In ESO area 439 we have found 4 low luminosity degenerates, that is 30% of the stars between $10 \leq m \leq 21$ and $\mu \geq 0.3$ arcsec/year) belong to this group. If this holds true for the whole sky, we then estimate that the missing mass might be accounted for by these faint objects.

Acknowledgements

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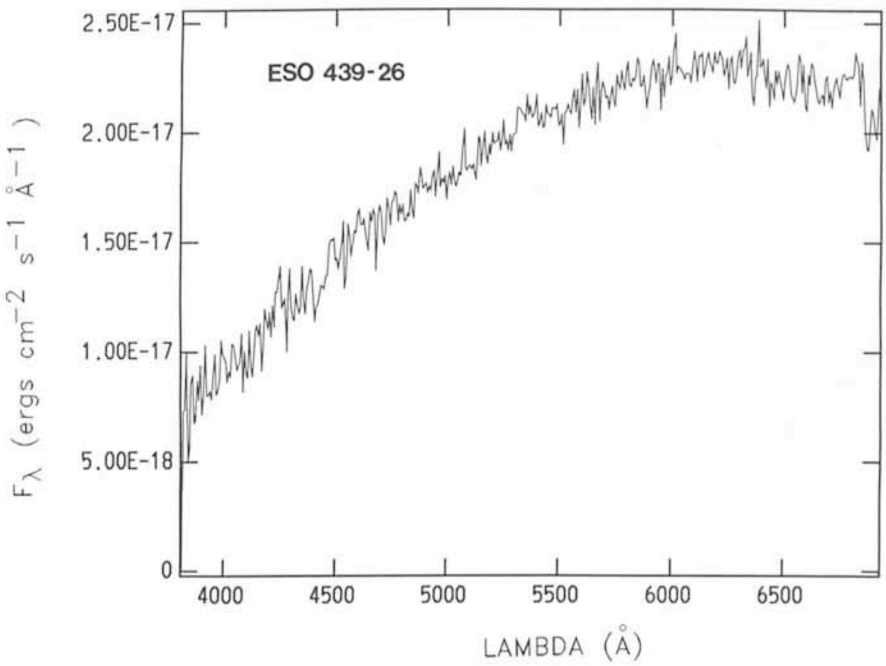

Figure 7: *Spectrum of the cold degenerate ESO 439-26. At a distance of 41.7 pc (measured by trigonometric parallax) its luminosity is $L \approx 3 \times 10^{-5} L_\odot$.*

A Search for Magnetic Fields in Blue Stragglers of M 67

G. MATHYS, Observatoire de Genève, Switzerland

Introduction

Blue stragglers (hereafter BS) are members of star clusters whose location in the HR-diagram of the cluster is beyond the turnoff point, in the vicinity of the zero age main sequence (ZAMS). The existence of these stars appears to be in contradiction with the current views about the formation of star clusters and the stellar evolution. Namely, if all the stars belonging to a cluster have formed contemporaneously, standard evolution theory does not predict the presence of stars in the region of the HR-diagram where BS are found.

Various tentative explanations of the BS phenomenon have been put forward. The most popular ones are that BS:

(i) have formed later than the rest of the cluster,

(ii) result from mass exchange in close binaries, with the consequence that the former secondary component of the pair has moved up the main sequence,

(iii) are coalesced stars (an extreme case of mass transfer),

(iv) are stars undergoing quasi-homogeneous evolution.

The latter hypothesis can be intuitively understood as follows: if mixing takes place inside a star, part of the processed material in the core is moved up to outer layers and is replaced in the central stellar regions by unprocessed material, so that core hydrogen burning can last longer and main sequence lifetime is accordingly extended. Recent detailed modelling carried out by Maeder (1987) actually shows that, at least for massive stars, a star that undergoes internal mixing, rather than evolving along the standard redwards track in the HR-diagram, would as it ages raise bluewards near the ZAMS, and would thus be observed as a BS.

