectral type for HD 344873. The weaker He II \( \lambda 4686 \text{Å} \) would then suggest a higher luminosity, and this is supported by the strong Si IV doublet. Therefore we take O9.7 II as the spectral type for HD 344873. The Hα region of HD 344873 is shown in Fig. 4. There is no hint of emission components.

3.1.2. HD 344863

Originally classified as B0 II? by Morgan et al. (1953), HD 344863 has been marked as a Be star by several authors. It appears as OB+ ce,h,r (Hα and Balmer discontinuity in emission) in the LS catalogue (LS II +24°12) and is given as B0?II-IIIe by Schmidt-Kaler (1967), but is reported to be strongly in absorption in 1982 (EW\(_{H\alpha} = +3.3 \text{Å} \)) by Peppel (1984). The spectrum of HD 344863 is clearly earlier than that of HD 344873. O II lines are basically absent from the spectrum, as also is the Si III triplet. He II \( \lambda 4541 \text{Å} \) is well developed, but
Fig. 3. Classification spectra of two outliers of NGC 6823, reported in the literature to have shown a Be phase, HD 344863 (top) and HD 344873 (middle). The bottom spectrum is that of the B0 III MK standard HD 48434, artificially spun up to 120 km s$^{-1}$, for comparison.

much weaker than He I $\lambda 4471$Å, suggesting a spectral type around O9. The fact that He II $\lambda 4541$Å $>$ He I $\lambda 4387$Å and He II $\lambda 4200$Å $>$ He I $\lambda 4144$Å would allow an O8.5 classification (N. Walborn, priv. comm.). As He II $\lambda 4686$Å is not stronger than C III $\lambda 4650$Å, it must have a relatively high luminosity. So we adopt O9 III for HD 344863, though it is close to O8.5.

The shape of H$\alpha$ (Fig. 4) shows that HD 344863 is not in a Be phase at present.

3.2. NGC 6871

NGC 6871 is a rather extended open cluster, whose boundaries are not well defined. It is believed to be the core of the Cyg OB3 association. Estimates of its distance and age vary by relatively large amounts between different authors. Recent searches of emission-line stars have been carried out by Bernabei & Polcaro (2001) and Balog & Kenyon (2002), resulting in the detection of several faint Be stars and some pre-main-sequence objects.

The brightest star in the cluster is the O9.5 I+WN4 binary HD 190918. The spectra of four other bright stars in the cluster core are displayed in Fig. 5 (though HD 227611 is actually a few arcmin apart).

3.2.1. BD +35°3956

BD +35°3956, classified B0.5 V by Morgan et al. (1953), was found to be a mild Be star by Grigsby & Morrison (1988). Its H$\alpha$ spectrum, shown in Fig. 2, confirms that it is still in the Be phase. The apparent brightness of BD +35°3956 compared to nearby stars known to be of high luminosity has prompted its inclusion in this work.

The classification spectrum of BD +35°3956 is shown in Fig. 5. All the lines are very broad. This is likely to be partly due to fast rotation, but the shape of the metallic lines strongly suggests that it is a double-lined spectroscopic binary, though it cannot be ascertained with this S/N and resolution. Consid-
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Fig. 5. The two brightest Be stars in NGC 6871 compared to two other bright stars at the cluster centre. Apart from the obvious difference in the rotational velocities, the Be stars appear clearly to be of rather lower luminosity. The four spectra displayed here have been obtained with the 1.52-m telescope at OHP and have resolutions more than twice better than the spectra in Figures 3, 7 and 8. The small gap around $\lambda = 4420$ Å indicates the division between two poses.

3.2.2. HD 227611

First quoted as an emission-line star by Merrill et al. (1925), HD 227611 (= MWC 327) was classified Bpe by Roman (1951) and B0 II?pe by Morgan et al. (1953), the peculiarity likely referring to the strength of its emission lines.

