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DEEP CCD PHOTOMETRY IN GLOBULAR CLUSTERS. I. THE MAIN SEQUENCE OF M4

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ABSTRACT

From deep *UBV* CCD images obtained with the CTIO 4 m telescope, we have constructed color-magnitude and color-color diagrams in a $4' \times 3'$ field of the globular cluster M4. Inspection of the color-magnitude diagram indicates that the main sequence down to almost 3 mag below the turnoff has an intrinsic width no wider than ± 0.02 magnitudes in $(B-V)$ implying that the variation in helium abundance (ΔY) in these stars must be less than ± 0.07 $(\Delta Z = 0)$ or that the fractional variation in metallicity $(\Delta Z/Z)$ is no larger than ± 0.22 $(\Delta Y = 0)$. To a similar limit on the main sequence, the binary frequency in the field studied must be very small and does not exceed 3% of all main-sequence stars (and may be zero). The luminosity function of M4 is rather flat and definitely turns over by $V = 20$ $(M_v = 7.5)$.

Field stars in the direction of the cluster yield $E(B-V) = 0.37 \pm 0.06$ while our best metallicity estimate for M4 is $[\mathrm{Fe/H}] = -0.93 \pm 0.31$. Based mainly on the apparent magnitude of the horizontal branch and somewhat on fitting a theoretical ZAMS, we derive $(m-M)_v = 12.50$. A fit to a main sequence defined by subdwarfs was found to be an unsatisfactory approach to determining the distance modulus because the subdwarfs appear to be significantly more luminous than globular cluster stars of the same metallicity and color. Finally, the corresponding isochrones from VandenBerg were found to be in excellent general agreement with our data. Depending on the metallicity of M4, we derive an age which is either 13 (± 1) or 15 (± 1) billion years.

Subject headings: clusters: globular — stars: abundances — stars: evolution

I. INTRODUCTION AND OBSERVATIONS

Late in 1982 June we began a program with the CTIO CCD prime focus camera system to search for white dwarfs in nearby globular clusters. The long-range plan was to secure deep *UBV* direct images of several $5' \times 3'$ fields (the detector size on the sky at the prime focus of the 4.0 m telescope) in a number of close globular clusters, measure every star on the frames, and arrive at a group of white dwarf candidates in each cluster which would then be studied in greater detail.

On our first observing run inclement weather restricted us to a single clear night in which we were able to observe two fields in M4, one in M15 (mainly for calibration purposes), a "blank field" near Graham's (1982) E9 region plus flat fields both on the sky and against the dome. In the first M4 field (which we call the E field) the exposures were 6×300 s in *V*, 3×750 s in *B*, and 3×1800 s in *U*. For the second field (which we call the F field) the exposures were the same in *V*, 4×500 s in *B*, and 2×2700 s in *U*. The filters used were obtained from Corion Corporation, are fully blocked, and were chosen to match the *UBV* system as closely as possible. The seeing was a steady 1."5 throughout the night, resulting in a well-sampled stellar image covering about 3 pixels FWHM.

In this paper we present the photometry from only the F field which was roughly centered on star 3402 of Lee (1977) and is located about 5.'5 due east of the cluster center. The data here is superior to that of the E field as the sky was somewhat darker (the 6 day old Moon had set). On these frames we chose not to measure the $1' \times 3'$ area closest to the cluster center as the crowding was very severe, so the effective field is about 12 arcmin^2. We will discuss here only the fundamental parameters for M4: the main-sequence morphology, reddening, metallicity, helium abundance, distance modulus, fit to isochrones, and age. A more detailed examination of the cluster (e.g., tables of photometry, finding charts, luminosity function, white dwarf content) will be published elsewhere (Richer, Fahlman, and Crabtree 1984).

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II. REDUCTION AND CALIBRATION

The first step in the reduction of CCD data is the removal of instrumental effects. These include (for the CTIO system) removing the bias, trimming the frame, interpolating over bad pixels, flat-fielding, and defringing (in *V* only). Flat-fielding was accomplished using both a spot illuminated on the inside of the dome and a region of sky which is entirely devoid of stars (to at least $V = 24$) and is conveniently close to M4 ($\alpha_{1950} = 16^{h}48^{m}16^{s}.93$, $\delta_{1950} = -15°17'29''.3$; this field was kindly pointed out to us by P. Seitzer). The fringes in *V* are caused by the strong night sky line at 5577 Å but are easily removed as the fringe pattern is very stable. No fringes are seen at *U* or *B*. Software available at CTIO was used to accomplish all the above tasks.

Photometry of the individual stellar images was carried out at KPNO using the profile fitting routines in RICHFLD (Tody 1981). Every visible image on the *B* frame was entered into a coordinate list, and the same list was then used for the other two colors after registering the frames. RICHFLD subtracts the fit to each image from the original frame; hence the subtracted frames were inspected and all stars missed or not fitted by RICHFLD were then done in a second pass. A third pass was deemed unnecessary. In this way we preserve the true luminosity function of the cluster down to a confusion limit except for the few bright stars ($V \lesssim 16$) which are saturated.

