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HOT SUBDWARFS IN GLOBULAR CLUSTERS

GORDON A. DRUKIER,[1] GREGORY G. FAHLMAN,[1] AND HARVEY B. RICHER[1]
Department of Geophysics and Astronomy, University of British Columbia
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ABSTRACT

We present spectra of faint blue stars in the globular clusters M71 and M4. The spectra suggest that they are hot subdwarfs. Arguments in favor of membership in their respective clusters and comments regarding their evolutionary status are given.

Subject headings: clusters: globular — stars: subdwarfs — stars: white dwarfs

I. INTRODUCTION

In the course of our searches for white dwarfs in the globular clusters NGC 6752 (Richer 1978, 1979), M4 (Chan and Richer 1986), and M71 (Richer and Fahlman 1988, hereafter RF88), a population of blue stars has been found that is too luminous for cluster white dwarfs, and fainter and bluer than classical blue stragglers. In M4 there appear to be two groups separated by color with the bluer group identified as cluster objects and the redder group with foreground white dwarfs. Many of the M4 cluster candidates are rather luminous; five have $M_V \leq 9.0$. Very few white dwarfs this luminous are expected in M4 and hence the observed objects are possibly something other than white dwarfs. A detailed CCD study of M71 using deep U, B, and V exposures revealed the presence of a faint white dwarf cooling sequence, together with another possible sequence of luminous blue stars. These are far too bright to be cluster white dwarfs and much too numerous to be foreground objects. Their colors are similar to cataclysmic variables, and we originally suggested that they might be cluster analogues of these objects. In this *Letter* we present spectroscopic and dynamical evidence that at least some of these stars are B-type subdwarf members of their respective globular clusters.

The sample in M71 was identified by RF88 (their Fig. 5) as a sequence of stars roughly parallel to, but some 2 mag bluer in $(U-V)$ than, the main sequence. The brightest of these is 4 mag brighter in U than the white dwarf sequence and has about the same U magnitude as the turnoff stars. A second set of candidates was identified in M4 from the ultraviolet-excess blink survey of Chan and Richer (1986). A $M_V - (U-V)$ color-magnitude diagram (CMD) containing the stars from both clusters together with a sample of faint sdO stars from Schönberner and Drilling (1984) and faint sdB stars from Downes (1986) is presented in Fahlman and Richer (1989). The colors and absolute magnitudes of the cluster candidates are consistent with their being subdwarfs. Little is known about these hot subdwarfs, and their identification in a globular cluster could provide clues to their evolutionary status.

II. OBSERVATIONS AND REDUCTION

The spectra were obtained at the 3.6 m CFHT on Mauna Kea using the Herzberg spectrograph with a 2″ slit and the 150 lines mm^{-1} grating. The dispersion was 300 Å mm^{-1} and the resolution 22 Å between 3400 and 7200 Å. The detector was the TH1 three-phase Thompson CCD with 23 μm pixels. The spectra were taken on the nights of 1988 July 18–20 UT. The three brightest stars in the M71 sequence were observed along with the brightest star in each of the two subgroups in M4, Chan and Richer (CR) stars numbered 774 and 831. The exposure times were from 1 to 2 hr. In addition, a sample of stars of known spectral type and similar colors were observed for comparison and spectrophotometric calibration. Preprocessing was done at the CFHT facilities in Hawaii using routines in IRAF. Spectral extraction was done at UBC with the apextract package of IRAF and calibration using routines in the onedspec package. The spectra were corrected for atmospheric extinction using the CFHT extinction curve (Beland, Boulade, and Davidge 1988) and for the color response of the spectrograph using Kitt Peak spectrophotometric standards. The effects of interstellar absorption were removed using the extinction curve of Savage and Mathis (1979) and their value of 3.1 for the ratio of total to selective absorption. The color excesses used were $E(B-V) = 0.28$ for M71 (RF88) and $E(B-V) = 0.37$ for M4 (Richer and Fahlman 1984). Color excesses for the subdwarfs from the sample of Schönberner and Drilling (1984) were taken from that paper.

III. DETAILS OF THE SPECTRA

A sample of our spectra is shown in Figure 1 and is discussed below.