HD 227611 is a very extreme Be star. In its red spectrum, I measure EW$_{H\alpha} = -88$ Å, which is close to the upper limit of values reported for Be stars. Its blue spectrum, shown in Fig. 5, is covered with double-peaked emission lines, corresponding to Fe II and other metals. Its spectral type and luminosity are therefore very difficult to determine. Considering that no He II lines are visible, it must be later than B0. As none of the Si IV doublet lines is comparable to the neighbouring He I lines (they are not even seen), but the O II/C III complex at $\lambda\lambda 6450 - 6550$ is prominent, it must be a main-sequence star earlier than B1 or a giant close to B1. It is certainly not a high-luminosity Be star.

3.2.3. HD 227733

A slightly fainter star in NGC 6871, HD 227733 was found to be an emission-line star during the Vatican survey (MacConnell & Coyne 1983). Bernabei & Polcaro (2001) suggested that it was surrounded by a bright nebula, prompting its study here.

The spectrum of HD 227733 is unremarkable, and it is not shown. Its spectral type is B1.5 Ve. No emission was present in H$\beta$ in the 2001 observation, but weak emission peaks appear inside the line in the 2002 spectrum.

3.2.4. HD 227634 and BD +35° 3955

Two of the brightest stars in NGC 6871 have been observed for comparison. Their spectra are displayed in Fig. 5. Other stars of similar apparent brightness are HD 190864 – O6.5 III(f) – and HD 190919 – B0.7 Ib (Walborn 1971).

HD 227634 displays moderately strong He II $\lambda 4686$ Å, which makes it earlier than B0.5 and Si IV $\lambda 4089$ Å $\geq$ He I $\lambda 4121$ Å, which makes it a luminous star. Comparison with other objects indicates that its spectral type is B0.2 II, though one would think it is slightly earlier and less luminous than HD 229239, discussed later. Walborn (1971) does indeed classify it B0 II.

BD +35° 3955 displays only a barely visible He II $\lambda 4686$ Å line, which puts it at B0.7. The narrowness of its lines and lack of Stark broadening in the Balmer lines indicates that it is very luminous. The strength of the O II and Si III lines puts it at B0.7 Iab, close to Ia, in excellent agreement with Walborn (1971).
3.3. NGC 6913

This young open cluster in the Cyg OB1 association, also known as M 29, contains a large number of luminous stars with spectral types around B0, several of which have been reported to present emission lines. As such, it represents a unique opportunity to correctly estimate the luminosities of the brightest Be stars.

3.3.1. HD 229221

Given as an emission line star (MWC 344) by Merrill & Burwell (1933), HD 229221 was classified B0 II?e by Roman (1951) and B0?I?pe by Morgan et al. (1953). HD 229221 appears to have displayed emission lines at all epochs, as it is given as B0e by Walker & Hodge (1968), mentioned to display EW_{Hα} = −13Å by Schild & Romanishin (1976), and classified Be by Massey et al. (1995). Wang & Hu (2000) classify it as B0 IIIe.

![Fig. 6. The blue spectrum of the Be star HD 229221, in NGC 6913. The strength of the emission lines is typical of a Be star. The star is moderately luminous, as metallic lines are clearly seen in spite of the relatively fast rotation.](image)

The classification of HD 229221 is complicated by the relatively strong emission spectrum. The weak He II λ4686Å and absence of He II λ4200Å make it later than B0. On the other hand, C III λ4650Å is very strong when compared to O II lines, suggesting a spectral type B0.2. The weakness of He II λ4686Å indicates then a relatively high luminosity, but Si IV λ4089Å does not appear very strong compared to the He I lines, preventing it from being higher than III. We take then B0.2 IIIe.

3.3.2. HD 229239

HD 229239 is given as an emission line star (MWC 1016) by Merrill & Burwell (1949), based on an observation obtained in 1946. It was classified B0.5 Ib by Roman (1951), but later is given as B0.5 Iab by Morgan et al. (1953), without reference to emission. Morgan et al. (1955) give it as B0 II and the luminous star catalogue lists it as OB,r (LS II +38°82), again without any reference to emission.