The output of RICHFLD provides scaling ratios, the amplitude of a stellar profile compared to a mean profile of a number of well-isolated stars on the frame (the point spread function, PSF). The scaling ratios thus are an *internally* consistent set of magnitudes which must be calibrated on the *UBV* system. While there are a number of stars on our frames which do have *UBV* colors (mainly due to Lee 1977), they are all saturated or very close to saturation and are unreliable for calibration purposes. In order to calibrate the data we obtained frames in a field in M15 which Sandage (1970) and Sandage and Katem (1977) have extensively observed. As was discovered by Butcher and Oemler (1978), we found that Sandage's photometry has a systematic error (increasing as a function of magnitude) for stars fainter than $V = 19.7$; hence, we only used photoelectrically measured stars brighter than this limit. Based on 12 stars, our instrumental magnitudes in M15 were found to transform to the *UBV* system via the equations $(B-V) = 1.285\ (\pm 0.043)\ (b-v) +$ constant, $(U-B) = 0.731\ (\pm 0.078)\ (u-b) +$ constant, and $V = v + 0.030\,(\pm 0.001)\,(B-V) +$ constant. The range in $(B-V)$ for the standards used was from 0.01 to 1.12. Since M4 is rather highly reddened, we were forced to extrapolate the color terms for M4 main-sequence stars fainter than $V = 19.5$.

The PSFs in M4 were then assigned magnitudes calibrated via aperture photometry in M4 and M15 after making appropriate corrections to the constants in the transformation equations to allow for the different exposure times and differential extinction between the M4 and M15 frames. This is less satisfactory than having standards on the frame and may introduce systematic errors particularly as we used mean extinction coefficients for CTIO. However, several lines of evidence imply that any zero point errors in the calibration are less than ± 0.02 magnitudes. These are (*a*) we derive (see § IV*a*) a reddening for the cluster based on our photometry which agrees with the best current values; (*b*) any zero point differences between the two fields which we observed in M4 are at the 0.02 magnitude level or less. These fields were observed at rather different air masses so that inappropriate extinction corrections would be readily apparent; and (*c*) we derive (see § VI) ΔM_v between the horizontal branch (observed by Cacciari 1979) and the turnoff of M4 (observed by us) to be 3.36, in excellent agreement with the mean of seven other globular clusters (Sandage 1982).

III. THE COLOR-MAGNITUDE DIAGRAM (CMD)

Figure 1 displays the CMD of M4 calibrated as discussed in § II. Fiducial cluster points are listed in Table 1. Inspection of the CMD leads to the following conclusions.

1. The main sequence down to almost 3 mag below the

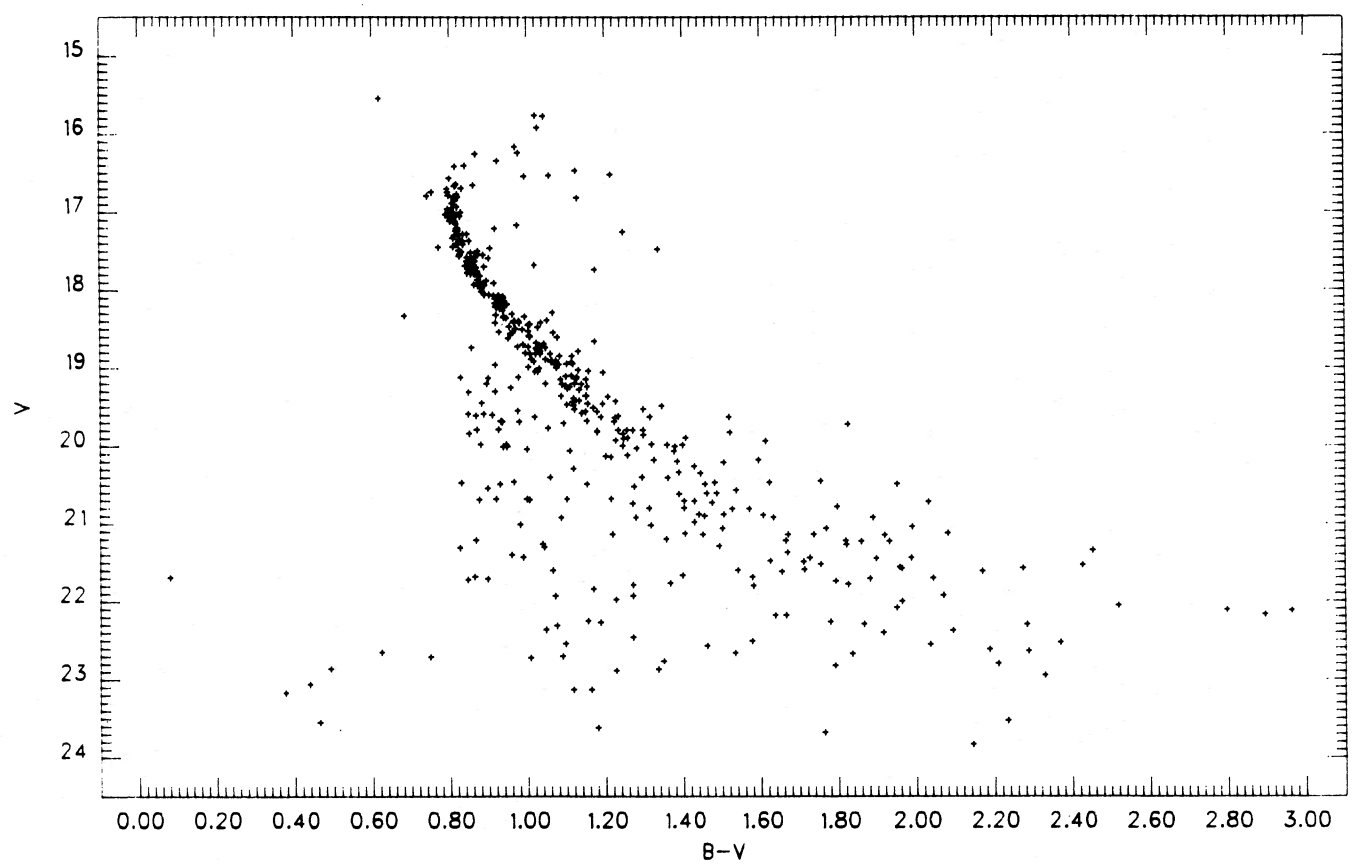

FIG. 1.—Color-magnitude diagram of the globular cluster M4. There are 469 stars in this diagram, and they represent *all* stars visible in a 4′ × 3′ field of the cluster centered about 5′.5 due east of the cluster center. No reddening or extinction corrections have been applied to the data.

