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DEEP CCD PHOTOMETRY IN GLOBULAR CLUSTERS. VI. WHITE DWARFS, CATACLYSMIC VARIABLES, AND BINARY STARS IN M71

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ABSTRACT

In a search for white dwarfs in the globular cluster M71, the inner $6' \times 4'$ of the cluster was imaged in U, B, and V at CFHT. Stars fainter than 25*th* magnitude are recorded in all three colors. A sequence of faint blue stars was detected, but, at a given color, the stars are somewhat fainter than expected if their properties are similar to field DA while dwarfs. Their colors and magnitudes are much better matched by a sequence consisting of DB stars or by a sequence $\sim 0.1\ M_{\odot}$ more massive than the canonical mass for disk white dwarfs. An unexpected result was the discovery of a very blue sequence of stars which appear to be much too luminous to be single white dwarfs. Their colors and magnitudes are consistent with their identification as cluster cataclysmic variables or as foreground white dwarfs, but the available statistics are incapable of deciding between these two options at present. Low-resolution spectroscopy, searching for Balmer emission lines could, however, be definitive in choosing between these possibilities. Finally, except possibly for a sample of blue stragglers which number more than 50 ($\sim$1% of all stars measured), the binary frequency in the cluster center is low.

Subject headings: clusters: globular — stars: binaries — stars: dwarf novae — stars: white dwarfs

I. INTRODUCTION

The white dwarf sequence remains as the only expected stellar sequence in a globular cluster that has not as yet been studied in detail. Richer (1978, 1979) and Chan and Richer (1986) have found a few faint blue stellar objects in NGC 6752 and in M4, but the confusing aspect of these are their rather bright luminosities if they belong to their respective clusters. Knowledge of the white dwarf content in several clusters with a wide range of physical properties can provide important constraints on numerous aspects of stellar evolution theory, globular cluster dynamics, and even cosmology. Among these are the extension of the cluster mass function to masses (initially) higher than the present turnoff, the contribution of degenerate stars to the dynamical evolution of a globular, the origin of white dwarf spectroscopic subclasses, and cluster distances using the white dwarfs themselves as standard candles (Fusi Pecci and Renzini 1979). In this paper we present the discovery of the first extensive white dwarf sequence found in any globular cluster and compare the properties of these white dwarf candidates with known ones in the field.

II. OBSERVATIONS AND REDUCTIONS

Over the past two observing seasons (1985, 1986) we have carried out an extensive program of imaging the central region of the globular cluster M71 from CFHT. This is probably the best cluster to use for a northern hemisphere search for globular cluster white dwarfs as the cluster is nearby and relatively open. This latter criterion is crucial as white dwarfs are expected to be centrally concentrated as they were recently the most massive luminous cluster members. The best data were secured during a six night run in July/August 1986 when the RCA double density CCD detector was available. At the prime focus each side of a pixel of this device subtends 0".21 on the sky which is well matched to good seeing periods at CFHT.

During this run the inner $6' \times 4'$ of the cluster was imaged in U, B, and V, generally under superb conditions. Four overlapping fields were observed, all of which included the center of the cluster. The best frames exhibit a point spread function with a full width at half-maximum (FWHM) of 0".5, and no frames with FWHM worse than 0".8 were used in the final reductions. This was crucial as it is the crowding not the faintness that limits the detection of the faintest stars. Excluding the short exposures taken to photometer the giants and horizontal branch stars (not discussed in this paper), in all the fields the U exposures were 1 hr in duration and only the single best one for each field was used in the reductions. The V exposure times were 600 s and usually the three best in each field were averaged together to produce the final frame, while the B exposures were 900 s long and, again, normally the three best were averaged together. Figure 1 displays a montage of the inner part of M71 produced from the U CCD frames. The lowest luminosity stars visible in the Figure have U magnitudes fainter than 25, and it is clear that they can be measured right into the center of the cluster.

The data reduction was carried out along standard lines. Flat fields were obtained using the twilight and dawn sky. Landolt standards (1983) were used to calibrate the data (all nights were photometric), the standards covering the color range from hot white dwarfs to K dwarfs. The data were reduced using DAOPHOT (Stetson 1987) after preprocessing the frames using the routines in IRAF. The particular CCD chip used had one peculiar feature. The glass substrate of the chip had been removed in order to provide the highest possible quantum efficiency in the ultraviolet part of the spectrum. This meant that the chip was no longer optically flat; in fact, under a microscope it appears somewhat like a potato chip. This introduces point spread function (PSF) variations across the chip with an associated photometric error amounting to a few percent if a constant PSF is used. This result comes from a