Further reference to HD 229239 as an emission line star is given by Perraud & Pelletier (1959), but no reference to emission is made by Walker & Hodge (1968). Unfortunately, none of these sources provides dates for the observations. No mention of emission lines is found in modern works. Massey et al. (1995) classify HD 229239 as B0 IV, while Wang & Hu (2000) give B0 I.

The Hα spectrum of HD 229239 is shown in Fig. 4 and clearly demonstrates that the star is not in a Be phase at present.

The classification spectrum of HD 229239 is shown in Fig. 7. The weak He II λ4686Å and absence of He II λ4200Å make it later than B0, the ratio of Si III to Si IV suggesting B0.2. The strength of the Si IV compared to the neighbouring He I lines indicates then a luminosity class III, in agreement with the strength of He II λ4686Å. Therefore we adopt B0.2 III.

3.3.3. HD 229227, HD 229234 and HD 229238

None of these stars has been reported as an emission-line object and they have been observed as comparison. Together with HD 229221 and HD 229239, they are the brightest members of NGC 6913 and constitute its obvious core. Their spectra are displayed in Fig. 7.

The lines in HD 229227 are rather broad, suggesting that it is a fast rotator. The condition He II λ4541Å ≃ Si III λ4552Å defines spectral type O9.7. The strength of He II λ4686Å is rather small, suggesting a relatively high luminosity. We adopt O9.7 III.

The spectrum of HD 229234 is very similar to that of HD 344863. The ratio of He II λ4541Å to He II λ4471Å supports an O9 spectral type. Metallic lines are moderately stronger than in HD 344863, indicating a slightly higher luminosity. We adopt O9 II.

The spectrum of HD 229238 is very similar to that of HD 229239. Again, the absence of He II λ4200Å and ratio of Si lines suggest B0.2. The Si IV lines, however, are clearly stronger in comparison to the He I lines, meaning that HD 229238 is more luminous. We adopt B0.2 II.

3.3.4. HD 194280

HD 194280 is a member of Cyg OB1, lying at some distance from NGC 6913. Classified as B0 Ib by Morgan et al. (1955), HD 194280 was recognised by Walborn (1972) as a C-rich star and reclassified OC9.7 Iab. Since then, it has been repeatedly observed by several authors as a reference star without any mention of emission characteristics (recent high-quality spectra are provided by Walborn & Howarth 2000). In spite of this, it appears in Wackerling’s (1970) catalogue, as it is given as OB,ce,h,r in the LS catalogue (LS II +38°73).

Our spectrum of HD 194280 shows no sign of emission in Hα (see Fig. 4). The spectrum shown by Walborn & Howarth (2000) could show a very weak incipient P-Cygni profile, but it would not have been detected in a low resolution spectrum. The possibility that HD 194280 has been an emission line star remains dependent on a single reference.

3.3.5. HD 194334

Less than 4 ′ from HD 194280, HD 194334 is another member of Cyg OB1. It was classified O7.5 V by Morgan et al. (1955).
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It is given as OB, ce, le, r (several emission lines) in the LS catalogue (LS II +38°74), and hence as an emission line star by Wackerling (1970).

The spectrum of HD 194334 displays strong selective N III emission features, typical of an O Type star. The S IV lines at λ 4486, 4504 Å, typical of luminous O-type stars are also present. He II λ 4686 Å is weakly in absorption and He I λ 4471 Å ≃ He II λ 4541 Å. The spectral type is hence O7 II (f).

Though the “le” classification in the LS catalogue generally implies Balmer emission lines, it seems likely that HD 194334 was classified as an emission-line star because of the lines typically seen in O-type stars of its luminosity. As the spectral type of HD 194334 falls well outside the range traditionally occupied by Be stars, and it is a high-luminosity O star, I will not take it as a serious Be candidate.