TABLE 1

FIDUCIAL POINTS FOR M4 MAIN SEQUENCE

V	$B-V$	$U-B$
16,70	0.810	0.124
16.80	0.810	0.124
16.90	0.810	0.124
17.00	0.810	0.124
17.10	0.815	0.125
17.20	0.821	0.127
17.30	0.826	0.129
17.40	0.833	0.133
17.50	0.840	0.138
17.60	0.850	0.145
17.70	0.860	0.152
17.80	0.872	0.161
17.90	0.883	0.173
18.00	0.90	0.19
18.20	0.93	0.24
18.40	0.96	0.29
18.60	1.00	0.35
18.80	1.03	0.39
19.00	1.07	0.46
19.20	1.11	0.54
19.40	1.14	0.61
19.60	1.18	0.70
19.80	1.23	0.82
20.00	1.28	0.97
20.50	1.40	...
21.00	1.53	...

turnoff is very tightly delineated. We can set limits on the intrinsic width of the main sequence by a comparison of our internal photometric errors with the observed spread in $(B-V)$ at a given V on the main sequence. Table 2 summarizes the results. Columns (2) and (3) contain the internal errors in our photometry estimated from measuring about 100 stars chosen at random (except constrained to adequately cover the entire V range) on each of the six individual V frames and four B frames. Column (4) of Table 2 is the observed width, while the final column is the derived intrinsic width of the main sequence in $(B-V)$. As can be read from column (5) of Table 2, down to about 3 mag below the turnoff, the intrinsic width of the main sequence is no larger than about ± 0.02 in $(B-V)$.

From VandenBerg's (1983*a*, *b*) main-sequence isochrones, we find that $\Delta(B-V)/\Delta Y = -0.030$ mag per 0.1 change in Y at constant Z ($Z = 0.002$ which we shall see in § IV*b* is appropriate for M4). Hence, $\Delta Y \leq 0.07$ for the main-sequence stars in M4, not a particularly tight constraint. Similarly, we find that $\Delta(B-V)/\Delta Z = 0.09$ mag for a change in Z of 0.002 (at constant Y). Hence ΔZ is restricted to 0.00044 or $\Delta Z/Z \leq 0.22$ ($Z = 0.002$) which is very small. Sandage and Katem (1983) have derived similar limits for M92.

2. The narrowness of the main sequence also demands virtually *no* differential reddening across our small field in M4, in agreement with the conclusions of Cacciari (1979).

3. From $V = 16.5$ through 20.0 a total of 220 main-sequence stars appear in Figure 1. Of these, at *most* 17 appear as if they *might* be main-sequence binaries; that is, they appear to lie above the main sequence by about 0.5 mag for their color. However, at least 10 of these can be explained by large errors in the photometry, a poor fit to the PSF probably due to crowding. Eliminating these objects, then, to $V = 20$, an upper limit to the main-sequence binary frequency in the field observed in M4 is about 3%, and it may well be zero.

4. The luminosity function of the cluster is clearly rather flat from $V = 17$–19 and appears to turn over by $V = 20$. Very few cluster main-sequence stars are present fainter than $V = 20$. Experiments with artificial star fields (Richer, Fahlman, and Crabtree 1984) indicate that at $V = 20$ we should be losing less than 20% of the stars due to confusion. Therefore, at the distance of our field from the cluster center (5′.5), either we are seeing the effects of stellar dynamics in removing the low-mass stars preferentially or there is a real cutoff in the initial mass function of the cluster.

5. The stars lying below the M4 main sequence are a mixture of extragalactic objects, and background disk, halo, and bulge stars; the last is believed to be the main component as M4 is seen projected against the nuclear bulge of our Galaxy. King, Hedeman, and Hodge (1968) carried out star counts in the direction of M4 and found a field component of 3.1 objects arcmin^{-2} to $B = 21$. In the 12 arcmin^2 of our field in M4 we thus expect 37 stars unrelated to the cluster, while from Figure 1 we count 42 such objects, in excellent agreement with King *et al.*

6. Seven cluster white dwarf candidates are present in Figure 1. We delay the discussion of these objects to a later paper.

TABLE 2

INTERNAL ERRORS IN PHOTOMETRY AND WIDTH OF M4 MAIN SEQUENCE

			$\sigma(B-V)_{\rm MS}$	
V RANGE (1)	$\sigma(V)$ (2)	$\sigma(B-V)$ (3)	Observed (4)	Intrinsic (5)
<17	0.002	0.004	0.010	0.009
17–18	0.008	0.011	0.020	0.017
18–19	0.017	0.026	0.035	0.023
19–20	0.035	0.048	0.052	0.020
20–21	0.065	0.082	0.100	0.057
21–22	0.080	0.106	...	...
22–23	0.130	0.184	...	...
23–24	0.180	0.269	...	...

