THE ASTROPHYSICAL JOURNAL, 459:L65–L68, 1996 March 10

THE MAIN-SEQUENCE STARS OF THE SAGITTARIUS DWARF GALAXY

G. G. FAHLMAN, G. MANDUSHEV, AND H. B. RICHER
Department of Geophysics and Astronomy, University of British Columbia, Vancouver, BC, Canada V6T 1Z4

AND

I. B. THOMPSON AND A. SIVARAMAKRISHNAN
The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101-1292
Received 1995 November 17; accepted 1995 December 28

ABSTRACT

The Sagittarius dwarf galaxy (SDG) is visible in the background field of the globular cluster M55. We present a deep *VI* color-magnitude diagram (CMD) of M55, which shows a prominent sequence of stars some 3.5 mag below the cluster main sequence. Through a comparison with a similar CMD for the globular cluster M4, we show that the M55 background field is not the Galactic bulge or spheroid. The SDG main sequence is almost as blue as that of M55 and thus, if it is metal rich, it must be younger than M55, a typical old Galactic globular cluster. The results from isochrone fitting indicate that the age of the SDG is 10–14 Gyr, similar to the ages inferred for the two associated globular clusters Ter 7 and Arp 2.

Subject headings: galaxies: individual: Sagittarius dwarf — globular clusters: individual: M55, M4

1. INTRODUCTION

Ibata, Gilmore, & Irwin (1994, hereafter IGI) discovered the Sagittarius dwarf galaxy (SDG) as a moving group of stars at a distance of about 24 kpc from the Sun. Their isopleth map showed that the SDG extends at least between $3° < l < 8°$ and $-10° < b < -20°$. The Optical Gravitational Lensing Experiment (OGLE) collaboration (Mateo et al. 1995a) also found a statistical excess of stars in a field more or less at the center of the above range and presented a *VI* color-magnitude diagram (CMD), which indicated that the bulk of the stellar population in the SDG is relatively metal rich, $\mathrm{Fe/H} \approx -1.1 \pm 0.3$, and is about 10 Gyr old. They also found RR Lyrae stars (Mateo et al. 1995b), which may indicate an older, more metal-poor population in the SDG. From the morphology of their *VI* CMD, Sarajedini & Layden (1995, hereafter SL) derived a metallicity of $\mathrm{Fe/H} = -0.52 \pm 0.09$ for the SDG and also suggested that a lower metallicity population with $\mathrm{Fe/H} \approx -1.3$ may be present. They derived distance estimates between 25 and 29 kpc, depending on the adopted absolute magnitude for the SDG horizontal branch and red clump stars. Their photometry extended about 2.5 mag below the horizontal branch but did not reach the main-sequence turnoff.

A number of cataloged globular clusters appear to be associated with the SDG. M54 (NGC 6715) is located on the sky where the SDG star counts of IGI are at maximum and was the subject of the SL study. Other associated clusters include Ter 7 and Arp 2, both of which have been noted as being younger than the majority of the Galactic globular clusters (Buonnano et al. 1994, 1995a, b) and Ter 8. Abundances and kinematics of the associated clusters are discussed in Da Costa & Armandroff (1995).

In this paper, we will present observations of the Galactic globular cluster M55, which lies along the line of sight (LOS) $l = +9°, b = -23°$. This cluster is not associated with the SDG, but, as was first noted by Mateo & Mirabel (1995), the SDG does contribute to the field star density in the background of M55. In this paper, we show that stars from the SDG define a background main sequence (MS) in the *VI* CMD of M55. We compare this CMD to similar observations of M4, which is along a LOS defined by $l = 351°$, $b = 16°$, i.e., in an almost mirrored direction with respect to both the Galactic plane (b) and the azimuthal axis (l), to demonstrate that the M55 field sequence identified as the SDG is not due to the spheroid or bulge of the Milky Way.

