Blue Stragglers, Be stars and X-ray binaries in open clusters

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Abstract. Combination of high-precision photometry and spectroscopy allows the detailed study of the upper main sequence in open clusters. We are carrying out a comprehensive study of a number of clusters containing Be stars in order to evaluate the likelihood that a significant number of Be stars form through mass exchange in a binary. Our first results show that most young open clusters contain blue stragglers. In spite of the small number of clusters so far analysed, some trends are beginning to emerge. In younger open clusters, such as NGC 869 and NGC 663, there are many blue stragglers, most of which are not Be stars. In older clusters, such as IC 4725, the fraction of Be stars among blue stragglers is very high. Two Be blue stragglers are moderately strong X-ray sources, one of them being a confirmed X-ray binary. Such objects must have formed through binary evolution. We discuss the contribution of mass transfer in a close binary to the formation of both blue stragglers and Be stars.

1. Introduction

Blue stragglers (BSs) are stars lying above the main sequence (MS) turnoff region in colour-magnitude diagrams, a region where, if the BSs had been normal single stars, they should already have evolved away from the main sequence (Stryker 1993). Several mechanisms have been proposed to explain the formation of BSs in different environments. 

• BSs may be stars formed later than the rest of the cluster or association. Though this may well happen in some regions with sequential star formation, in many clusters there are no stellar sequences connecting the BSs with the turn-off, arguing against a second epoch of star formation.

• BSs might be evolved stars back in the blue region of the HR diagram after a red supergiant phase. However, abundances of Nitrogen in blue stragglers are much lower than those predicted by models for stars in blue loops (Smartt et al. 2002).

• BSs may be stars that, for some reason, have evolved bluewards. In particular homogeneous evolution has been proposed as a mechanism that can result in blueward evolution for very high (near-critical) initial rotational velocity (Maeder 1987). However there is no strong a priori reason to believe that many such extreme rotators will be formed.
• BSs may be formed by coalescence of two stars. This mechanism requires a high stellar density environment. Though it is probably the major channel for the formation of BSs in globular clusters, it is unlikely to be able to explain BSs in OB associations.

• BSs result from mass exchange in close binaries. Examples of this process abound amongst massive binaries (see review by Negueruela in these proceedings). Therefore this channel must contribute some BSs in young clusters and associations.

While the properties of BSs in globular clusters have been the object of many studies, the mechanisms for forming BSs in young open clusters have deserved little attention. The most relevant works are those of [Mermilliod (1982)] and [Mathys (1987)].

2. Observations

As part of our programme to fully characterise a sample of young open clusters, we have obtained spectroscopy of large numbers of stars in the young open clusters NGC 663, NGC 869 and NGC 3766, and the moderately older clusters NGC 6649 and IC 4725.

We obtained spectra for 38 bright stars in h Persei and the immediately surrounding area on 2003 November 15th, using the 4.2-m WHT at the La Palma Observatory, equipped with the ISIS spectrograph and the R600B grating (0.4 Å/pixel). In addition, 17 members were observed with the 2.5-m INT, also at the La Palma Observatory, with the IDS spectrograph and the R900V grating (0.6 Å/pixel), in July 2003.

Spectra for 140 members of NGC 663 were obtained in two runs during October/November 2002, one with the INT+IDS and the R400V grating (1.2 Å/pixel) and the other one with the 1.93-m telescope at Observatoire de Haute-Provence and the Carélec spectrograph and the 300 ln/mm grating (1.8 Å/pixel).

Spectra of the brightest members of NGC 6649 were obtained with the WHT+ISIS and the R300B grating (0.9 Å/pixel) on 2004 May 20th.

Finally observations of NGC 3766 and IC 4725 were obtained in May 2004 with the New Technology Telescope (NTT) at La Silla, equipped with EMMI in the longslit spectrograph mode.