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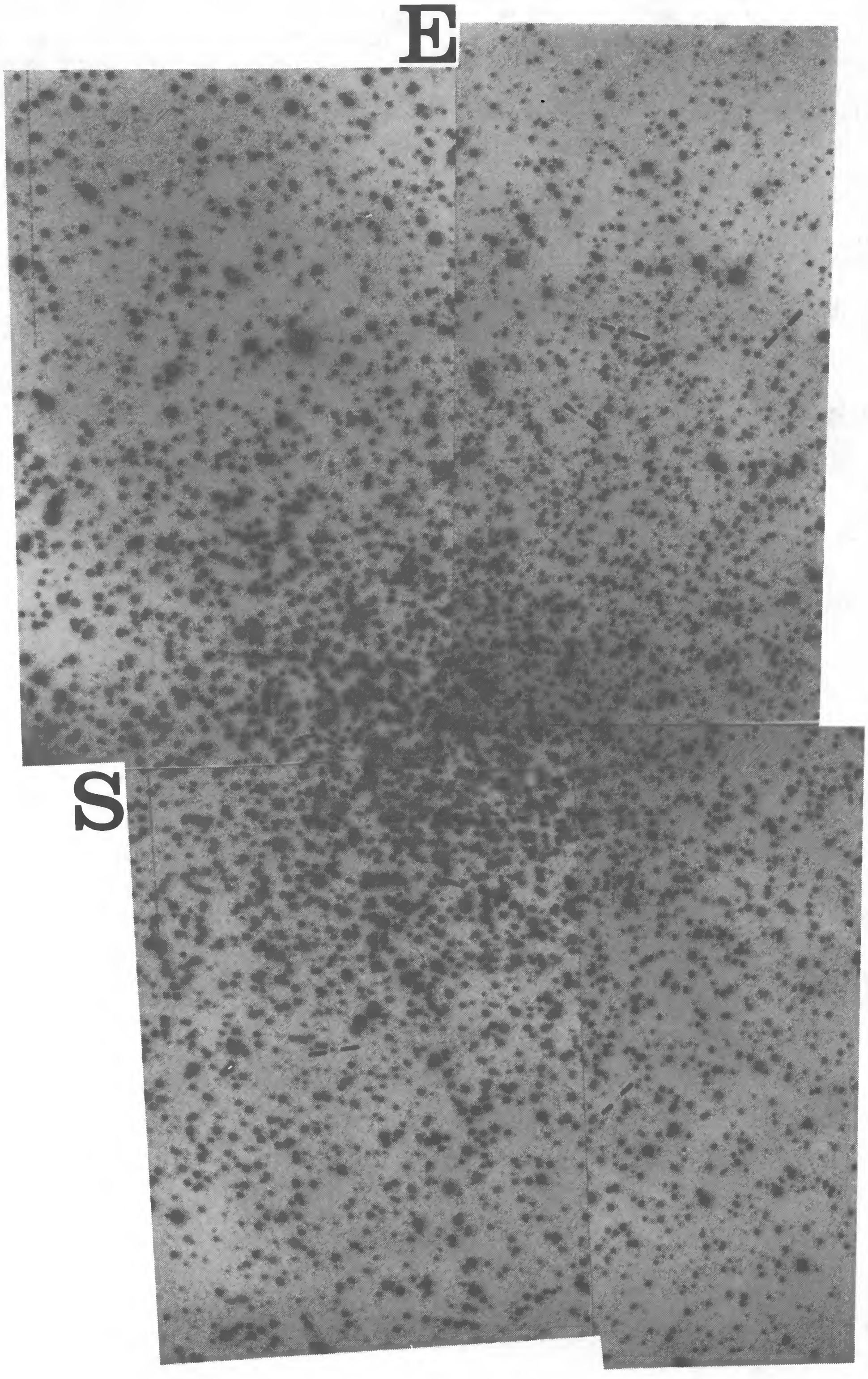

FIG. 1.—A montage of U CCD frames of the inner region of M71. Each frame is a single 1 hr exposure, with the seeing as good as $0\overset{''}{.}6$ on the best frame. Stars fainter than 25*th* magnitude are recorded in all frames. The objects indicated are all white dwarfs and cataclysmic variable candidates brighter than $U = 23$. The one white dwarf is the object in the northwest quadrant.

comparison of large aperture photometry with PSF fitting. While these variations could be modeled and accounted for, in practice they were ignored. All possibly peculiar stars (these include the white dwarfs, cataclysmic variable candidates, and blue stragglers) were visually inspected on our image display system to insure that they were single, stellar, and not contaminated by bad pixels.

III. THE U, $(U-V)$ COLOR-MAGNITUDE DIAGRAM

Of the three colors obtained, a color-magnitude diagram (CMD) in U versus $(U-V)$ is the most favorable for isolating hot white dwarfs because they are brightest in U and have extremely blue $(U-V)$ colors. Also, the B data which we secured was generally the poorest of the three colors; it being difficult to reach *25th* magnitude with this filter. For these reasons we will present and discuss only the U, $(U-V)$ CMD. The main morphological features in a globular cluster CMD using these colors has been discussed by Richer and Fahlman (1987).