3.4. Berkeley 87

This moderately reddened cluster has been little studied, as stars are rather faint in the blue, because of high extinction. Its parameters are poorly known, but it is believed to be part of Cyg OB1.

3.4.1. BD +36°4032

This O-type star, lying at the core of Be 87 is given as an emission-line star in SIMBAD, though no references appear to mention emission features in this object. Even at this relatively low resolution, the star appears to be a spectroscopic binary. The lines are very broad and asymmetric, and their shapes change between the two spectra available. The composite spectrum has an approximate spectral type O8.5 V.

3.4.2. V439 Cyg

This emission-line star close to the centre of Be 87 has been suggested to display strong variability and have had an M-supergiant spectrum in the past (Polcaro & Norci 1998). It displays relatively strong Be features, with strong Balmer emission (EW Hα = − 41 Å). Unfortunately, our spectrum is not of very high quality and the presence of metallic emission lines makes exact classification difficult, but all features seen are compatible with a spectral type B1.5 Ve. It is certainly not a luminous Be star.

3.4.3. HD 229059

The brightest member of Be 87, though lying slightly off the core region, HD 229059 was identified as an emission line star (= MWC 1014) by Merrill & Burwell (1949). It has been classified B1.5 Ie by Roman (1951) and B1.5 Iap by Morgan et al. (1953).

Its spectrum, seen in Fig 8 certainly merits the “peculiar” classification. The presence of Si IV λ 4089 Å and He II λ 4686 Å (the feature at λ 4200 Å could be He II or N II) would make it earlier than B1. Its N II spectrum, however, is typical of a B2 supergiant. If one assumes the early spectral type, the object could be a B0.7 III star with strong N-enhancement and moderate C-deficiency. However, the weakness of all features in the spectrum of HD 229059, in spite of their sharpness, strongly suggests the possibility that the spectrum is actually a composite of a B2 I supergiant and a lower-luminosity late-O or B0 star. This possibility would explain the brightness of HD 229059 when compared to other cluster members (it is almost two magnitudes brighter than BD +36°4032). Further support for an O-type star in HD 229059 is given by the likely presence of N III λ 4097 Å in the wing of Hδ.
If we accept the possibility of a BN0.7 III star, its intrinsic magnitude would be far too low for it to be a member, when its reddening clearly supports membership (Turner & Forbes 1982).

HD 229059 displays moderately strong emission in Hα, Hβ and several He I lines (see Fig. 9). These lines are clearly asymmetric. Hα and Hβ display two peaks, with a much stronger blue one.

If HD 229059 is a single star, the shape of the lines would indicate that it is a Be star undergoing V/R variability, as it cannot be produced by an expanding envelope. A second possibility is that the lines are produced in a (mildly) interacting binary. In both cases, the asymmetry of the lines is expected to be variable. Clearly further observations of this object at higher resolution are needed in order to settle its nature, the origin of the emission lines and their possible variability.

3.5. HD 207329

Though not an obvious member of any open cluster or association, HD 207329 seems to be a bona fide high-luminosity Be star. Identified as an emission line star (= MWC 378) by Merrill & Burwell (1933), it was classified B1.5 Ib?e by Morgan et al. (1955). It appears in several works on Be stars, but in the LS catalogue, it is classified simply as OB (LS III +51°28) and Walborn (1971) classifies it as B2.5 Iat((n)), without reference to emission lines.

As can be seen in Fig. 8 and 10, emission lines in the spectrum of HD 207329 are, with the exception of Hα, weak and they may have been missed in low-resolution spectra, especially if they only covered the blue region.

The classification spectrum of HD 207329, displayed in Fig. 8 clearly shows that it is a very fast rotator of high luminosity. Comparison to the B1 Ib supergiant ζ Per (which is artificially spun up to 200 km s⁻¹ in Fig. 8) indicates that it is of later spectral type, as the C II λ4267 Å line is clearly stronger than neighbouring O II lines. The fact that N II λ4631 Å is rather weaker than O II λ4640 Å makes it earlier than B2 and prevents it from being N-enhanced. Therefore we take B1.5 as the spectral type. In spite of the broad profiles, the strength of Mg II λ4481 Å and the Si III lines indicates a supergiant. I take B1.5 Ib.