2. OBSERVATIONS AND DATA REDUCTION

All the data discussed here were obtained through Johnson V and Cousins I filters at the du Pont Telescope of the Las Campanas Observatory. The M55 observations were made in 1992 August (by G. G. F. and I. B. T.) with a 1024×1024 Tektronix CCD, whose 21 μm pixels give a field of view of $4' \times 4'$. The photometry was calibrated against Landolt (1992) standards. The data reductions were performed with the ALLFRAME software of Stetson (1994). A complete discussion of the M55 data will be given by Mandushev et al. (1996), and here we note only that the photometric errors in $(V - I)$ are $\simeq \pm 0.15$ mag at $V = 25$. The M4 data were obtained in 1990 June (by I. B. T. and A. S.) with a Ford (Loral) 2048×2048 CCD with 15 μm pixels and a field of view of $5'.5 \times 5'.5$. The frames were rebinned 2×2 pixels during the readout of the CCD. These data were also calibrated against Landolt standards. The enhanced scatter in the photometry of the bright stars in the CMD (see Fig. 1) is due to differential reddening across the observed field. We derive a reddening gradient of 10 ± 2 mmag arcmin^{-1} in $(B - V)$ by measuring the color of the turnoff stars as a function of east-west position in the observed field. This is twice the value derived by (Cudworth & Rees 1990), but the reddening is probably patchy.

3. RESULTS

Our CMDs for M55 and M4 are shown in Figure 1. The background sequence of interest here is located approximately 3.5 mag below the sequence defined by the M55 stars. We identify this as the MS of the SDG, because the implied distance to these stars is about 5 times that to M55, consistent

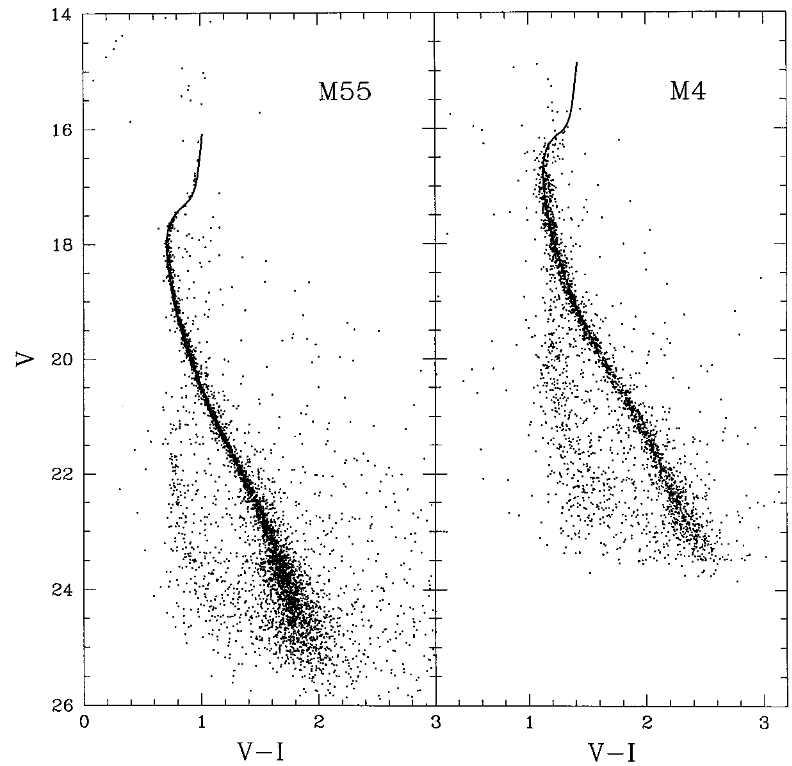

FIG. 1.—CMDs for M55 and M4 are shown. The solid lines are 16 Gyr isochrone fits with Fe/H = −1.77 and Fe/H = −1.27 for M55 and M4, respectively. See the text for discussion of the background sequences visible in each field.

with the inferred distance to the SDG. This sequence appears to terminate near $V \approx 21$, and the turnoff, defined as the bluest point along the locus, is below this level, near $V \approx 21.5$. In the M4 field, we also see a very prominent background sequence located about 3 mag below the cluster locus. If we assume that the Galactocentric solar distance is $R_o = 8$ kpc, then we find that this sequence is consistent with the expected location of Galactic bulge main-sequence stars, which are located at the tangent point relative to the center of the Milky Way. The bulge turnoff is confused by the overlap with the M4 main sequence, but the bulge subgiants can be seen extending to higher luminosities redward of the M4 MS above $V \simeq 17.5$.

In order to compare the field populations in these two directions, we need the reddening *difference* between them. In the M55 field, we adopt $E(B-V) = 0.14$ from Shade, VandenBerg, & Hartwick (1988). Their reddening and apparent distance modulus, $(m-M)_V = 14.10$, are consistent with the Vandenberg & Bell (1985, hereafter VB85) isochrones we will use to get the age difference between the two clusters and the SDG. The fit to the VB85 isochrone with Fe/H = −1.77 (Zinn & West 1984) and an age of 16 Gyr is shown in Figure 1.