The main observable manifestation of quasi-homogeneous evolution, apart from the BS nature of the star, is expected to be the appearance of nuclear processed material from the core on the stellar surface. More precisely, the abundances of carbon and nitrogen determined from the analysis of the stellar spectrum should markedly differ from the standard main sequence abundances of these elements and be characteristic of the CN-equilibrium in the CNO cycle of hydrogen burning. On the other hand, the triggering agent responsible for the mixing of the stellar interior could possibly als reveal itself to observation. Internal mixing of a star could for instance be induced by turbulent diffusion resulting from rapid rotation or from tidal forces in binaries, or could be produced by magnetic buoyancy.

The BS of M 67

In order to get a new insight into the nature of BS, I initiated a programme of observations of the BS of M 67, with the aim of testing the hypothesis that they are quasi-homogeneously evolved stars.

M 67 (= NGC 2682) is one of the oldest galactic clusters known (with an age of 3.5 10^9 yr), and one of those having the richest BS populations. A colour-magnitude diagram of M 67 is shown in Figure 1, which was kindly provided by J.-C. Mermilliod. V is plotted against B-V for all the stars having a membership probability higher than 80% and V < 16 for which Mermilliod has been able to compute average photometric parameters from measurements found in the literature. The BS, represented by filled squares, are easily distinguished. Their spectral types range from late B to early F; most of them are thus A-type stars.

The main goal of the observing programme is to determine the abundances of C, N and O in the BS of M 67 in order to see whether they have standard main

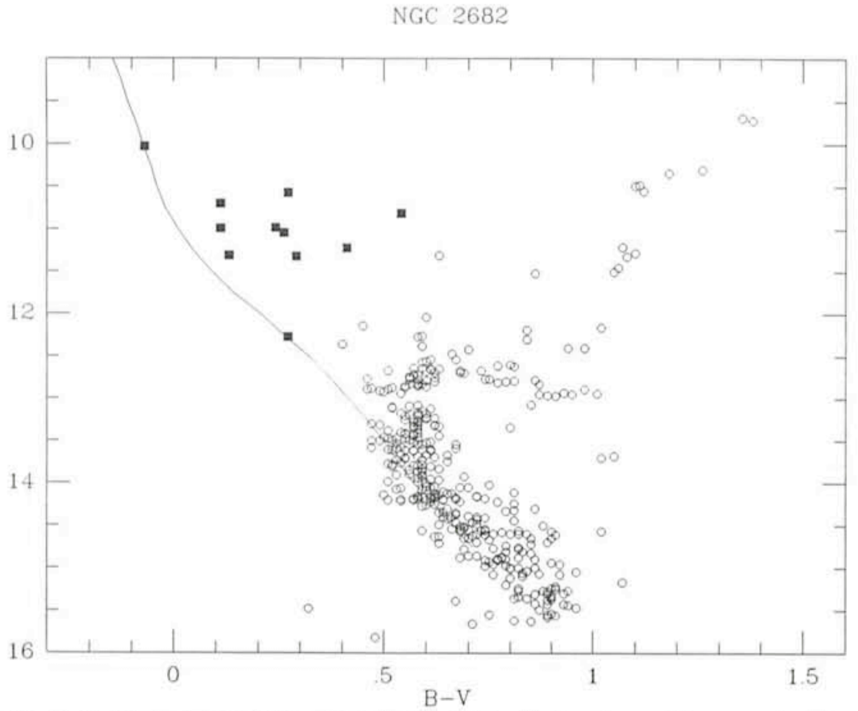

Figure 1: (B−V, V) *diagram of the open cluster M 67. All the stars with a membership probability greater than 80 % and V < 16 for which Mermilliod has been able to compute average photometric parameters from measurements found in the literature have been included. The eleven BS are represented by filled squares. The ZAMS is also plotted.*

sequence values or, rather, values characteristic of CN-equilibrium. In addition, it was decided to look for evidence of the presence of two agents that could be responsible for a possible mixing of the stellar interior, namely rapid rotation (from the determination of *v* sin *i*) and magnetic field. Here I present a preliminary report about the latter point, the first one to have been completed within the frame of this project.