IV. FUNDAMENTAL CLUSTER PARAMETERS

a) *Reddening*

We estimate the reddening to M4 from the 10 bright ($V < 18$) field stars apparent in Figure 1. A color-color diagram of these 10 objects indicates that three of them appear to be more heavily reddened than the other seven or to have modest UV excesses. Since the CMD of Figure 1 has already constrained any differential reddening to be very small (certainly less than 0.02 mag) we adopt the latter view. This is not a surprising result as, on average, these stars are about 300 pc below the plane (assuming they are dwarfs), and we expect a mixture of stellar populations at this height. The best fit to the seven remaining stars is $E(B-V) = 0.37 \pm 0.06$ obtained by dereddening the stars along a trajectory $E(U-B)/E(B-V) = 0.80$ which is appropriate to these relative red stars (Böhm-Vitense and Szkody 1973). Although a rather poorly determined value due to the small

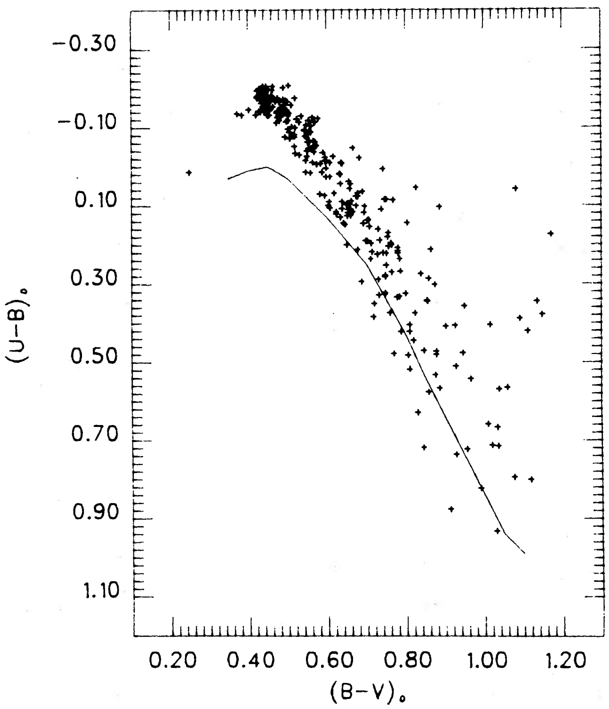

FIG. 2.—Color-color diagram for M4 cluster members (based on location in CMD) only. The solid line is the Hyades sequence. A reddening correction of $E(B-V) = 0.37$, $E(U-B)/E(B-V) = 0.80$ has been applied to the data.

number of stars used, it is consistent with the most recent reddening values for M4 (Sturch 1977; Cacciari 1979; Harris and Racine 1979).

b) Metallicity

A wide range of metallicity estimates for M4 exist in the literature ranging from [Fe/H] = −0.5 (Lee 1977) through −1.0 (Cacciari 1979; Mould, Stutman, and McElory 1979) and at the low end −1.4 (Smith and Butler 1978; Zinn 1980). From our three-color photometry we can investigate the colors of main-sequence stars in M4 as a clue to their metallicity.

Figure 2 is a color-color diagram of only the main-sequence stars in M4 after the reddening correction $E(B-V) = 0.37$, $E(U-B)/E(B-V) = 0.8$ has been applied. Shown also is the Hyades sequence (*solid line*) taken from Sandage (1969). It is well known that the ultraviolet excess, $\delta(U-B)_{0.6}$, defined as $(U-B)_0$ (Hyades stars) − $(U-B)_0$ (cluster stars) at $(B-V)_0 = 0.6$ is a reliable metallicity index (Wallerstein and Carlson 1960; Wallerstein 1962; Sandage 1969, 1970; Carney 1979*a*). The most comprehensive calibration of this index as a function of metallicity is that of Carney (1979*a*) and is based on field subdwarfs. *Assuming* that the atmospheric colors of subdwarfs are similar to globular cluster stars of the same metallicity, we can use Carney's calibration to estimate [Fe/H] for M4. A ridge line drawn through the data of Figure 2 indicates that $\delta(U-B)_{0.6} = 0.13 \pm 0.03$ for M4 and Carney's calibration then gives [Fe/H] = -0.51 ± 0.15. Given the amount of scatter evident in the subdwarf data, the formal uncertainty quoted above is probably too small. More realistically, the subdwarf calibration indicates that the metallicity of M4 lies in the range −0.3 to −1.0.

TABLE 3

$[Fe/H]_Z$ AND $\delta(U-B)_{0.6}$ FOR GALACTIC GLOBULAR CLUSTERS

Cluster	$[Fe/H]_Z$	$\delta(U-B)_{0.6}$	Source[a] $\delta(U-B)_{0.6}$
M71	−0.40	0.10	1
47 Tuc..................	−0.64	0.09	2
NGC 6752	−1.52	0.22	3
M5	−1.58	0.21	4
M3	−1.69	0.17	5
M13	−1.73	0.21	5
M15	−2.15	0.23	5
M92	−2.19	0.24	5

[a] SOURCES OF DATA.—(1) Arp and Hartwick 1971. (2) Hesser and Hartwick 1977. (3) Carney 1979*c*. (4) Arp 1962. (5) Sandage 1970.

Eight galactic globular clusters have *U* main-sequence photometry from which we can derive a relationship between $\delta(U-B)_{0.6}$ and [Fe/H]. The data are shown in Table 3 where we have adopted the Zinn (1980) scale of [Fe/H]. There is clearly large scatter in this data, but at least it is independent of the subdwarfs. At low abundances we expect an asymptotic behavior in $\delta(U-B)_{0.6}$ (see Sandage 1969 and Carney 1979*a* for details) but the data clearly only justify the first-order fit shown in Figure 3 which is $[Fe/H]_Z = 0.41 - 10.33\delta(U-B)_{0.6}$. This leads to a value of $[Fe/H]_Z = -0.93 \pm 0.31$ for M4. This result differs from the value derived by Zinn himself by about 0.5 dex, but is in good agreement with both Cacciari (1979) and Mould, Stutman, and McElory (1979). Further, a value near −1.0 seems consistent with the general run of parameters for M4 as tabulated by Sandage (1982, Table 1).