The reddening toward M4 is high and variable across the face of the cluster. Richer & Fahlman (1984) derived $E(B-V) = 0.37 \pm 0.06$ from *UBV* photometry in a field which overlaps that discussed here. Cudworth & Rees (1990) derived a mean value of $E(B-V) = 0.40 \pm 0.04$ from the apparent colors of the instability strip edges. Adopting $E(V-I) = 1.25\ E(B-V)$ (Bessell & Brett 1988), we find here that $E(B-V) = 0.44$ is required to fit the 16 Gyr VB85 isochrone with Fe/H = −1.27 (Zinn & West 1984). This fit, with $(m-M)_V = 12.65$, (Richer et al. 1995) is shown in Figure 1. We emphasize that the value of $E(B-V)$ determined this way (i.e., by forcing an isochrone fit) may be incorrect, since the isochrones could have a systematic color offset. It is well known that the VB85 isochrones are systematically too blue in the *BV*-plane, and they were never similarly tested rigorously in the *VI*-plane. It is the reddening difference between the M4 and M55 fields that is important in the following discussion, and the isochrone fits indicate only that the differential measure derived above, $\Delta E(B-V) = 0.30$, is approximately correct.

With the reddening difference known, we can now adjust the photometry in the M4 field so that the Galactic bulge stars seen at the tangent point have the same apparent distance modulus and reddening as those seen at the tangent point along the M55 LOS. After this was done, the two data sets were overlayed as shown in Figure 2 (Plate L9). The following points may be noted. (1) The M55 and M4 loci show a small color offset, which was forced to be consistent with the 16 Gyr VB85 isochrones shown in Figure 1. However, it can be seen that the overlap of the bulge stars from M4 and the corresponding sequence in M55 (visible to the red of the M55 MS between $18 < V < 20$ in Fig. 1) is very good, which adds additional confidence to the applied reddening differential. (2) The Galactic bulge sequence is redder than that of M4, which suggests that the these stars are more metal rich than M4, provided the two populations are coeval. The bulge could be more metal poor only if it were substantially older than M4, a prospect that seems unlikely given the inferred old age for M4 (Buonanno, Corsi, & Fusi Pecci 1989). (3) The SDG sequence is bluer than the bulge population and, indeed, is almost as blue as the M55 MS locus. Since all the available evidence suggests that the SDG is more metal rich than M55, this observation implies that the SDG MS population must be

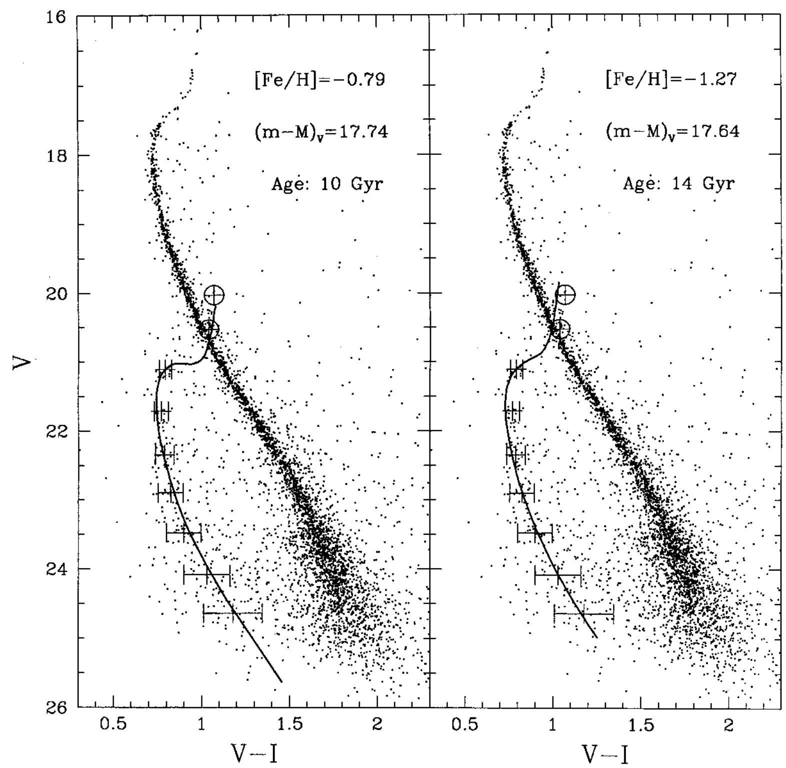

FIG. 3.—M55 data (*points*) are plotted together with the ridge line of the SDG MS (*points with error bars*) and two subgiant points from SL (*circled crosses*). The VB85 isochrones with the indicated metallicity, apparent distance modulus, and age have been overlayed on the SDG sequence. In each case, the applied reddening has been fixed at $E(B - V) = 0.14$, the value used for the isochrone fit to M55 itself shown in Fig. 1.