3. Results

3.1. HR diagrams

In order to detect BSs in our sample of open clusters, we use two types of HR diagram. When Strömgren photometry of a sufficient large sample exists, we use the observational $M_V/c_0$ diagram for the determination of cluster ages. If we have spectroscopy of a large number of members, we can also construct a “theoretical” HR diagram using the following procedure: from our spectra, we determine accurate spectral types and then take the corresponding $T_{\text{eff}}$ from the tabulation of [Humphreys & McElroy (1983)]. We then calculate the individual reddening for each star, using precision $UBV$ (and $RI$ where available)
photometry from the literature and $JHK$ from 2MASS. The photometry and the Kurucz model corresponding to the spectral type are used as input for the $\chi^2$ code for parameterised modelling and characterisation of photometry and spectroscopy implemented by Maíz-Apellániz (2004), which estimates the reddening. After dereddening, we correct for the adopted distance modulus and transform to $M_{\text{bol}}$ using the calibration of BC for a given spectral type given by Humphreys & McElroy (1984). All the isochrones shown are from Schaller et al. (1992).

3.2. NGC 3766

We have Strömgren photometry for 55 stars in this cluster from Shobbrook (1985) and Shobbrook (1987). The cluster HR diagram (Fig. 1) clearly demonstrates the age of the cluster, $\sim$ 25 Myr. This age is fully consistent with the spectral types of the stars around the MS turn-off (B2 V). However, there is an object with $M_V = -3.9$ lying clearly to the left of the isochrone. This star (S5) is located at the very centre of the cluster. Its spectral type B0.7 III confirms that it is earlier than any other member, but also that its parameters (distance and reddening) are those of a cluster member. We thus conclude that this object is a blue straggler in NGC 3766.

The other object marked with an open square (S326, BF Cen) also is a very interesting case. Its spectrum clearly shows that it is a double-line spectroscopic binary. Helt et al (1989) found that it is an eclipsing binary with a 3.7-d orbital period. The primary component is a B1.5 V star with $8.7M_\odot$ and $5R_\odot$, while
the secondary component is a B6III star with $3.8M_\odot$ and $7R_\odot$. The latter rotates synchronously, while the primary rotates much faster, implying that it is a post-mass transfer system. Taking into account that the secondary contributes a substantial amount of light, the B1.5 V star alone would be located to the left of the turn-off and be a mild blue straggler. This is a good example of a blue straggler created by mass transfer.

3.3. NGC 869

In the observational photometric diagram of NGC 869, there are many stars to the left of the MS turn-off (Marco & Bernabeu 2001). This is also evident in the theoretical HR diagram (Fig. 2) built from our spectral types and the photometry from Keller et al. (2001). The spectral types of the stars leaving the main sequence (B1.5 V) are compatible with an age of $\sim 15 - 20$ Myr. However, a large number of evolved stars lying to the left of the turn-off have spectral types indicating higher masses.

We can distinguish two kinds of BSs. Most of them concentrate around the log $t = 7.1$ isochrone. Though Strom et al. (2005) show that many of these objects are not very fast rotators now, the fact that all of them are evolved from the MS leads us to speculate that their position to the left of the turn-off may be related to initial fast rotation. A few other BSs occupy positions indicating much higher masses. The B2 Ia and B3 Ia supergiants are amongst the most massive B-type supergiants in the sample of McErlean (1999), with evolutionary masses of the order of $\sim 30M_\odot$. Both types of BSs are present at the cluster core and most of them are certainly cluster members.
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Figure 3. **Left panel** $M_V - c_0$ diagram for NGC 3293, based on the photometric data from Balona (1994), with spectral types from Evans et al. (2005). **Right panel** $M_V - c_0$ diagram for NGC 4755, based on the photometric data from Balona & Koen (1994), with spectral types from Evans et al. (2005).

A similar effect, well-defined MS turn-off and most of the evolved stars lying to the left, can also be seen in two other relatively massive clusters, perhaps slightly younger than NGC 869, for which abundant data exist in the literature: NGC 3293 and NGC 4755 (see Fig. 3). In these three open clusters and many others of similar age, there are B-type supergiants lying well above the corresponding isochrones for the cluster. Their progenitors are stars more massive than $\sim 20 M_\odot$ and therefore they are necessarily BSs in clusters older than 10 Myr.

### 3.4. NGC 663

From the observational photometric diagram, the cluster has an age $\sim 25$ Myr, again in good agreement with the spectral types of stars close to the turn-off (B2 V). We find two obvious photometric BSs located near the cluster core (S4 and S30). Their spectral types (B1 III in both cases) support their BS nature and their cluster membership. Our spectra reveal at least three other spectroscopic BSs which were saturated in our photometry. They include the O9.5 V star S162 and, of particular interest, LS I +61° 235 (S194), a B0.5 IVe star in the Be/X-ray binary RX J0146.9+6121.