There is not much to chose between the two values of [Fe/H] derived here; both are quite uncertain. The subdwarf

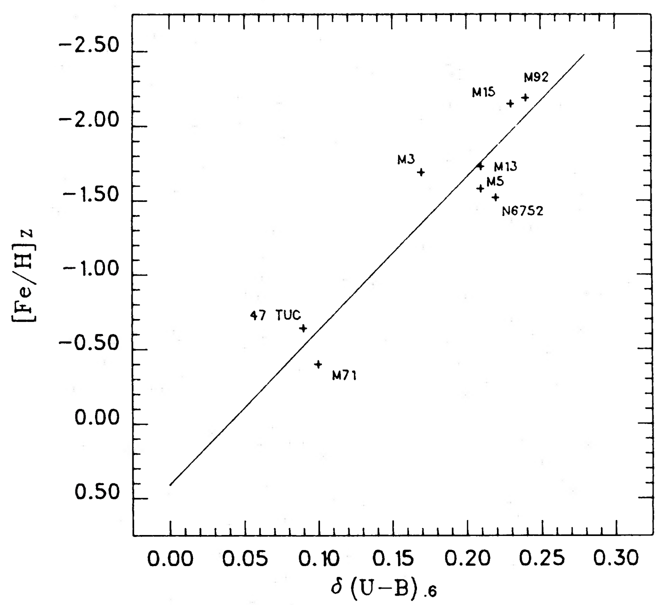

FIG. 3.—[Fe/H] as determined by Zinn (1980) plotted against $\delta(U-B)_{0.6}$ for eight galactic globular clusters. The solid line is the least squares fit to the data: $[Fe/H]_Z = 0.41 - 10.33\delta(U-B)_{0.6}$.

calibration assumes that the atmospheric colors of the globular cluster stars are the same as those of the subdwarfs at the same metallicity, while the globular cluster calibration is based on difficult U photometry of faint main sequence stars. Four factors, however, sway us in the direction of the lower value of [Fe/H]. (1) It does not rely on the subdwarfs. This is an important point as evidence presented in § IV*c* indicates a real difference between the subdwarfs and globular cluster stars. (2) As mentioned above, the general run of parameters for M4 suggest that it is more metal poor than, for example, 47 Tuc or M71, and is rather similar to the clusters NGC 362, 6362, and 6712, all of which are near $[\mathrm{Fe/H}]_Z = -1.0$. (3) Clusters more metal rich than $[\mathrm{Fe/H}]_Z \approx -0.6$ are not observed to contain RR Lyrae variables whereas M4 has an abundance of them. (4) Allowing the helium abundance and the distance to M4 to be completely free parameters, we attempted to fit isochrones (VandenBerg 1983*a*, *b*) for $[\mathrm{Fe/H}] = -0.5$ to our data. No combination of Y and distance modulus could simultaneously fit both the main sequence and the turnoff. Similarly, we were not able to obtain satisfactory fits with [Fe/H] as low as -1.3. For all these reasons, then, we feel the metallicity of M4 lies between $[\mathrm{Fe/H}] = -0.7$ and about -1.1, and that the formal result derived from the globular cluster calibration $[-0.93 \pm 0.31]$ is our best estimate.

Our derived value of [Fe/H] of course depends on the adopted reddening. If the reddening is as large as Newell (1970) suggests $[E(B-V) = 0.45]$, then $\delta(U-B)_{0.6} = 0.09$ and the cluster rivals 47 Tuc and M71 in metallicity. This seems unlikely based on points (2) and (3) above. If the true reddening is as low as $E(B-V) = 0.29$, $\delta(U-B)_{0.6} = 0.17$ which is more in line with the Zinn (1980) and Smith and Butler (1978) values for the metallicity of M4. However, with this reddening value and metallicity, the cluster would have to be older than 25×10^9 years (based on a rough extrapolation of VandenBerg's isochrones) and be located at an apparent distance modulus less than 12.0. This would put the horizontal branch (see § IV*c*) fainter than $M_v = 1.3$ which seems very unlikely.

Thus appealing to an error in the adopted reddening value as a solution to our somewhat high value of [Fe/H] (compared to Zinn and Smith and Butler) does not lead to a resolution. In fact, the discussion in the preceding paragraph suggests that $E(B-V) = 0.37$ for M4 cannot be substantially in error.

c) *Distance Modulus*

A number of approaches are available in establishing the distance to M4. They are as follows: (1) assigning an M_v to the horizontal branch; (2) fitting the observed main sequence of M4 to some observational fiducial sequence; and (3) fitting the observed main sequence to an appropriately chosen isochrone. We discuss each of these in turn and summarize the results in Table 4.

1. The horizontal branch of M4 is at $V = 13.34 \pm 0.06$ (Cacciari 1979). If we follow the precepts laid down by Sandage (1981, 1982), we can assign an absolute magnitude to the RR Lyrae stars in M4 by utilizing the Oosterhoff-Sawyer period shift, $\Delta \log P$, with respect to the M3 RR Lyrae stars. According to Sandage, the RR Lyrae stars in M3 have $M_v = 0.80$ and $\Delta \log P = 0.035$ for M4 which puts the RR Lyrae stars in M4 at $M_v = 0.91$ and yields $(m-M)_v = 12.43$ for the cluster. Recently, Cox, Hodson, and Clancy (1983) have argued that the RR Lyrae stars in M3 have $M_v = 0.66$ which yields $(m-M)_v = 12.57$ for M4, again using the period shifts as determined by Sandage (1982).