Observations

The observations were carried out in January 1988 with the 3.6-m telescope and the CASPEC. The choice of the instrumentation was dictated by the need for observing lines of C, N and O, which in A-type stars mostly are found in the red portion of the spectrum and are weak (with typical equivalent widths of the order of 50 mÅ or less) making it necessary to obtain spectra of fairly high resolution and S/N ratio. Using the CASPEC furthermore had the advantage that, due to the availability of a Zeeman analyzer as a standard option of this instrument, it was possible to look for magnetic fields in the studied stars at little extra cost. With the Zeeman analyzer one simultaneously records the stellar spectrum in right and left circularly polarized light. The difference between both polarizations yields information about the magnetic field, while their sum gives back the full intensity spectrum as it would be obtained in the standard mode, without the Zeeman analyser.

The 11 BS of M 67, as shown in Figure 1, were first observed in the spectral range 6900–7900 Å, which is the most interesting one as far as the primary goal of this study, the determination of the C, N, O abundances, is concerned. The CASPEC was used in its standard configuration, with the 32 lines/mm^{-1} échelle grating. The spectra obtained that way were used to select those stars in the sample whose lines were sharp enough to be observed with the Zeeman analyzer in an attempt to evidence a magnetic field. Four stars proved to be suitable for such a study; they are listed in Table 1. These four BS were observed in the spectral range 5300–6250 Å, with the Zeeman analyzer. The 52 lines/mm^{-1} échelle grating had to be used in order to avoid the overlapping of adjacent orders due to their splitting by the Zeeman analyzer (see Mathys and Stenflo, 1986, for more details). With this grating, in the considered spectral region, there are gaps in the wavelength coverage between adjacent orders (portions of up to 15 Å of the spectrum are missing); fortunately, none of the lines of interest of C, N or O lies in these gaps. The remaining 7 BS were observed in the same spectral range without the Zeeman analyzer, but otherwise with the same instrumental configuration.

TABLE 1. *The four sharpest-lined BS of M 67*

Star*	V	B−V
F 131	11.22	0.42
F 153	11.31	0.13
F 185	11.04	0.26
F 238	10.57	0.27

* Fagerholm number

The four spectra obtained with the Zeeman analyzer will be discussed in the rest of this paper. The journal of observations is given in Table 2. Each spectrum is the average of three exposures that have been consecutively taken and from which the "cosmic ray" spikes have been removed as much as possible through intercomparison prior to taking the average. The reduction was performed within MIDAS, using procedures that have been specifically written to deal with spectra obtained with the CASPEC and Zeeman analyzer. Great care was taken in the wavelength calibration step, and the normalization of the spectral orders to the continuum was performed by an automatic routine so that it is as objective and uniform as possible. More details about the reduction will be given in a forthcoming paper. The final spectra have a S/N ratio $\gtrsim 70$ in the continuum, in each polarization. A sample plot of them is shown in Figure 2.

Results and Discussion

Before discussing the results of the present observations, it should be pointed out that the hypothesis that BS are related to the presence of a magnetic field receives some indirect support from a number of observational evidences, at least for BS in intermediate-age clusters, from $10^{8.3}$ to 10^9 years old (see Abt, 1985, for more details). Indeed, it is noticeable that a significant fraction of the BS in these clusters are Ap stars, of the Si and Sr-Cr-Eu varieties. It has even been suggested that all the BS in the considered age range

TABLE 2. *Journal of observations*

Mid-observation time (HJD)	Exposure duration (min)	Star
2447189.601	60	F 131
2447189.655	60	F 153
2447189.703	60	F 185
2447189.751	60	F 238