### 3.5. NGC 6649

The age of this cluster is $\sim 50$ Myr (Walker & Laney 1987), confirmed by the study of the characteristics of the double mode Cepheid member V367 Sct. We build the theoretical HR diagram from our spectra and the photometry of Walker & Laney (1987). The spectral types of the brightest blue members show good agreement with this age, presenting a MS turn-off around B4 V (Fig. 4). There are two obvious BSs, the brightest of which is a B1 IIIe star (S9), unam-
Figure 4. **Left panel** Theoretical HR diagram for NGC 6649 built from the observations following the procedure indicated in the text. **Right panel** Theoretical HR diagram for IC 4725 built from our spectra and photometry by Johnson (1960). Be stars appear as filled squares.

biguously associated with an *XMM-Newton* X-ray source. This object appears to be a low luminosity Be/X-ray binary or a member of the class of $\gamma$-Cas-like X-ray sources (see contribution by Motch et al. in these proceedings).

### 3.6. IC 4725

The age of this cluster has been set at 90 – 100 Myr by several different studies and is also constrained by the presence of a classical Cepheid, U Sgr. From the spectral types, we find the MS turn-off around B6 V, in good agreement with this age, but leaving at least four evolved BSs, three of which are Be stars (see Fig. 4).

### 4. Discussion and conclusions

Though the sample of open clusters for which a detailed analysis has been made is still quite small, we observe the following interesting trends:

- Blue stragglers are found in all open clusters surveyed

- In clusters $\sim$ 15 Myr old, most evolved stars appear too massive for these ages. In particular, many of these clusters contain Ia and Iab supergiants, which must be descended from stars with $\gtrsim 20M_\odot$ according to all theoretical evolutionary paths. Such massive stars have lifetimes $< 10$ Myr (Meynet & Maeder 2003), rendering all these supergiants BSs.

- Among clusters younger than $\sim$ 25 Myr, very few BSs are Be stars.
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- From the data on IC 4725 and NGC 6649, incomplete samples in NGC 2516 and IC 2488 and data in the literature (Mermilliod 1982), it would seem that most BSs in clusters in the 50 − 150 Myr range are Be stars.

- Our data suggest that a non-negligible fraction of BSs in moderately young open clusters are formed by mass transfer in a close binary (X-ray sources in NGC 663 and NGC 6649, eclipsing binary in NGC 3766), but not all BSs are binaries, making it unlikely that this might be the only channel.

- Likely different mechanisms are dominant at different ages.

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References

Balona, L.A. 1994, MNRAS 267, 1060
Balona, L.A., Koen C. 1994, MNRAS 267, 1071
Helt B.E., Andersen J. & Kamper B.C. 1989, SSRv 50, 346
Evans, C.J., et al. 2005, A&A 437, 467
Humphreys, R.M., & McElroy, D.B. 1984, ApJ 284, 565
Johnson, H.L. 1960, ApJ 131, 620
Keller, S.C., Grebel, E.K., Miller, G.J., & Yoss, K.M. 2001, AJ 122, 248
Maeder, A. 1987, A&A 178, 159
Maíz-Apellániz, J. 2004, PASP, 116, 859
Marco, A.& Bernabeu, G. 2001, A&A 372, 477
Mathys, G. 1987, A&A 71, 201
McErlean, N.D., Lennon, D.J. & Dufton, P.L. 1999, A&A 349, 553
Mermilliod J.C. 1982, A&A 109, 37
Meynet, G., & Maeder, A. 2003, A&A 404, 975
Schaller, G.; Schaerer, D.; Meynet, G.; Maeder, A. 1992, A&AS 96, 269
Shobbrook, R.R. 1985, MNRAS 212, 591
Shobbrook, R.R. 1987, MNRAS 225, 999
Smartt, S.J., et al. 2002, A&A 391, 979
Strom, S.E., Wolff, S.C., & Dror, D.H.A. 2005, AJ 129, 809
Stryker, L. L. 1993, PASP 105, 1081
Walker, A.R.; Laney, C.D. 1987, MNRAS 224, 61