RF-1 M71.—This is the brightest star in the RF88 sequence. The Balmer series is clearly visible in absorption through to Hϵ. The shape of the spectrum and the depth of the absorption lines (especially Hα through Hγ) are nearly identical with the B-type subdwarf Feige 108. The lines are much shallower than those in the DA 4 star EG 162 observed the same night. There is no sign of any He lines.

RF-2 M71.—This star is a magnitude fainter than RF-1 and has about the same color. Any lines of the depth of those in the previously discussed spectrum would be lost in the noise here. On the other hand, strong emission lines typical of cataclysmic variables would have been detected as can be seen from the spectrum of the dwarf nova WZ Sge. The similarity in the shape of the continuum to RF-1 and the absence of both strong emission and absorption lines suggests that this object is also likely to be a hot subdwarf.

CR-774 M4.—This is the brightest star in the "foreground" population in M4. The star is clearly cooler than the rest of the stars shown. Hα is clearly visible together with a broad feature

[1] Visiting Astronomer, Canada-France-Hawaii Telescope. CFHT is operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique of France, and the University of Hawaii.

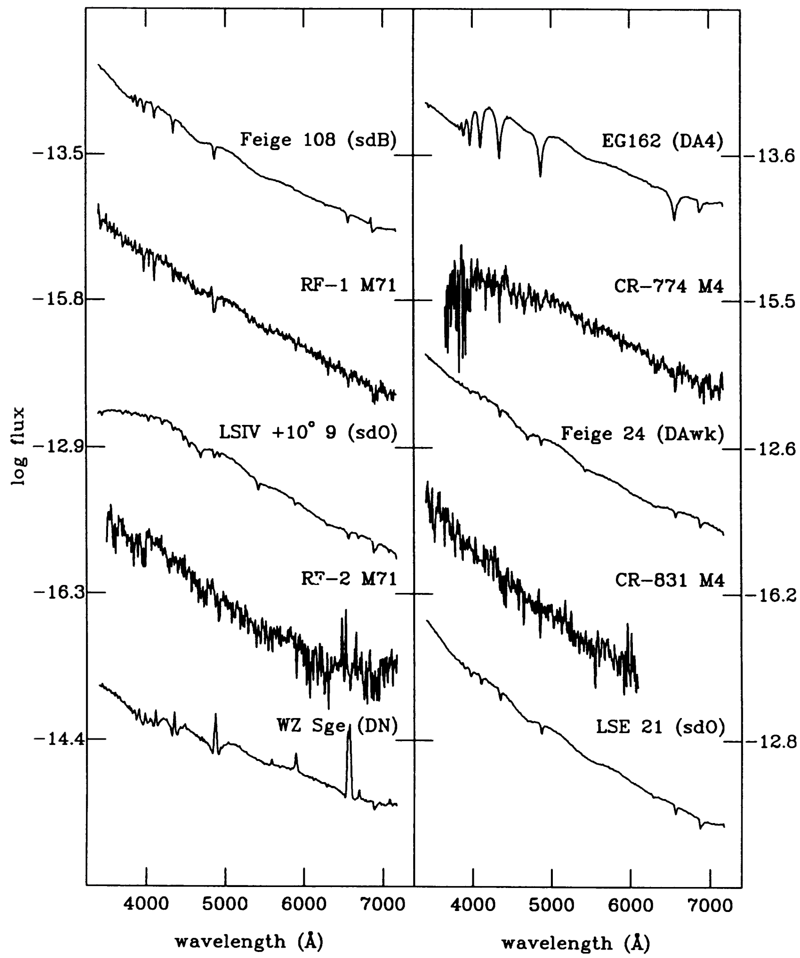

FIG. 1.—Dereddened and flux calibrated spectra of selected luminous blue objects in M4 and M71 together with a sample of hot comparison objects. RF-1 has $V = 19.5$, RF-2, 20.6, CR-774, 19.0, and CR-831, 20.3. Tick marks on the ordinate are separated by 1 dex and are labeled with the appropriate log flux (in ergs cm^{-2} s^{-1} Å^{-1}) for each spectrum at approximately 5000 Å.

at the position of Hβ. The most likely interpretation for this star is as a field DA with weak hydrogen such as Feige 24.