2. Fitting the main sequence of M4 to an appropriate observationally determined main sequence would seem to be the most straightforward approach, particularly as it bypasses the somewhat uncertain horizontal-branch calibration. The difficulty here, however, is the choice of such a fiducial sequence. At first sight Carney's (1979*b*) subdwarf sequence seems somewhat too metal poor for M4, although we note that the lower main sequence of 47 Tuc (Harris, Hesser, and Atwood 1983; $(m-M)_v = 13.1$, $E(B-V) = 0.04$, $Z = 0.006$) actually lies along this sequence! The reason for this is that the VandenBerg (1983*a*, *b*) isochrones appropriate to Carney's subdwarfs ($Y = 0.2$, $Z = 0.0003$) lie about 0.4 mag *below* the subdwarf sequence, but, remarkably enough, this metal-poor subdwarf sequence can be approximately fitted by theoretical ZAMSs (VandenBerg 1983*a*, *b*) with $Z = 0.003$ ($Y = 0.2$) or $Z = 0.006$ ($Y = 0.3$) which are much more metal rich than the stars. We illustrate this result in Figure 4 where we have plotted two isochrones from VandenBerg together with eight subdwarfs from Carney that supposedly have reliable metallicities, colors, and parallaxes. The mean metallicity of the subdwarfs is near $[\mathrm{Fe/H}] = -1.7$, while the isochrones shown have $[\mathrm{Fe/H}] = -1.77$ and -0.79, $Y = 0.2$, $\alpha = 1.5$, and age $= 15 \times 10^9$ years. The two subdwarfs plotted with open circles have very low [Fe/H] (≈ -2.3), whereas the remaining six are all near $[\mathrm{Fe/H}] \approx -1.4$. The slope of the six more metal-rich subdwarfs is reasonably well matched by the slope of the isochrones but clearly their absolute location in the $[M_v, (B-V)]$ plane is not in agreement with the isochrones. If VandenBerg's (1983*a*, *b*) isochrones are assumed to be a reasonable representation of globular cluster stars (and our data certainly supports this assumption; see § V), *we must conclude that the subdwarfs are significantly*

TABLE 4

SUMMARY OF DISTANCE DETERMINATIONS TO M4

Method	$(m-M)_v$	M_v (HB)
Assign M_v (HB) following Sandage	12.43	0.91
Assign M_v (HB) following Cox *et al.* and Sandage	12.57	0.77
Fit to theoretical ZAMS ($Z = 0.003$, $Y = 0.3$, $\alpha = 1.5$)	12.36	0.98
Fit to theoretical ZAMS ($Z = 0.003$, $Y = 0.2$, $\alpha = 1.5$)	12.54	0.80
Fit to theoretical ZAMS ($Z = 0.002$, $Y = 0.3$, $\alpha = 1.5$)	12.24	1.10
Fit to theoretical ZAMS ($Z = 0.002$, $Y = 0.2$, $\alpha = 1.5$)	12.42	0.92
Adopted	12.50	0.84

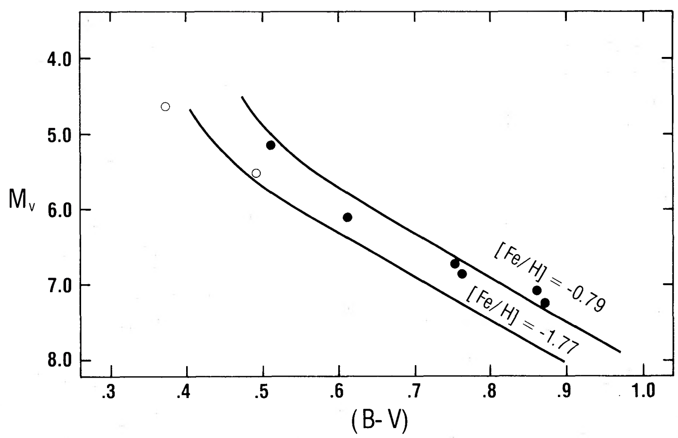

FIG. 4.—Color–absolute magnitude diagram for subdwarfs discussed by Carney (1979*b*). The two subdwarfs plotted with open circles have $[Fe/H] \approx -2.3$ while the remainder are near -1.4. The isochrones shown are from VandenBerg (1983*a*, *b*) and are labeled according to their metallicity; both are for age $= 15 \times 10^9$ yr, $Y = 0.2$, and $\alpha = 1.5$.

more luminous than globular cluster stars at the same metallicity and color. Possible explanations for this are that the subdwarfs (1) have a much lower helium abundance, (2) are more evolved than the cluster stars, or (3) have parallaxes which are systematically too *small*. In any case, what is apparent is that with the current data the subdwarfs do *not* provide an appropriate observational main sequence that can be used to fit the lower main sequences of globular clusters. For this reason we reject the idea of fitting our M4 main sequence to a subdwarf sequence.