younger than M55. (4) The Milky Way bulge population does contaminate the SDG sequence; in particular, it confuses the turnoff and subgiant region. This clearly will hamper an assessment of isochrone fits to the SDG locus.

Our two best VB85 isochrone fits to the SDG sequence are shown in Figure 3. The ridge line of the SDG MS is indicated by the large points, which are modal values within defined magnitude bins. The error bars are (twice) the median of the absolute deviation in color of the individual stars from the mode. Stars within 2 σ of the M55 MS fiducial were excluded in deriving these estimates. The two circled crosses are points read off the SDG subgiant branch from the SL CMD. SL derived $E(B - V) = 0.13 \pm 0.02$ along the LOS to M54, essentially the same as we have adopted for M55. Hence, these points, which provide a useful constraint on the isochrone fits, were plotted without further adjustment. The reddening applied to the isochrones was fixed to be that adopted for M55, and only the distance modulus was adjusted to give an acceptable fit to the data.

In the left panel of Figure 3, we show the fit for an Fe/H = −0.79 isochrone with an age of 10 Gyr. Correcting the apparent distance modulus of $(m - M)_V = 17.74$ for extinction using $A_V = 3.12E(B - V)$ (Bessell & Brett 1988), we find a distance to the SDG of 28.9 kpc. The 12 Gyr Fe/H = −0.79 isochrone fits almost as well at the smaller distance modulus of 17.54 or 26.3 kpc. Both distance estimates are consistent with the SL results. The more metal-rich VB85 isochrones with Fe/H = −0.49 are too red to fit our data.

In the right panel of Figure 3, the data is fit with a 14 Gyr, Fe/H = −1.27 isochrone at a distance of 27.6 kpc. The circles around the SL points span $\approx \pm 0.05$ mag in color, a reasonable assessment of the uncertainty in locating these points in our data, and so the apparent misfit to these points is marginally acceptable. However, the isochrone turnoff is somewhat too blue as well, and therefore neither younger nor older isochrones at this metallicity provide a better fit. A somewhat more metal-rich isochrone with a somewhat younger age is to be preferred. The VB85 isochrones with Fe/H > −1.27 can probably be excluded from consideration in any case by the observations of the SDG giant branch, which is clearly incompatible with very low metallicity. We conclude from Figure 3 that isochrones with Fe/H = -1.0 ± 0.2 and ages between 10 and 14 years provide the best match to our data.

4. SUMMARY AND DISCUSSION

The main-sequence turnoff of the stellar population in the SDG has been detected in the background field along the LOS to the Galactic globular cluster M55. From a direct comparison with the M55 MS, our observations show that the SDG is located between 25 and 29 kpc from the Sun. If we accept the previous observations, which imply that the dominant population in the SDG is significantly more metal rich than M55, then the comparably blue MS of the SDG shows immediately that this dominant population must be younger than a normal halo cluster like M55.

The turnoff is contaminated by foreground stars from the Galactic bulge, and thus the age sensitive subgiant region is impossible to delineate in our data. The observed main sequence shows scatter, which may reflect inherent age and abundance differences as well as depth-of-field effects, which also complicates any analysis. Supplementing our data with the subgiant observations of SL, we show that the VB85 isochrones with $-1.27 < \mathrm{Fe/H} < -0.79$ provide good fits to the observations for ages between 10 and 14 Gyr and distances between 26 and 29 kpc. These distances do depend on the absolute reddening along the LOS to M55 and are probably uncertain at about the $\pm 10\%$ level. A reddening free estimate of the SDG distance is that it is between 4.88 and 5.35 times the distance to M55.