In Figure 2 we exhibit the U, $(U-V)$ CMD for the $2' \times 3'$ field stretching north and east from the cluster center. The photometry in this field is the best that we were able to obtain in any field, and we use it here to illustrate the major cluster sequences. There are 1545 stars in this diagram and it includes all stars which pass the simple test of having an error in their photometry which lies within 3 σ of the mean for its magnitude.

In this CMD the cluster turnoff is well defined at $U = 18.5$ and the main sequence can be traced to $U = 25$. A small portion of the subgiant branch is seen but saturation (in V) limits the extent of this feature. A clear sample of blue stragglers is seen stretching above the turnoff for almost 1 mag. The apparent cutoff in the blue straggler population is not real as, again, saturation on these long exposures has limited the photometry at the bright end. This group of ~ 15 stars is heavily concentrated to the cluster center which is to be expected if they are more massive than the turnoff stars (Nemec and Harris 1987). There is no evidence for equal mass binaries in the cluster which would make their presence known by a sequence paralleling the main sequence with a separation of 0.75 mag. In fact, after correcting for field star contamination from our blank field CMD, a detailed analysis of the width of the main sequence implies that the nearly equal mass binary frequency in the cluster probably does not exceed a few percent of all main-sequence stars. At the faint blue end of the CMD, there are two stars which appear to have about the correct colors and magnitudes to be cluster white dwarfs. Finally, an unexpected group of stars appears at the blue end of the CMD at a magnitude level which is much too luminous for single white dwarfs. The blank field CMD, obtained in an area $\sim 20'$

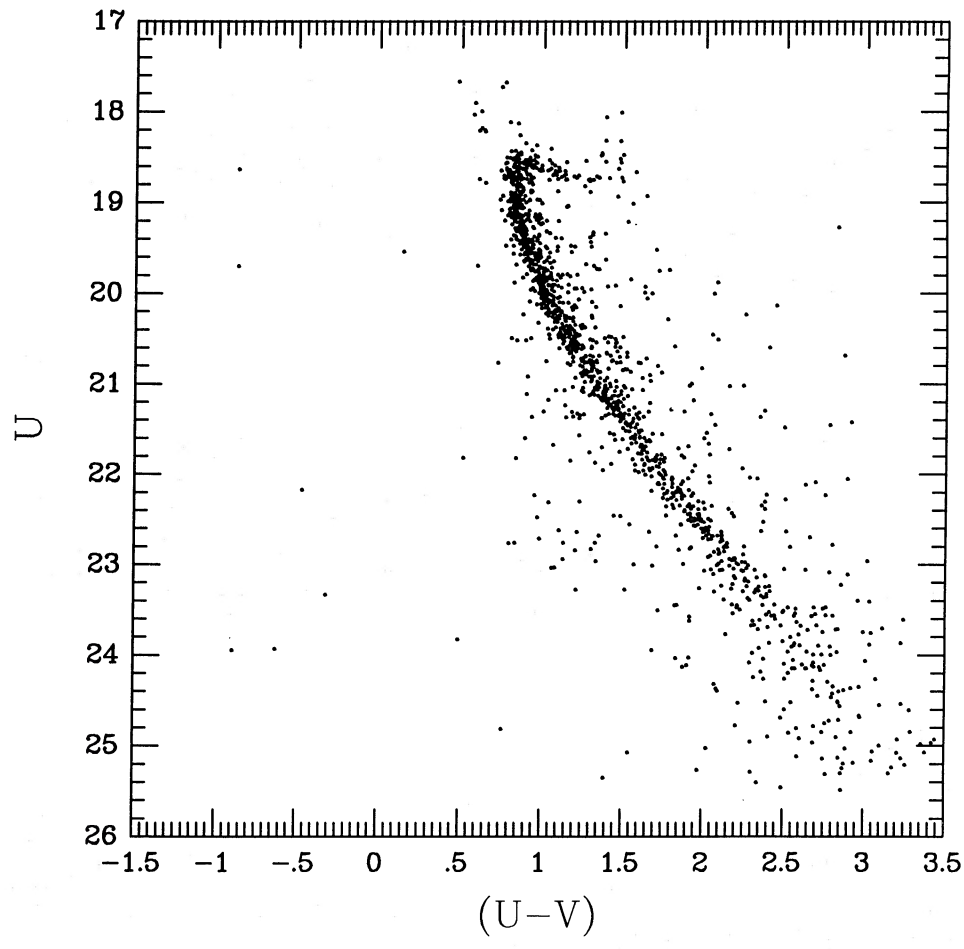

FIG. 2.—The U, $(U-V)$ color magnitude diagram for the field stretching north and east of the cluster center. There are 1545 stars in this diagram. Saturation in V has limited the bright end of the diagram.