3. It may not be entirely unreasonable to adopt the view that the theoretical isochrones have less uncertainty associated with them than any observational fiducial sequence. If this were so, the best approach would be to fit a theoretical ZAMS. This would, of course, limit any detailed comparison between theory and observation; particularly negating any check on zero point errors in the models. In the spirit of the above assumption we fit our observed main sequence to the four theoretical ZAMSs (VandenBerg 1983*a*, *b*) characterized by all combinations of the parameters $\alpha = 1.5$, $Z = 0.003$ and 0.002, $Y = 0.2$ and 0.3. Since model isochrones for red main-sequence stars tend to lie slightly to the blue of the observed locus by a few hundredths of a magnitude (VandenBerg *et al.* 1983), forcing a fit should produce distance moduli that are systematically too small by about 0.1 mag. Table 4 summarizes all our distance determinations to M4.

Keeping in mind that the fits to the theoretical loci are probably systematically too small by about 0.1 mag, there is very good consistency between these and the horizontal-branch fits. We thus adopt an apparent distance modulus of 12.50 for M4 and note that this places the horizontal branch at $M_v = 0.84$. The uncertainty in this distance modulus is somewhat difficult to estimate, but probably does not exceed ± 0.15 mag.

V. COMPARISON WITH ISOCHRONES AND THE AGE OF M4

In Figures 5*a* and 5*b* we present the CMD for M4 on which are *superposed* isochrones from VandenBerg (1983*a*, *b*). We have displayed the two *best* fitting sets of isochrones for the derived cluster parameters [$(m-M)_v = 12.50$, $E(B-V) = 0.37$, $Z = 0.002$ and 0.003]. Isochrones for $Z = 0.006$ and $Z = 0.001$ both gave unacceptably poor fits irrespective of Y. The isochrones for $Z = 0.006$ at $(m - M)_v = 12.50$ lay a full 0.2 mag above the observed main sequence (for $Y = 0.3$) and 0.4 mag above for $Y = 0.2$. For $Z = 0.001$ the isochrones deviated by about the same amount but in the opposite sense. The isochrones for $Y = 0.2$, $Z = 0.003$ were significantly too red for the cluster; even $Y = 0.25$ at this metallicity, while fitting the lower main sequence quite well, gave a very poor representation of the turnoff region. For $Y = 0.30$ and $Z = 0.002$ the isochrones were far too blue; $Y = 0.25$ at this metallicity helped somewhat but was still a poor fit compared to those shown in Figure 5.

Both sets of isochrones shown in Figure 5 appear somewhat too blue for the lower main sequence, but the effect is actually quite small; amounting to about 0.03 mag in $(B-V)$ at $V = 19$ ($M_v = 6.5$). It is possible that this error is in the photometry as (1) our reddest standard was $(B-V) = 1.12$ and the color terms were extrapolated beyond this, (2) we used mean extinction coefficients for CTIO, and (3) we did not have standards on our frame but were required to do a transfer from the M15 frames. On the other hand VandenBerg *et al.* (1983) have shown that there is in general a tendency for the cooler dwarfs to lie somewhat redward of the isochrones. The upper main sequence, the turnoff region, and the poorly populated subgiant branch, however, are beautifully matched by the isochrones.

Based on the fits alone of Figure 5 there is no clear choice between the two possibilities. The $\delta(U-B)_{0.6}$ value (calibrated against the globular clusters) and the run of other M4 parameters (Sandage 1982) favor the lower metallicity, while Cacciari (1979) suggests a helium abundance ($Y = 0.28$) which would require the higher metallicity. The age of the cluster, as is obvious from Figure 5, critically depends on the choice of metallicity being 13 (± 1) $\times 10^9$ years for $Z = 0.003$ and 15 (± 1) $\times 10^9$ years for $Z = 0.002$.

VI. SUMMARY AND DISCUSSION

We have presented the first photometry of the main sequence of M4. To our knowledge, this also represents the first extensive stellar photometry in a galactic globular cluster done with a CCD detector. The new results from our study are as follows:

1. There is no indication of a significant population of binaries among the main sequence stars.
2. There is no evidence of significant chemical inhomogeneity among the main-sequence stars unless the abundances of helium and the heavy elements are delicately correlated.
3. The luminosity function has a turnover at $M_v = 7.5$ (in the field studied here).
4. The ultraviolet excess of the main-sequence stars leads to a metallicity of $[Fe/H] = -0.93 \pm 0.31$, significantly more metal rich than the Zinn (1980) value.
5. The difference between the main-sequence turnoff and the horizontal branch is $\Delta M_v = 3.36$, in good agreement with the mean of the seven other clusters studied by Sandage (1982).

From our photometry we have derived an independent reddening estimate of $E(B-V) = 0.37 \pm 0.06$, consistent with other more accurate determinations based on many more