HD 207329 displays moderately strong asymmetric emission lines in Hα, Hβ (though the emission does not reach the continuum level) and several He I lines (see Fig. 10). The situation is exactly the opposite as in HD 229059, with the red peak being slightly dominant. Again, this configuration could be interpreted as typical of a Be star displaying V/R variations. This kind of emission lines could also arise in an expanding envelope. This possibility is directly testable with further observations: if the star is a Be star (in the sense that its mass loss occurs in the form of a Keplerian disk), the asymmetry of the lines will change over time. If the mass loss occurs in a spherically symmetric configuration, it should not change.

In any case, the fact that HD 207329 is a very fast rotator for its luminosity seems to support the idea that it is a Be star. If it was so, it would be the most luminous one known, clearly justifying further observations.

3.6. LS I +56°92

LS I +56°92 was observed during a survey for possible members of the Cam OB3 association (cf. Negueruela & Marco 2003) and found to display strong emission lines over the spectrum of a luminous mid-B star.
Fig. 9. In this montage of different sections of the spectrum of HD 229059, four emission lines are clearly visible, Hβ (top panel), He I λ5875 Å (mid panel) Hα and He I λ6678 Å (both in lower panel). He I λ4922 Å and He I λ5016 Å could show some emission components. All present the same symmetry, with the blue peak appearing much stronger. Such shape could not arise from an expanding envelope.

Previous references to this star are scarce. It is listed B6 Iah in the LS catalogue, and hence given as an emission-line star. The only other reference quoting spectroscopic observations is McCuskey (1956), who gives it as O8 and comments “very weak H lines”. The discrepancy between the two spectral types is certainly surprising, as LS I +56°92 lies in a region of the sky where confusion is extremely unlikely. The blue spectrum of LS I +56°92 is shown in Fig. 11, together with that of the B3 II standard ι CMa. The degree of Stark broadening in the lines of LS I +56°92 is at least as low as that in ι CMa, confirming that the luminosity class is at least as high. The rather higher strength of the Si II λ4128 Å doublet compared to He I λ4121 Å and of Mg II λ4481 Å against He I λ4471 Å indicate that LS I +56°92 is later than the standard. The weakness of the Si III triplet indicates that this is not a bright supergiant. We conservatively adopt B4 II, though B5 Ib would give a better fit to the distance modulus of Cam OB3.

Further confirmation of the high luminosity of LS I +56°92 is given by the presence of a relatively strong C II doublet to the red of Hα, as seen in Fig. 12.

Fig. 10. In this montage of different sections of the spectrum of HD 207329, four emission lines are visible, Hβ (top panel), He I λ5875 Å (mid panel), Hα and He I λ6678 Å (both in lower panel). All present the same symmetry, with two peaks, the red one slightly stronger. Such shape could arise from either a Keplerian disk or an expanding envelope. For line identification, see Fig. 9 as lines in HD 229059 are rather sharper.

4. Discussion

4.1. Consistency check

Before attempting to interpret results, it may be sound to check whether the spectral types derived provide a consistent way of comparing stars in clusters. For this, I have calculated the corresponding distance moduli for the stars under study using the intrinsic colours of Wegner (1994) and the spectral type to intrinsic magnitude calibration used in Negueruela & Marco (2003), conveniently interpolated when necessary. The distances obtained are listed in Table 3.