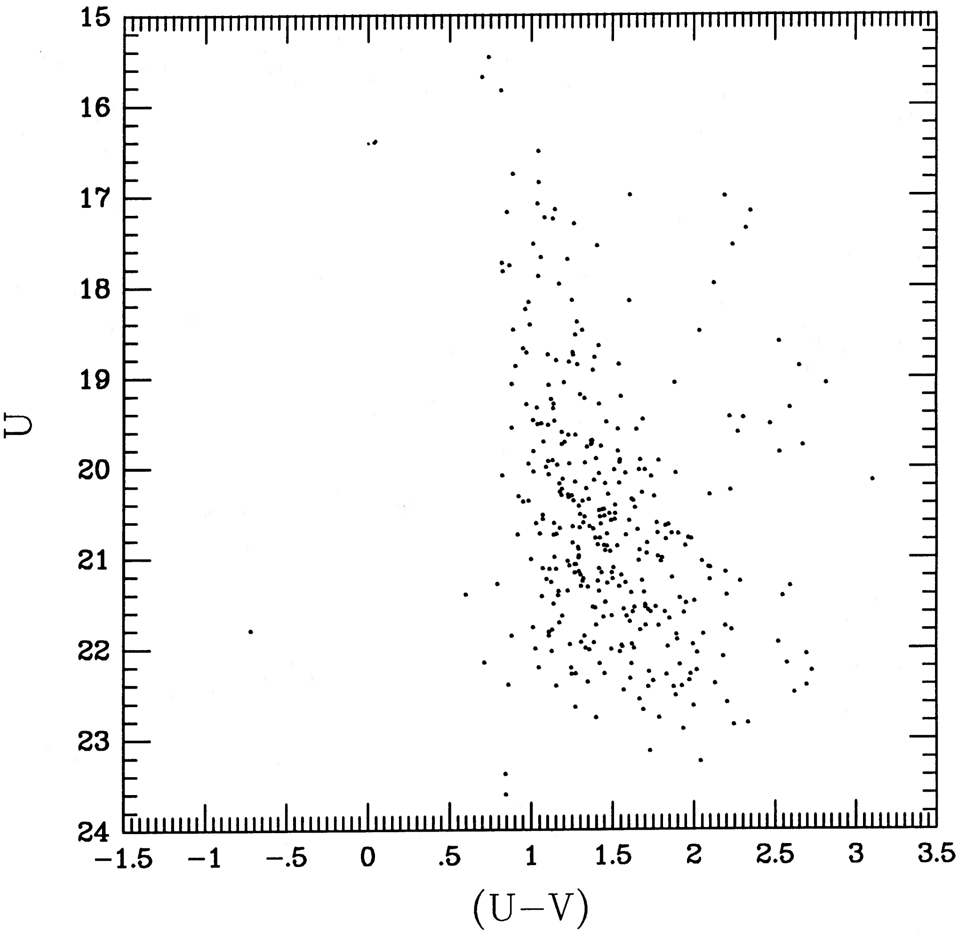

FIG. 3.—The U, $(U-V)$ color magnitude diagram for a blank field located 20′ north of the cluster. The exposure times were 2700 s in U and 600 s in V. These data were secured in seeing averaging only 1″.1, and this explains why this diagram is not as deep as in Fig. 2.

north of the cluster center and shown in Figure 3, does contain one star in this portion of the CMD at $U = 21.8$ and $(U-V) = -0.72$. The objects in M71 appear to commence near the turnoff and continue to fainter than $U = 23$. We discuss these objects in more detail below, but they are likely to be either field white dwarfs or cluster cataclysmic variables or some combination of these two.

The features seen in Figure 2 are amplified and extended in Figure 4 wherein we display the CMD for 5157 stars from three of the fields studied. The data obtained in the field extending to the southeast of the cluster center was significantly poorer than that in the other three fields so it is excluded in the following discussion. The two white dwarf candidates seen in Figure 2 are now joined by 10 others and the 12 appear to define a real cooling sequence beginning at $U \approx 22.4$ and $(U-V) \approx -1.1$ and extending to $U \approx 24.8$ at $(U-V) \approx -0.5$. The much brighter blue objects also define a sequence in this diagram extending from $U \approx 18.5$ (which is about the turnoff magnitude) to at least $U = 24$. All of these latter objects are very blue, the most luminous having $(U-V) \approx -1.0$, while the least luminous have $(U-V) \approx 0.0$. The magnitudes and colors of these stars are consistent with their identification as cluster cataclysmic variables (Mumford 1966; Warner 1976; Patterson 1984) or field white dwarfs. It is very unlikely that these objects are QSOs. First, there are too many. QSO counts appear to flatten at $B \approx 21$ (Koo and Kron 1982; Schmidt and Green 1983), thus implying that not even one QSO is expected on the three frames. Second, the M71 objects are too blue. Mean QSO colors are $(U-V) = -0.6$ with very few bluer than -0.8. The seven cataclysmic variable candidates brighter than $U = 23$ have a mean color of $(U-V)_0 = -1.01$. Spectroscopic observations can distinguish between these two possibilities, and this is planned for the near future.