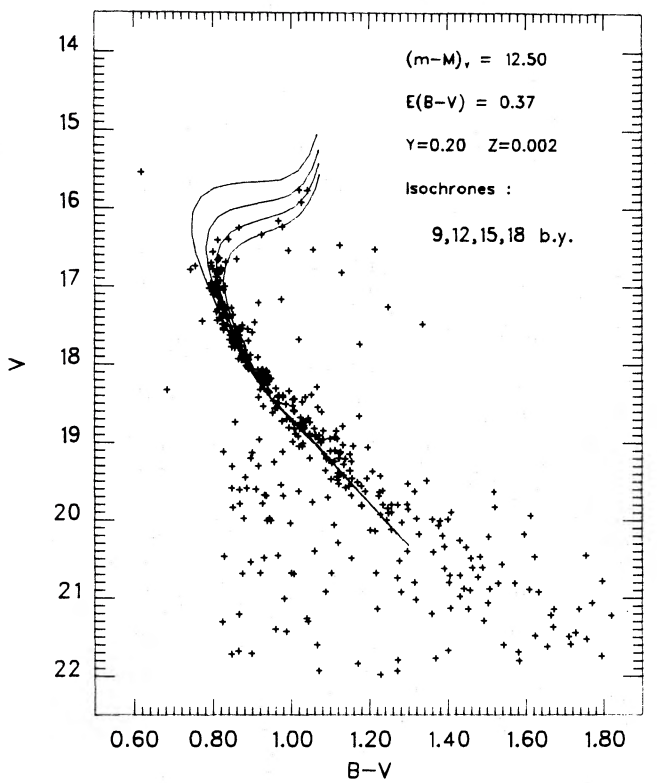

FIG. 5a

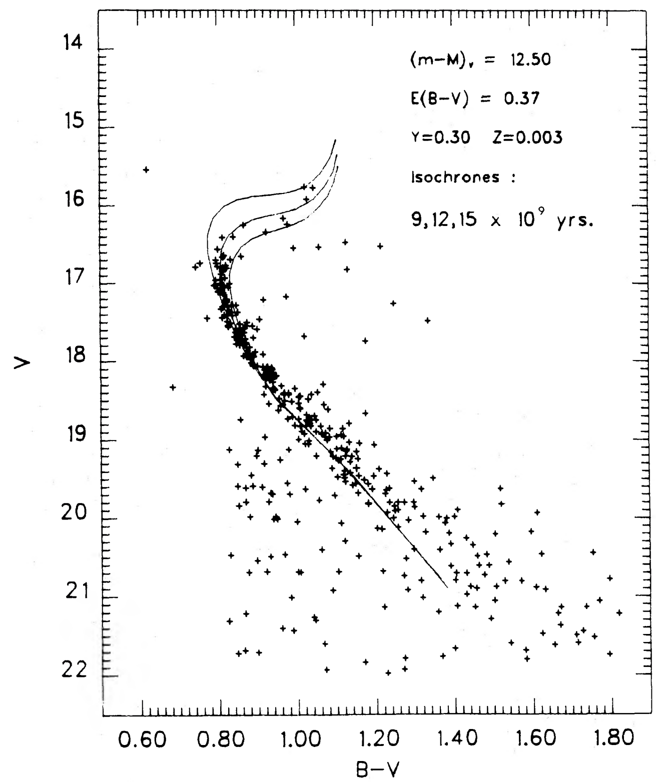

FIG. 5b

FIG. 5.—Observed color-magnitude diagram of M4 and overlaid (*not fitted*) isochrones from VandenBerg (1983*a*, *b*) for $Y = 0.2$, $Z = 0.002$, and ages 9–18 billion years (*a*), and for $Y = 0.3$, $Z = 0.003$, and ages 9–15 billion years (*b*). The isochrones were shifted so that they represent a cluster with $(m-M)_v = 12.50$ and $E(B-V) = 0.37$.

stars. Our adopted apparent distance modulus of $(m-M)_v = 12.50$ is based primarily on the Sandage (1982) technique of calibrating the cluster RR Lyrae stars with additional support from fitting theoretical ZAMSs, taken from VandenBerg (1983*a*, *b*), to our data. Sandage's technique assigns a magnitude difference to a given cluster horizontal branch relative to that of M3 which is proportional to the Oosterhoff-Sawyer period shift of the cluster RR Lyrae stars relative to the variables in M3. It has the great virtue of being independent of reddening or metallicity, but, of course, the zero point of the scale must be determined separately. At the moment, Sandage (1982, 1983) relies heavily on the calibration of his cluster main-sequence photometry (M3 in particular) against the same subdwarf sequence of Carney (1979*b*) which we have shown in this paper to be, at best, unreliable. Cox, Hodson, and Clancy (1983) using pulsation theory, have derived a somewhat higher luminosity than Sandage for the M3 variables, but, perhaps more importantly, they have shown that the helium abundance of the stars must be higher than assumed by Sandage and, in effect, have undermined the foundation on which Sandage has built his arguments. It is sobering indeed to realize just how weak the observational basis is for assigning distances to globular clusters. Although our adopted distance modulus does not rely on theory, it certainly leans heavily on it.

We have shown that the recently published isochrones of VandenBerg (1983*a*, *b*) provide a remarkably faithful representation of the main sequence in M4. The comparison between observation and theory shows that the model age of the cluster could, in principle, be the most accurately known parameter of all (to better than 10% uncertainty) if only one had a better handle on the metallicity and helium abundance. The metallicity question could be settled directly if detailed spectroscopic studies of the main-sequence stars were done, a project which appears to be within reach, or if a large enough sample of subgiants were to be observed as the isochrones in that region of the CMD are very sensitive to Z. Unfortunately, our data has too few subgiants to draw any conclusions, and the available published photometry (mainly Lee 1977) is not quite deep enough to reach the turnoff. We also note that the helium and metallicity are correlated through the isochrone fits.

At the higher helium abundance, $Y = 0.3$, and metallicity, $Z = 0.003$, the cluster appears to be $13(\pm 1) \times 10^9$ years, considerably younger than the derived age of 47 Tuc (Harris, Hesser, and Atwood 1983) or the clusters discussed by Sandage (1982, 1983). With $Y = 0.2$, $Z = 0.002$, the age of $15\ (\pm 1) \times 10^9$ years is in better agreement with the mean age of the cluster system determined by Sandage (1982). However, we are reluctant to draw wider conclusions based on these isochrone fits partly because of the nagging problem with the subdwarfs, which cannot be convincingly fitted with the VandenBerg isochrones, and partly because of the uncertainty in the distance modulus, helium abundance, and metallicity of the cluster. In particular, our work shows that at this time it is unlikely that a meaningful constraint is placed on the

Hubble age by appealing to isochrone fits to globular cluster photometry.

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