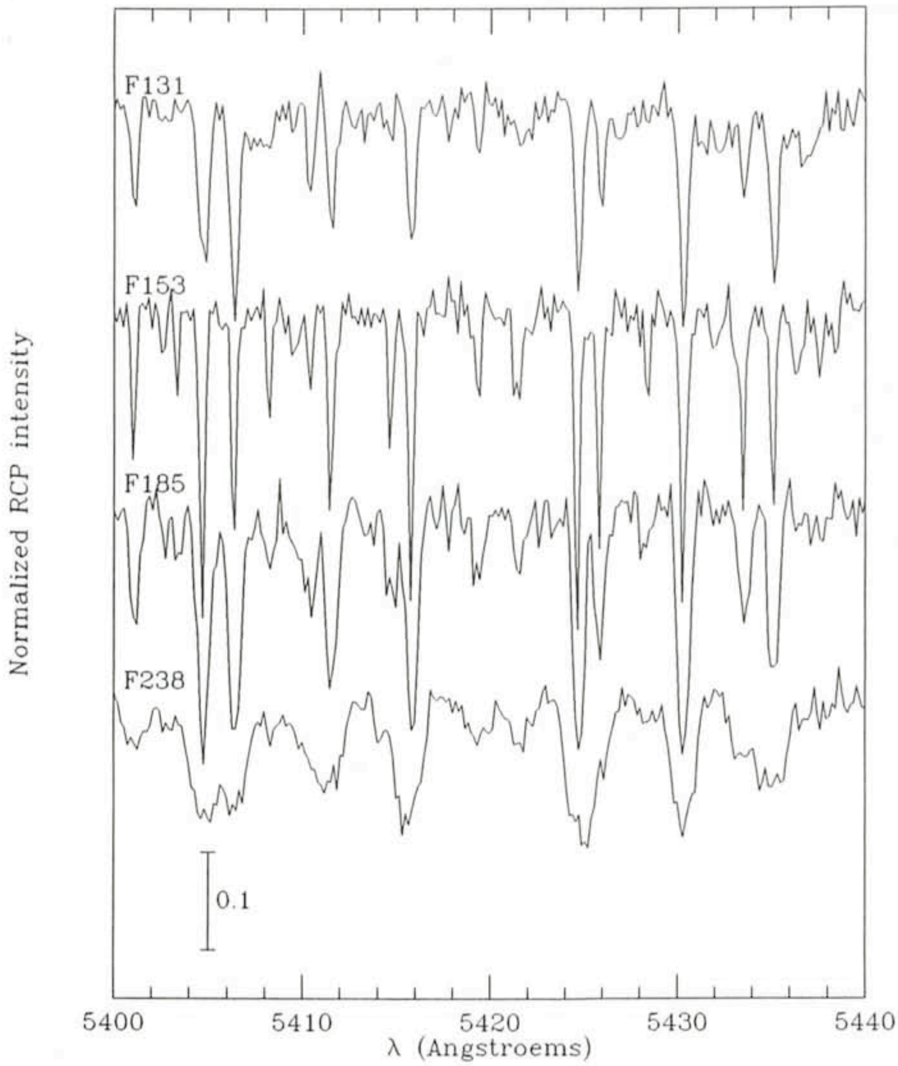

Figure 2: *Part of the spectrum of the four BS where magnetic fields have been looked for, as recorded in right circularly polarized (RCP) light with the Zeeman analyzer of the CASPEC. It can be noticed that, due to the faster rotation of F 238 and the related line blending, there are considerably fewer lines suitable to search for a magnetic field in the spectrum of this star than for the other three stars.*

are Ap stars (Pendl and Seggewiss, 1976). Ap stars are the only nondegenerate stars definitely known to possess a magnetic field with a large-scale organization, which is detectable by the observation of circular polarization inside spectral lines. The order of magnitude of this magnetic field is a few kG; the measured field of most Ap stars varies periodically due to the changing aspect of the visible stellar hemisphere resulting from stellar rotation. On the other hand, it has recently been discovered that several A-type BS have a flux deficiency between 1200 and 2000 Å similar to that observed in Ap Si stars and possibly related to the presence of a magnetic field in the latter (Durán and Graziati, 1986). It thus appeared to be worthwhile to attempt a direct detection of a magnetic field, more exactly of a large-scale organized magnetic field (see below), in some A-type BS.