One cataclysmic variable candidate appears in two of our overlapping fields. The photometry in these two fields was obtained 3 days apart and the object varied by 0.3 mag in V over this period of time. This strongly suggests that it is a cataclysmic variable as the error in its V photometry is only 0.03 mag, which is typical for a star at this brightness ($V = 22.1$).

From a statistical point of view we can use the blank field data together with an estimate of the number of foreground white dwarfs expected (Fleming, Liebert, and Green 1985) to try and decide whether these objects are cataclysmic variables or field white dwarfs. The Fleming, Liebert, and Green luminosity function implies that ~ 0.9 hot field white dwarfs should be present to $U = 23$ ($V = 23.5$) in the blank field, and, indeed, one white dwarf is seen. Over the three cluster fields this implies that about three white dwarfs should be present that are unrelated to the cluster. Figure 4 illustrates that to $U = 23$ ($V = 23.5$) there are seven hot stellar objects which we identify as either field white dwarfs or as possible cluster cataclysmic

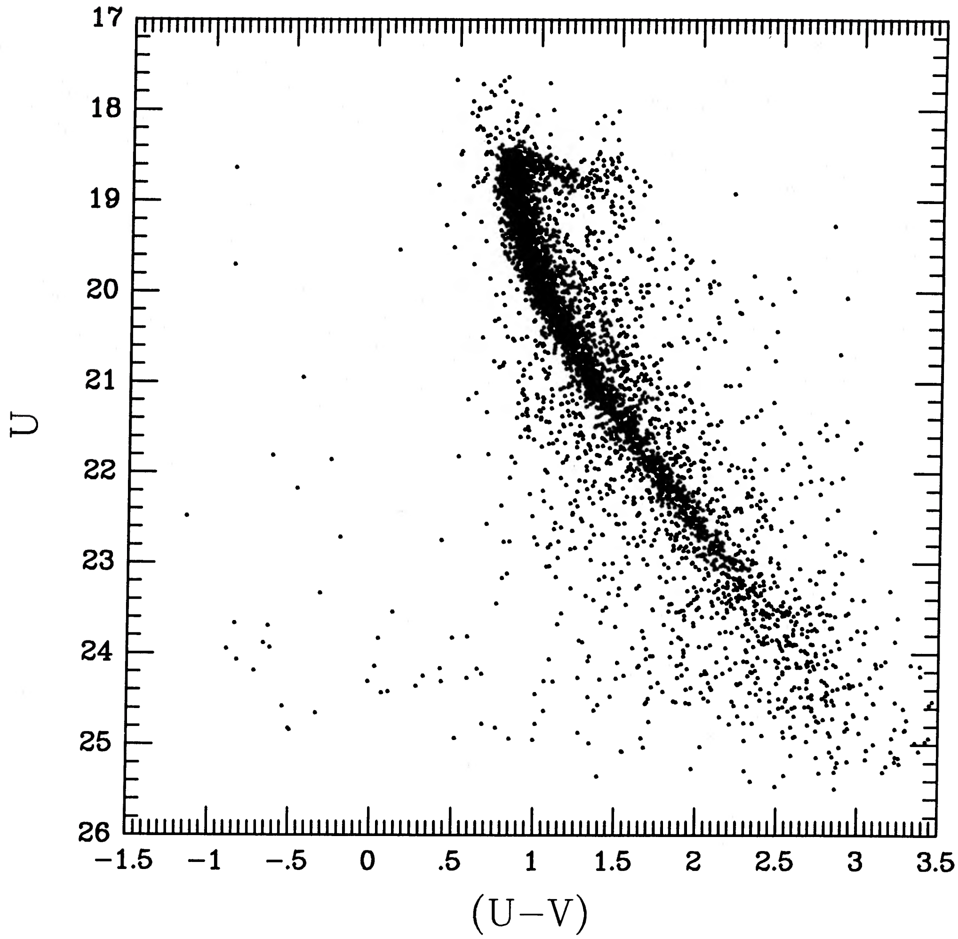

FIG. 4.—The U, $(U-V)$ color magnitude diagram for three of the fields observed. The data in the southeast field was significantly poorer than that in the other three regions so it is not included in this diagram. A total of 5157 stars are present in this figure.

variables. With these small number statistics it is not possible to exclude the hypothesis that all are field objects, only the spectroscopic observations mentioned, searching for Balmer emission lines, will be definitive. However, the apparent magnitude distribution of the discovered objects is unlike that expected from a field sample. For example, two stars are observed brighter than $U = 19.8$, and less than 0.1 are expected.