4.1.1. NGC 6871

The four stars observed have basically identical $E(B - V)$, fully compatible with the average $E(B - V) = 0.46$ found by previous workers. Their spectroscopic distances show a large spread, but it would fall within what is expected from the method if BD +35°3956 is indeed a binary (for two stars
Table 3. Distance moduli calculated using the spectral types derived here and photometry from the literature. The primary reference is Hiltner (1956), who has been found to be in good accord with other references when more than one measurement exists. For stars not observed by Hiltner photometry has been taken from Hoag et al. (1965, BD +35°3955) and Coyne et al. (1975, HD 227733).

| Assoc. | Object | Spectral Type | V   | (B − V) | E(B − V) | DM  |
|--------|--------|---------------|-----|---------|----------|-----|
| Vul OB1 | HD 344863 | O9 III | 8.83 | 0.68 | 0.94 | 11.4 |
|         | HD 344873 | O9.7 II | 8.77 | 0.77 | 1.00 | 11.4 |
| Cyg OB3 | HD 227634 | B0.2 II | 7.91 | 0.25 | 0.46 | 12.1 |
|         | HD 227733 | B1.5 V(e) | 10.31 | 0.24 | 0.46 | 11.7 |
|         | BD +35°3955 | B0.7 Iab | 7.38 | 0.25 | 0.45 | 12.3 |
|         | BD +35°3956 | B0.5 Ve | 8.85 | 0.19 | 0.43 | 11.3 |
| Cyg OB1 | HD 229221 | B0.2 IIIe | 9.21 | 0.92 | 1.14 | 10.8 |
|         | HD 229227 | O9.7 III | 9.38 | 0.80 | 1.04 | 11.6 |
|         | HD 229234 | O9 II | 8.92 | 0.77 | 1.04 | 11.6 |
|         | HD 229238 | B0.2 II | 8.88 | 0.90 | 1.11 | 11.2 |
|         | HD 229239 | B0.2 III | 8.92 | 0.87 | 1.10 | 10.6 |
|         | HD 194280 | OC9.7 Iab | 8.39 | 0.76 | 0.99 | 11.6 |
|         | HD 194334 | O7 II(f) | 8.77 | 0.84 | 1.13 | 11.2 |

Fig. 11. Classification spectrum of LS I +56°92 (top), showing the presence of strong single-peaked emission lines. The spectrum of the B3 II standard at similar resolution is shown for comparison. Though LS I +56°92 is obviously later, the Stark broadening of the Balmer lines is comparable or smaller, indicating a high-luminosity.

Fig. 12. Hα region in LS I +56°92 showing the strong single-peaked emission line. Though the shape is typical of a Be star, the strong C II λλ 6578, 6583 Å doublet clearly confirms that this is a star of high luminosity. Continuum units are shown in the vertical axis.

4.1.2. Cyg OB1

The distance moduli have been calculated assuming that $R = 3.1$, though there are strong reasons to believe that the reddening to NGC 6913 does not follow the standard law (Crawford et al. 1977; Wang & Hu 2000). It is hoped that they can still be used for internal comparison.

Surprisingly, all the luminosity I and II objects give very consistent distances, but the two objects proposed as Be stars, which have luminosity class III give rather shorter distances.

In the case of HD 229221, this is partly due to the overestimate of the interstellar extinction, as the observed $E(B − V)$ must have a component of circumstellar origin, like in all Be stars. If we rather assume that all the stars are at the same distance, we find that HD 229221 and HD 229239 are (almost) as luminous as cluster members with luminosity class II, while HD 229227, a fast rotator but not a Be star, is rather fainter. We have to conclude that the two confirmed Be stars, HD 229221 and HD 229239 are rather luminous stars.

For Berkeley 87, no attempt has been made at deriving distance moduli, as none of the stars observed appears to be a single non-emission-line star.
4.2. Variability

Variability is a well known characteristic of the Be phenomenon. We find that several stars that have been classified as emission-line stars in the past do not display any sign of emission now. In principle, we will ignore the possibility of a wrong identification and rather cavalierly assume that the lack of emission lines in modern spectra must be taken precisely as demonstration of variability, identifying our targets as Be star (rather than other types of emission line stars).

The only exceptions to this boldness would be HD 194280 and HD 194334. The former is well observed, has a very high luminosity and a single reference to emission lines. The latter does not look a strong case either. In the case of BD +36°4032, we may assume that the presence of double lines may have induced confusion with emission components. Moreover, there appears to be no reliable source identifying the object as an emission-line star.