The VB85 isochrones assume a solar mixture for the heavy elements that may be inappropriate (Chieffi, Salaris, & Staniero 1991), and thus the absolute ages are not necessarily correct (Bergbusch & VandenBerg 1992). They are used here because there are no α-element enhanced models available for comparison with data on the *VI*-plane. These isochrones give an age of $\simeq$16 Gyr for M55 and M4. The difference in age between these clusters and the SDG is likely to be more reliable, although compositional differences could affect this comparison as well.

In general, our results suggest that the dominant MS population in the SDG has an age that is similar to that of the young associated globular clusters, Ter 7 and Arp 2; i.e., about 3–4 Gyr younger than the majority of the Galactic globular clusters. Ter 8, on the other hand, appears to be as old as M92 (Ortolani & Gratton 1990), and M54 has not yet been observed at the turnoff. If old ages are confirmed for these two associated clusters, then Ter 7 and Arp 2 are "young" objects, even in the context of their parent galaxy, and thus were formed after the SDG itself was largely assembled.

There are two other points of interest in this data. (1) There is no obvious sign of the SDG in the M4 field shown here, nor in the deeper *Hubble Space Telescope* (*HST*) data of Fahlman et al. (1996). Hence, the surface star density of the SDG must be very low in this direction. The isopleths of IGI are elongated more or less along a great circle parallel to l and centered at $l \simeq 6°$. The undetectably low SDG star density in the M4 field ($l = -9°$) is a constraint on the size and shape of the SDG itself and, likely, on the orbit. (2) The bulge component is evidently weaker in the M55 field than in the M4 field. Whether this can be fully accounted for by the differences in the field of view and the Galactocentric distances to the tangent points for an axisymmetric bulge is as yet unclear. A careful analysis of this and similar data can provide constraints on the density distribution in the Galactic bulge and will be the subject of a separate discussion.

We are grateful to Peter Stetson for permission to use ALLFRAME for the M55 photometry and thank Mario Mateo, Rodrigo Ibata, and Leonard Searle for helpful discussions. This work was partially supported by research grants to G. G. F. and H. B. R. from The Natural Sciences and Engineering Research Council of Canada.

REFERENCES

Bergbusch, P. A., & VandenBerg, D. A. 1992, ApJS, 81, 163
Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
Buonanno, R., Corsi, C. E., & Fusi Pecci, F. 1989, A&A, 216, 80
Buonanno, R., Corsi, C. E., Fusi Pecci, F., Fahlman, G. G., & Richer, H. B. 1994, ApJ, 430, 1121
Buonanno, R., Corsi, C. E., Fusi Pecci, F., Richer, H. B., & Fahlman, G. G. 1995a, AJ, 109, 650
———. 1995b, AJ, 109, 663
Chieffi, A., Salaris, M., & Staniero, O., 1991, in ASP Conf. Ser. 13, The Symp. on the Formation and Evolution of Star Clusters, ed. K. Janes, (San Francisco: ASP), 219
Cudworth, K. M., & Rees, R. 1990, AJ, 99, 1491
Da Costa, G. S., & Armandroff, T. E. 1995, AJ, 109, 2533
Fahlman, G. G., et al. 1996, in The Dynamical Evolution of Star Clusters–Confrontation of Theory and Observations, ed. J. Makino & P. Hut (Dordrecht: Kluwer), in press
Ibata, R. I., Gilmore, G., & Irwin, M. J. 1994, Nature, 370, 194 (IGI)
Landolt, A. U. 1992, AJ, 104, 3340
Mandushev, G., Fahlman, G. G., Richer, H. B., & Thompson, I. B. 1996, in preparation
Mateo, M., & Mirabel, N. 1995, in The Origins, Evolution, and Destinies of Binaries in Clusters, ed. E. F. Milone (San Francisco: ASP), in press
Mateo, M., Udalski, A., Szymański, M., Kałużny, J., Kubiak, M., & Krzemiński, W. 1995a, AJ, 109, 588
Mateo, M., Kubiak, M., Szymański, M., Kałużny, J., Krzemiński, W., & Udalski, A. 1995b, AJ, 110, 1141
Ortolani, S., & Gratton, R. 1990, A&AS, 82, 71
Richer, H. B., & Fahlman, G. G. 1984, ApJ, 277, 227
Richer, H. B., et al. 1995, ApJ, 451, 117
Sarajedini, A., & Layden, A. C. 1995, AJ, 109, 1086 (SL)
Shade, D., VandenBerg, D. A., & Hartwick, F. D. A. 1988, AJ, 96, 1632
Stetson, P. B. 1987, PASP, 99, 191
———. 1994, PASP, 106, 250
VandenBerg, D. A., & Bell, R. 1985, ApJS, 58, 561 (VB85)
Zinn, R., & West, M. 1984, ApJS, 55, 45