IV. THE PROPERTIES AND NUMBER OF M71 WHITE DWARFS

With the identification of an apparently real white dwarf cooling sequence in M71, we can investigate the properties of the stars, the location of the sequence in the cluster CMD, and compare the number of stars found with theoretical estimates. In order to derive the stellar properties and compare the cluster white dwarf sequence with that of a field sample, we require the cluster reddening, metallicity, and distance modulus. From our own data we have determined that the reddening is $E(B-V) = 0.28$, or $E(U-V) = 0.48$ for blue stars. This result comes from the color-color diagram of the cluster. The $(U-B)$ excess at $(B-V)_0 = 0.6$, $\delta(U-B)_{0.6} = 0.11$, implying, as is well known, that the cluster is quite metal rich, roughly having the same metallicity as 47 Tuc. From a fit of local subdwarfs to the main sequence of M71 (Fahlman, Richer, and VandenBerg 1985) an apparent distance modulus of $(m-M)_V = 13.70$ was derived. Coupled with a horizontal branch apparent magnitude of $V = 14.42$ (Cudworth 1985), this places the horizontal branch at $M_V = 0.72$. This is identical to that of 47 Tuc (Hesser *et al.* 1987) which has a similar metal abundance.

With the above cluster parameters, the location of the observed white dwarf cooling sequence is fainter than expected if the M71 white dwarfs are similar to DA white dwarfs in the field. However, the observed sequence is well matched by a DB sequence at the cluster distance. We illustrate this in Figure 5 where we overlay on the cluster CMD both DA and DB sequences taken from Eggen and Greenstein (1965) and Greenstein (1984). Photometric errors are indicated for three white dwarfs covering the range in magnitude over which these objects are observed. The M71 white dwarfs are clearly too faint or too blue to be identical to field DAs (unless the cluster parameters are badly in error), but the sequence is well represented by a field DB locus. There are, however, apparently no compelling reasons, either based on kinematics or on the nature of their spectra, to identify field DB white dwarfs with Population II (Oke, Weidemann, and Koester 1984; McCook and Sion 1984), so that the most important conclusion from Figure 5 is *not* that M71 white dwarfs are DBs, but simply that they appear to be fainter than field DA stars (by ~0.5 mag). The reason for this is not yet clear, but it may be that the masses of Population II white dwarfs are higher than Population I objects.