Stellar magnetic fields can be diagnosed by taking advantage of the Zeeman effect that they induce in spectral lines. The most convenient approach is to measure the shift between the wavelength of a line as recorded in right circular polarization, λ_R, and the wavelength of the same line as recorded in left circular polarization, λ_L. This shift can in a first approximation be expressed as:

$$\lambda_R - \lambda_L = k\bar{g}\lambda_0^2 H_z,$$

where λ_0 is the nominal wavelength of the line and $\bar{g}$ is its effective Landé factor, an atomic parameter which characterizes the sensitivity of the line to a magnetic field. H_z is the average over the visible stellar disk of the component of the magnetic vector along the line of sight, suitably weighted to account for the different relative contribution of the various regions of the stellar surface to the observed lines. H_z is called the mean longitudinal magnetic field or, less precisely, the effective magnetic field. k is a constant, whose numerical value is 9.34 10^{-13} Å^{-1}.G^{-1}. It can be seen that the wavelength shift $\lambda_R - \lambda_L$ is usually quite small: for a field of 1 kG and a line at λ_0 = 6000 Å having an effective Landé factor $\bar{g}$ = 1.5 (a typical value), one finds $\lambda_R - \lambda_L$ = 0.05 Å. This explains why magnetic fields can only be determined with the described method in stars rotating slowly enough. On the other hand, it must be stressed that the quantity that is measured that way is the average value of the line of sight component of the field vector. Therefore, if the magnetic field has a complex structure, somewhat like the structure of the solar field, with many small regions of the stellar surface covered by fields of opposite polarities and approximately the same strength, there will be no detectable effect in circular polarization recordings of spectral lines averaged over a whole stellar disk. Only if it has a sufficient large-scale organization, so that the contributions of various parts of the stellar surface do not cancel out, will the field be detectable through the considered kind of observations. That is the reason why the Ap stars are the only nondegenerate stars in which magnetic fields have been measured through spectropolarimetry, because their field has a unique large-scale organization. Stars that are not detected as magnetic from spectropolarimetric observations may nevertheless possess fields of the same order as those of the Ap stars, but with a more complex structure – and some do indeed. Consequently, the present approach is restricted to the search for stellar magnetic fields having a large-scale organization, similar to those of the Ap stars.

I have, to my knowledge, been the only visiting astronomer to this date to have used the Zeeman analyzer of the CASPEC to measure stellar magnetic fields. This instrumentation has never been calibrated with respect to other spectropolarimeters. It is however essential to check the consistency of the magnetic field measurement obtained with the CASPEC Zeeman analyzer against those that have been achieved at other observatories. Such a calibration is currently in progress, within the framework of a more specific programme dedicated to systematic stellar magnetic field measurements, which I am pursuing in collaboration with J. O. Stenflo. This project is not fully completed yet, and the discussion of the performance of the Zeeman analyzer of the CASPEC would anyway be out of the scope of the present paper. I will just mention here that the results obtained up to now indicate that the magnetic field values determined with the Zeeman analyzer of the CASPEC are essentially correct. This is illustrated in Figure 3,