CR-831 M4.—This is the brightest star in the "cluster" population of M4. It is the bluest object observed and appears hotter than Feige 108 but similar to the sdO star LSE 21. Schönberner and Drilling (1984) estimate the temperature of the latter star to be $\sim 110{,}000$ K. The red end of this spectrum is contaminated by a red star lying nearby. No features are observed in the spectrum and none would be expected given the noise level and features the depth of those in LSE 21.

We also obtained a single, 2 hr spectrum of the third brightest star in the M71 sequence but this was of very low signal-to-noise ratio. The apparent slope of the continuum is consistent with it being somewhat cooler than the other two observed in this cluster as indicated by their respective colors. Thus of the three stars observed in M71, one is a spectroscopically confirmed B-type subdwarf and a second is very likely similar, while the third, and faintest, such object in this cluster has at least the correct continuum shape to be a hot subdwarf. The apparent cluster member CR-831 in M4 is also a very hot subdwarf while CR-774 appears to be much too cool to be a cluster member.

IV. DISCUSSION

There are three lines of evidence to suggest that the stars discussed here are associated with their respective clusters.

1. The spectra suggest that they are extremely hot subdwarfs and not typical field DA's or DB's. The absolute magnitudes inferred for at least the brightest ones under the assumption that they are cluster members agree reasonably well with those of similar field objects (Schönberner and Drilling 1984; Fahlman and Richer 1989).

2. Downes (1986) finds that the space density of field B subdwarfs is about 2×10^{-6} pc^{-3}. For the case of M71, based on our survey (RF88) and adopting a distance of 3.7 kpc, we would expect to see only 0.07 sdB stars in the foreground. If the stars are in the background, the nearest would be expected at a distance of about 8.3 kpc, and if identified with the brightest star, would have $M_V = 4.0$. This is somewhat brighter than the mean of Downes's sample. However, the height of the object above the plane would be 660 pc, higher than the sdB scale height of 325 pc (Green, Schmidt, and Liebert 1986).

3. A background field obtained 20′ north of the center of M71 exhibited none of the bright blue objects seen in the cluster fields (RF88).

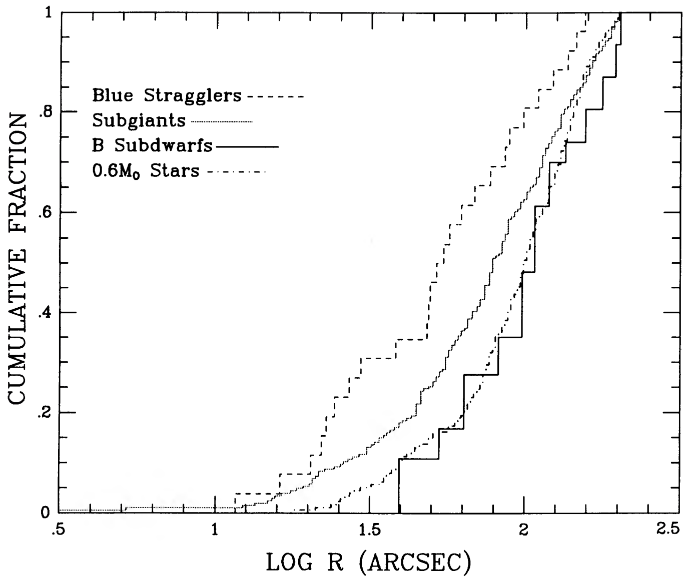

FIG. 2.—The cumulative radial frequency of four groups of stars within 205″ of the cluster center in the globular cluster M71. The subgiants are all those objects in the color-magnitude diagram of Richer and Fahlman (1988) with U brighter than 19, and $(U-V)$ redder than 1.0, while the blue stragglers are brighter than 18.2 and bluer than 1.0. The 0.6 $M_\odot$ stars are all the main-sequence stars in the magnitude range 23–24. The subdwarfs all possess a U magnitude brighter than 24.4 and $(U-V) \leq 0.1$. Excluded from this latter sample were all the objects identified as cluster white dwarfs.