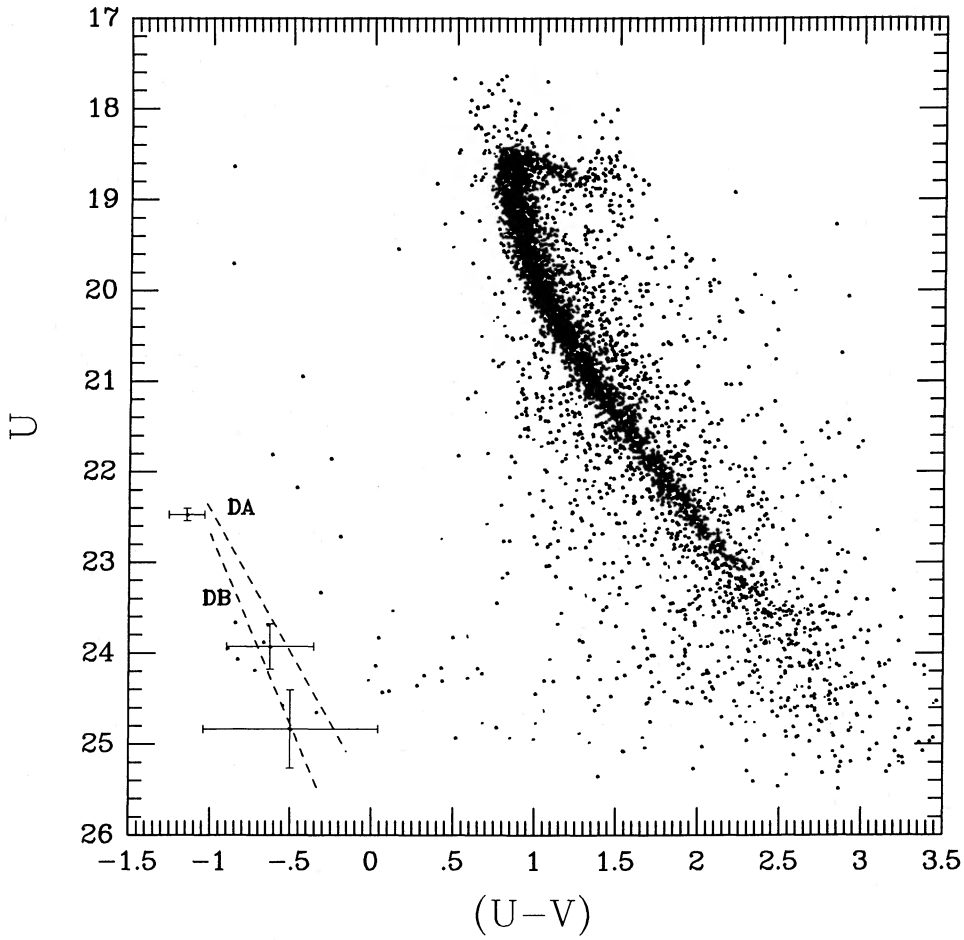

FIG. 5.—As in Fig. 4 except that the location of field DA and DB white dwarfs is included in the diagram as well as photometric error estimates of three white dwarfs whose magnitudes span the range of that observed.

Derivation of the properties of these white dwarfs from the available photometry does lead to the suggestion that they are somewhat more massive and thus smaller and hence less luminous at a given temperature than disk field white dwarfs. These data are contained in Table 1 where the effective temperature and bolometric corrections assume that the stars radiate as black bodies. The stellar radius and mass are derived from expressions in Weidemann (1968) and Hamada and Salpeter (1961) and assume zero temperature and a pure C^{12} composition. The average radius of the stars in our sample is 0.0106 $R_{\odot}$, and this can be compared with an unbiased mean for disk DA stars of $\sim$0.0111 $R_{\odot}$ (Shipman 1972, 1979). The mean mass derived for the M71 white dwarfs is 0.7 $\pm$ 0.2 $M_{\odot}$ where the error quoted is the standard deviation in the mass distribution. The error in the mean is $\pm$0.06 $M_{\odot}$. Using the errors in the photometry, the uncertainty in mass for a single object amounts to $\pm$0.3 $M_{\odot}$, so there is no evidence for a real variation in the masses of the white dwarfs. For comparison, the cluster turnoff mass is near 0.9 $M_{\odot}$ (VandenBerg and Bell 1985). The mean mass of field white dwarfs is thought to be strongly peaked near 0.6 $M_{\odot}$ (Koester, Schultz, and Weidemann 1979; Shipman and Sass 1980) with the disk stars evolving from main-sequence progenitors in the mass range 1 through perhaps 5 or 6 $M_{\odot}$. A major difference then between Population I and II white dwarfs might simply be that the precursors of Population II stars lose much less mass while in the giant and AGB phases of evolution.

TABLE 1

OBSERVED AND DERIVED PROPERTIES OF M71 WHITE DWARFS

Star	U	$(U-V)$	M_v	M_{bol}	T_{eff} (K)	log $(R/R_{\odot})$	Mass $(M_{\odot})$
10240......	23.69	−0.64	10.63	9.4	16,000	−1.83	0.4
10660......	24.83	−0.51	11.64	10.7	14,000	−1.98	0.7
10934......	24.19	−0.72	11.21	9.8	18,000	−2.02	0.8
11628......	23.66	−0.85	10.81	8.7	24,000	−2.05	0.8
11664......	23.93	−0.63	10.86	9.7	16,000	−1.89	0.6
11778......	22.48	−1.15	9.93	4.7:	70,000:	−2.18:	1.1:
11945......	23.95	−0.89	11.14	8.8	26,000	−2.14	1.0
12534......	23.88	−0.67	10.85	9.4	18,000	−1.94	0.7
13012......	24.58	−0.54	11.42	10.5	14,000	−1.94	0.7
13034......	24.07	−0.83	11.20	9.3	22,000	−2.09	1.0
13418......	24.84	−0.50	11.64	10.7	14,000	−1.98	0.7
13654......	24.65	−0.34	11.29	10.6	12,000	−1.82	0.4

The number of cluster white dwarfs found with M_V brighter than 11.0 is 5. These, of course, do not represent all the white dwarfs actually present in the cluster to this magnitude limit as many have been missed due to crowding. To evaluate the number actually within the three fields observed, faint stars with white dwarf colors were added into the frames and the data were rereduced in the identical manner. These incompleteness corrections implied that the actual number present to $M_V = 11.0$ is 41. Fusi Pecci and Renzini (1979) showed that the number of white dwarfs brighter than M_V in a cluster can be estimated by scaling the number of horizontal branch stars by the ratio of the white dwarf cooling time spent with a luminosity brighter than M_V to the typical lifetime of a horizontal branch star. In M71 there are a total of 37 horizontal branch stars with $V < 14.55$, and $(B-V) \leq 1.15$ which have a probability (based on their proper motion) of greater than 80% of belonging to the cluster (Cudworth 1985). Since we have only surveyed three fourths of the entire inner part of the cluster, we take 28 as the number appropriate to our search area. The Fusi Pecci and Renzini prescription, together with Green's (1980) cooling curve for hot white dwarfs, predicts 42 white dwarfs brighter than $M_V = 11.0$ in the area searched. Bahcall (1985) also considered the number of cluster white dwarfs. In his approach, an empirical luminosity function is used for the cluster, and theoretical models are then employed to estimate the cluster production rate of white dwarfs. Following this approach, only eight should exist in M71 brighter than $M_V = 11.0$ (see Renzini (1985) for further details). The observations seem to clearly favor the Fusi Pecci and Renzini prescription.