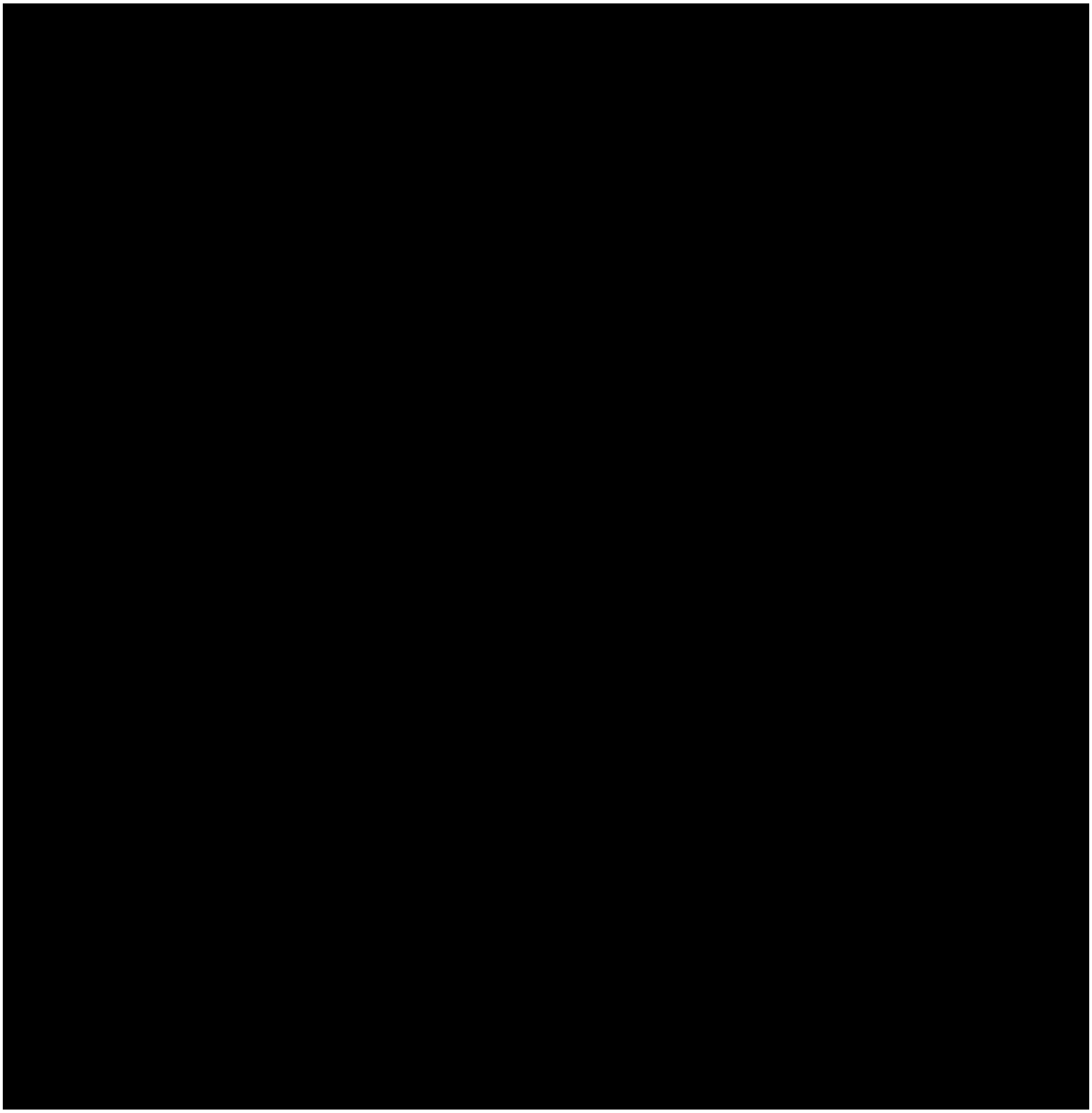

FIG. 2.—M4 data (*red*) have been overlayed on the M55 data (*blue*) after applying the indicated vertical and horizontal shifts, which ensure that the Galactic bulge stars in the two fields have the same reddening and apparent distance modulus. See the text for additional discussion.

FAHLMAN et al. (see 459, L66)