If we now assume that the subdwarfs are indeed cluster members, does their presence reveal new information on their origin? Since M71 exhibits mass segregation (Richer and Fahlman 1989), the radial distribution of the subdwarfs in this cluster can be used to infer their mean mass. The cumulative distribution of the radial positions of the 13 subdwarf candidates (27.7 after incompleteness corrections are applied) found in M71 is shown in Figure 2 togther with the distributions for 206 subgiants, 26 blue stragglers, and 274 (369.3 after incompleteness corrections are applied) faint main-sequence stars in the U magnitude range 23–24 with masses estimated at about 0.6 $M_\odot$. This mass determination comes from the mass-luminosity relation found in Hesser *et al.* (1987). Kolmogorov-Smirnov statistical tests applied to these distributions yield the following results: (1) With a confidence exceeding 99%, the subgiant and 0.6 $M_\odot$ star distributions are not drawn from the same sample. (2) A comparison of the subgiant and subdwarf distributions yields with a confidence level of about 92% that these two samples were not taken from the same distribution. (3) However, the hypothesis that the 0.6 $M_\odot$ stars and the subdwarf distributions were not drawn from the same sample can only be rejected at the 40% level. The conclusion, then, is that that the subdwarfs have a mass below that of the turnoff stars.

There are two rather different possibilities for the evolutionary phase of these stars. In one case they are presumed to be a class of horizontal-branch stars with very small envelope masses (Vauclair and Liebert 1987). This picture is most plausible for those clusters which show an extended blue horizontal branch (EHB); e.g., NGC 6752 (Caloi *et al.* 1986). However neither M71 nor M4 show any evidence of an EHB. An added point is that such horizontal-branch stars all have a He core mass of ~ 0.5 $M_\odot$ and relatively high luminosity. Their evolution from the ZAHB would proceed to the blue; i.e., from sdB to sdO on an H-R diagram. Subsequently, they are expected to follow a normal CO white dwarf cooling curve. Hence, it is very difficult to account for the apparent sequence of these objects, extending over 5 mag, in our CMD of M71 (RF88, Fig. 5).

The second possibility is that the stars discussed here are the result of the merger of helium degenerates formed in close binary systems as described by Iben and Tutukov (1986*b*). Direct evidence for main-sequence binaries is lacking, but we note that M71 contains a significant population of blue straggler stars. Nemec and Harris (1987) showed that the blue stragglers in NGC 5466 are more massive then the cluster subgiants and therefore are consistent with being the products of close binary evolution on the main sequence. The case is somewhat less conclusive for M71. The blue stragglers appear to be more centrally concentrated (and hence more massive) than the cluster subgiants (see Fig. 2) but the Kolmogorov-Smirnov test of the hypothesis that the two groups are drawn from the same parent population can be rejected only at the 85% confidence level. The case for M4 is weaker. The main sequence is observed to be very tight (Richer and Fahlman 1984), ruling out a significant population of equal mass binaries, and there is no sign of blue stragglers. However, such stars are expected to be centrally concentrated and as yet the central regions of M4 have not been studied in sufficient detail to completely eliminate the possibility of a binary population.

In the Iben-Tutukov scenario, the merged products can have a mass spread although most are expected to have a mass of ~ 0.5 $M_\odot$. A merger product with a helium mass larger than some critical value near 0.5 $M_\odot$ would ignite the core helium. It would thus be essentially indistinguishable from the EHB stars discussed above and its subsequent evolution will be the same. If the merger product has a mass smaller than the critical value, it would not ignite the central helium but would simply follow the cooling track for a helium degenerate. Such a cooling sequence is located on an H-R diagram at a significantly higher luminosity than that of the more massive CO white dwarfs (Iben and Tutukov 1986*a*). Therefore in this picture we could identify the brightest and hottest of the blue objects discussed here with the more massive, nuclear powered merger products and the extended sequence of cooler and fainter objects seen on the M71 CMD with lower mass He degenerates on their cooling tracks.

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GORDON A. DRUKIER, GREGORY G. FAHLMAN, and HARVEY B. RICHER: Department of Geophysics and Astronomy, University of British Columbia, 2219 Main Mall, Vancouver, B.C. V6T 1W5, Canada