V. SUMMARY

We have imaged the center of the globular cluster M71 in three colors to a limiting magnitude of ~ 25 in each color. The main objective of this program was to search for white dwarfs in the cluster center. A faint blue stellar sequence was found but the stars are ~ 0.5 mag fainter than expected if they are similar to DA stars in the field. The observed sequence is well matched by either a DB sequence, or by one for stars $\sim 0.1\ M_\odot$ more massive than the mean for DA white dwarfs in the disk. The binary frequency in the cluster center was found to be very low, not exceeding a few percent of all main-sequence stars. About 1% of all the stars observed are blue stragglers. Finally, a bright blue stellar sequence was discovered which runs roughly parallel to the main sequence. This consists either of foreground white dwarfs or cluster cataclysmic variables. Spectroscopy of a few bright members of this group of objects should be able to distinguish between these two possibilities through the presence or absence of Balmer emission lines.

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REFERENCES

Bahcall, J. N. 1985, in *IAU Symposium 113, Dynamics of Star Clusters*, ed. J. Goodman and P. Hut (Dordrecht: Reidel), p. 481.
Chan, E., and Richer, H. B. 1986, *Ap. J.*, **302**, 257.
Cudworth, K. M. 1985, *A.J.*, **90**, 65.
Eggen, O. J., and Greenstein, J. L. 1965, *Ap. J.*, **141**, 83.
Fahlman, G. G., Richer, H. B., and VandenBerg, D. A. 1985, *Ap. J. Suppl.*, **58**, 225.
Fleming, T. A., Liebert, J., and Green, R. F. 1985, *Ap. J.*, **308**, 176.
Fusi Pecci, F., and Renzini, A. 1979, *Astronomical Uses of the Space Telescope*, ed. F. Machetto, F. Pacini, and M. Tarenghi (Geneva: ESO), p. 181.
Green, R. F. 1980, *Ap. J.*, **238**, 685.
Greenstein, J. L. 1984, *Ap. J.*, **276**, 602.
Hamada, T., and Salpeter, E. E. 1961, *Ap. J.*, **134**, 683.
Hesser, J. E., Harris, W. E., VandenBerg, D. A., Allwright, J. W. B., Shott, P., and Stetson, P. B. 1987, *Pub. A.S.P.*, **99**, 739.
Koester, D., Schultz, H., and Weidemann, V. 1979, *Astr. Ap.*, **76**, 232.
Koo, D. C., and Kron, R. G. 1982, *Astr. Ap.*, **105**, 107.
Landolt, A. U. 1983, *A.J.*, **88**, 439.
McCook, G. P., and Sion, E. M. 1984, *A Catalogue of Spectroscipally Identified White Dwarfs* (2d ed; Villanova Univ Obs. *Contr.* No. 3).
Mumford, G. S. 1966, *Ap. J.*, **146**, 411.
Nemec, J. N., and Harris, H. C. 1987, *Ap. J.*, **316**, 172.
Oke, J. B., Weidemann, V., and Koester, D. 1984, *Ap. J.*, **281**, 276.
Patterson, J. 1984, *Ap. J. Suppl.*, **54**, 443.
Renzini, A. 1985, *Astronomy Express*, **1**, 127.
Richer, H. B. 1978, *Ap. J. (Letters)*, **224**, L9.
———. 1979, *White Dwarfs and Variable Degenerate Stars*, ed. H. M. Van Horn and V. Weidemann (Rochester: University of Rochester Press), p. 259.
Richer, H. B., and Fahlman, G. G. 1987, *Ap. J.*, **316**, 189.
Schmidt, M., and Green, R. F. 1983, *Ap. J.*, **269**, 352.
Shipman, H. L. 1972, *Ap. J.*, **177**, 723.
———. 1979, *Ap. J.*, **228**, 240.
Shipman, H. L., and Sass, C. 1980, *Ap. J.*, **235**, 177.
Stetson, P. B. 1987, *Pub. ASP*, **99**, 191.
VandenBerg, D. A., and Bell, R. A. 1985, *Ap. J. Suppl.*, **58**, 561.
Warner, B. 1976, *The Structure and Evolution of Close Binaries, IAU Symposium 73*, ed. P. Eggelton, S. Mitton, and J. Whelan (Dordrecht: Reidel), p. 85.
Weidemann, V. 1968, *Ann. Rev. Astr. Ap.*, **6**, 351.

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