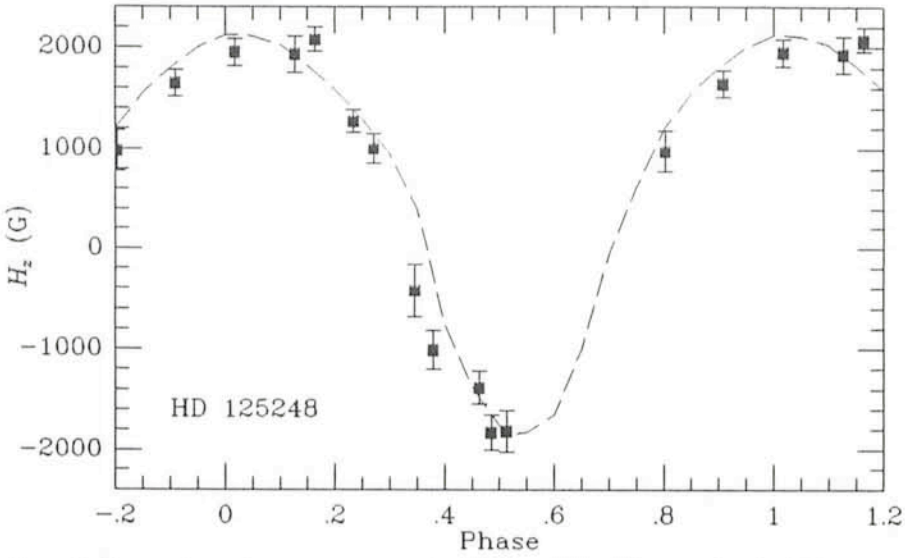

Figure 3: *Comparison of my measurements* (filled squares with error bars) *of the mean longitudinal magnetic field of HD 125248 with the curve of magnetic variation of this star* (dashed curve) *as obtained by Babcock (1960). The abscissa is the rotation phase (see Mathys and Stenflo, 1988, for more details).*

where as an example my measurements of the magnetic field of the A star HD 125248 are plotted together with the curve of magnetic variation for this star that was obtained by Babcock (1960).

The mean longitudinal magnetic field of the four BS observed in this programme is given in Table 3. It was obtained from the measurement of the shift between right and left circularly polarized spectra of the wavelength of FeI lines. The number of such lines used in each case is given in Col. 3 of the table. This number is smaller for stars rotating faster, because only unblended, sufficiently well defined lines can be measured for the present purpose. The values of the field H_z that are given in Col. 2 of Table 3 were obtained by carrying out a linear regression of the measured wavelength shifts $\lambda_R - \lambda_L$ for the lines of the sample, as a function of their respective $\bar{g}\lambda_0^2$. The quoted uncertainties affecting the derived values of H_z correspond to the rms deviation of the $\lambda_R - \lambda_L$ measurements about this regression. They are quite consistent with the random measurement errors in $\lambda_R - \lambda_L$ that are expected from the consideration of the S/N of the spectra and of the depth and width of the measured lines. It can be seen that no large-scale organized magnetic field was detected in any of the four observed BS. This does not mean that none of these stars, taken individually, can have a field like those of the Ap stars. Indeed, as already mentioned, the mean longitudinal field of the Ap stars varies with the rotation period of the star. It cannot be excluded that, observing a star of this type only once, one could unluckily spot a phase where H_z is close to zero, while it becomes much larger at other phases (see the case of HD 125248 in Figure 3, around phases 0.25 and 0.75). However, it would be very unlikely, if all four observed BS had Ap-like magnetic fields, that all of them could have been observed at such an unfavourable phase. Hence it can be inferred that BS in old open clusters do not in general possess large-scale organized magnetic fields similar to those of the Ap stars with strengths in excess of a few hundred gauss.

TABLE 3. *Mean longitudinal magnetic fields*

Star	H_z (G)	Number of lines
F 131	257 ± 206	19
F 153	− 261 ± 236	20
F 185	− 51 ± 272	14
F 238	748 ± 700	6

In conclusion, large-scale organized, strong magnetic fields do not appear to be responsible for the BS phenomenon in old open clusters, or at least all BS in such clusters cannot be explained by the presence of such fields. This, of course, does not rule out the interpretation that BS are quasi-homogeneously evolved stars, since mixing of the stellar interior can be achieved independently of the presence of a large-scale organized magnetic field. This latter point will be tackled through the determination of the C, N, O abundances in the BS of M 67, which is currently in progress. It should finally be mentioned that the programme that has partly been reported in this paper participates in a broader project aiming at setting constraints on the stellar evolution theory through the consideration of the changes in surface abundances of the C, N, O elements along stellar lifetimes.

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