Among the initial candidates, the three objects in NGC 6871 and V439 Cyg have been found to be indeed Be stars, but close to the main sequence, rather than luminous stars. We are left with 4 candidates that displayed emission lines at the time of the observations (HD 229221, HD 207329, LS I +56°92 and HD 229059, which may not be a Be star after all), two other candidates that did not display emission lines, but have been reported as Be stars by several independent sources (HD 344863 and HD 229239) and one possible Be star which has only been reported once (HD 344873).

Another high-luminosity Be star reported in the literature is HD 333452. This object was classified B0III:n by Morgan et al. (1955), the use of both an uncertainty marker and the “p” tag clearly indicating some peculiarity. The Luminous Star catalogue classifies it as OB,ce,le,r. However, HD 333452 was observed by Steele et al. (1998) in 1998 and appeared as a normal absorption-line O9II star.

Another potential high-luminosity Be star is BD +56°511, in h Per. This object has spectral type B1 III (Steele et a. 1999) and is widely reported to be a mild Be star (cf. Vrancken et al. 2000). Vrancken et al. (2000) find an effective gravity of only log $g = 3.1 \pm 0.1$, based on model atmosphere analysis, which would suggest a rather high luminosity. However, using the generally accepted distance modulus to $h$ Per ($m - M = 11.7$ (e.g., Marco & Bernabeu 2001; Keller et al. 2001) and $V = 9.11$, $(B - V) = 0.38$ from Keller et al. (2001), the implied absolute magnitude (for standard reddening) is $M_V = -4.4$, which does not look particularly high for B1 III.

4.3. Outlook

As outlined in Section II one of the drivers to undertake this study was the suspicion that stars that appear as B0-I Be stars could later appear as mid-to-late B-type stars of luminosity classes I or II, while still keeping their emission lines. It may therefore appear surprising that all the high-luminosity Be stars found, with the relative exception of LS I +56°92, are early B-type objects.

This might be (at least, in part) due to a selection effect. The criteria for telling luminosity class II from III are relatively straightforward for B0 stars, but become more subtle for mid-B stars and may be rather difficult to apply for emission line objects. It might then be that some objects classified as Be giants have slightly higher luminosities but have not been recognised as such.

The interesting point, however, is the very existence of these early-type luminous Be stars. Objects like HD 344863 or HD 333452 must have started their lives as rather massive stars ($M \gtrsim 25M_\odot$), in a region of the HR diagram (spectral types O8 or earlier) where Be stars are extremely scarce. As a matter of fact, only one Be star with spectral type earlier than O8 is well documented in the literature, HD 155806 (O7.5 IIIe, Conti & Leep 1974), and even for this one observations suggest some sort of “peculiarity” with respect to other Be stars (Hanuschik et al. 1996). Understanding these very few mid-range O-type stars displaying emission lines that morphologically resemble Be stars is very important in order to constrain the physical causes leading to the Be phenomenon. Based on the few examples known, one might suspect that these objects develop emission lines only late in their lives, but the crucial point would be to determine whether they actually bear the same phenomenology as classical Be stars. Therefore this parameter range will be studied in further work.

Meanwhile, the present work shows that there are at least a few stars of high luminosity presenting emission lines that morphologically will classify them as Be stars. More detailed analysis of their astrophysical parameters is required in order to determine whether the resemblance implies a common physical mechanism. It would appear, however, rather tempting to conclude that a B4II emission-line star displaying the same morphology as a B4IIIe star is also a classical Be star.

The number of these luminous Be stars, however, seems to be rather small, as few convincing candidates were found in the literature and a substantial fraction do not qualify as such when looked at in detail. The existence of an upper limit in the luminosity that a Be star can have appears certain, and the implication that the Be phenomenon must cease at some point in the life of a Be star has a bearing on our quest to understand this phenomenon.

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