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STELLAR VELOCITY DISPERSIONS FOR FOUR LOW-CONCENTRATION GLOBULAR CLUSTERS

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ABSTRACT

Mean velocities and velocity dispersions are presented and discussed for four clusters of low central concentration: NGC 5466, NGC 6121 (M4), NGC 6656 (M22), and NGC 6838 (M71). They are derived from measurements with a typical accuracy of ± 1 km s^{-1} made for 12–19 members of each cluster. The measured dispersions range from 1.7 ± 0.6 km s^{-1} for NGC 5466 to 8.5 ± 1.9 km s^{-1} for M22. To within the uncertainties of 20%–40%, each agrees with the theoretical central velocity dispersion tabulated by Peterson and King on the assumption of a solar mass-to-light ratio.

This result, in conjunction with those of several other recent investigations of globular clusters, shows that their mass-to-light ratios fall in the range $0.5 \leq M/L \leq 4$, whatever their total mass or concentration. Yet in dwarf spheroidal galaxies, mass-to-light ratios may be an order of magnitude larger. If so, the dark matter which dominates those systems is almost entirely absent from globular clusters in the vicinity of the Sun.

Subject headings: clusters: globular — radial velocities — stars: stellar dynamics

I. INTRODUCTION

Velocity dispersions find many applications in the study of globular clusters, as reviewed by Freeman (1985).

1. The determination of the total mass of a cluster and its mass-to-light ratio is possible from the excellent fit of theoretical cluster models to star counts and surface photometry (King 1966). Peterson and King (1975) assembled or determined the structural parameters for a large number of clusters and predicted central velocity dispersions assuming $M/L = 1$. Concurrently Illingworth (1976) measured central velocity dispersions from integrated-light spectra of 10 relatively concentrated southern clusters. He found a limited range in mass-to-light ratios: in solar units, $0.9 \leq M/L \leq 2.9$.

2. Proper-motion studies (e.g., Cudworth 1976*a*, *b*, 1979*a*, *b*, 1985, 1986; Cudworth and Monet 1979) yield two-dimensional velocity dispersions which shed light on the isotropy of the distribution of velocities. Radial velocities and proper motions combined have provided a distance determination for M3 (Cudworth 1979*a*; Gunn and Griffin 1979), and M13 (Cudworth and Monet 1979; Lupton, Gunn, and Griffin 1985). When long baseline information of high accuracy becomes available, this approach should provide a fundamental check on the distances of nearby globulars, being completely independent of stellar-evolution considerations.

3. Thorough evaluations of cluster structure have become available from extremely accurate radial velocities for very large numbers of stars in a given cluster, pushing the models to the limit in some cases (e.g., Gunn and Griffin 1979; Seitzer 1983; Mayor *et al.* 1984; Lupton, Gunn, and Griffin 1985).

At the present moment, however, there is very little published information on the velocity dispersions of low-concentration clusters. Their central surface brightnesses are too low for integrated-light measurements. The small size of the velocity dispersion of M71, coupled with the problem of contamination by nonmembers, kept Cudworth (1985) from reaching firm conclusions on M/L from proper motions. In their investigation of the absolute velocity of NGC 5466, Brosche, Geffert, and Ninković (1983) report no results for its internal velocity dispersion.

We have undertaken to fill this gap somewhat by determining the central velocity dispersions of four low-concentration clusters. M71 and M22 are prime targets thanks to the recent proper motion studies of Cudworth (1985, 1986). M4 was added because Norris (1981) found a moderate velocity dispersion from giants, but Peterson (1985*a*) measured a very small dispersion from more accurate velocities of blue horizontal-branch stars. NGC 5466 is extremely sparse, moderately to extremely metal-poor (Table 1 of Buonanno, Corsi, and Fusi Pecci 1985), and contains the only anomalous Cepheid known outside the dwarf spheroidals (Zinn and Dahn 1976).

During 1985 June 2–6, spectra of roughly a dozen members of each cluster were obtained with the echelle spectrograph and intensified Reticon detector on the 1.5 m telescope of the Whipple Observatory at Mount Hopkins, Arizona. The observations, data reduction, and analysis are summarized in § II. The overall results for velocities are given in § III, and the velocity dispersions in § IV. In § V, mass-to-light ratios for globular clusters are compared to those for dwarf spheroidals and the implications for dark matter are noted.

II. OBSERVATIONS AND DATA ANALYSIS

Latham (1985) has recently given an overview of three similar systems employing an echelle plus intensified Reticon to measure radial velocities, one on the Multiple Mirror Telescope (MMT) and one on the 1.5 m Tillinghast reflector at Mount Hopkins, plus one on the 1.5 m Wyeth reflector at Oak Ridge Observatory, Massachusetts. Briefly, in each system, a single echelle order of roughly 50 Å centered near 5200 Å is recorded at low to moderate signal-to-noise ratio (S/N) by a dual photon-counting Reticon array. Cross-correlation techniques (Tonry and Davis 1979; Wyatt 1985) are used to determine the radial velocity of an object by comparing the position of its spectral lines with those recorded in a "template," a high S/N spectrum obtained with the same system for a star of similar spectral type and known velocity.

In this work, four templates rather than one were used in the cross-correlation, and their results were averaged to produce the final result. Three templates are spectra obtained with the MMT echelle on 1985 February 25–26 by Peterson, Olszewski, and Aaronson (1986): one of the twilight sky, one of the F-type standard HD 112299, and one of the M3 giant vZ 238 = AA. The fourth template spectrum, also of the sky, was obtained at the 1.5 m during this run.

Relative velocities of extremely high accuracy were determined for the templates by correlating them against 16 high S/N exposures of the sky obtained at the 1.5 m between 1985 May 29 and 1985 June 7 (UT), during which the echelle grating setting was not changed. Assuming a velocity of 0.0 km s^{-1} for the sky of June 2, the velocities (in km s^{-1}) deduced for the MMT templates obtained are -0.20 ± 0.02 for the sky, $+3.81 \pm 0.02$ for HD 112299, and -149.14 ± 0.02 for M3 AA. The errors are the internal errors only of one template with respect to the June 2 sky exposure.

The zero point and its internal error were established for the new 1.5 m data by correlating the 15 other 1.5 m sky exposures against the June 2 sky. The result, -0.03 ± 0.07 km s^{-1}, is zero to within its error, as it should be for the Sun, so the template velocities above were adopted without change.

The same four templates and the same relative template velocities were used to determine the velocities of metal-poor giants in remote globular clusters by Peterson, Olszewski, and Aaronson (1986). The zero point of the MMT observations was found to be the same, with an internal uncertainty of ± 0.5 km s^{-1}, from the three high S/N sky exposures made during the two-night run. An independent confirmation of this zero point comes from comparing the velocities deduced for the three M3 stars in this work with those of Pryor, Latham, and Hazen-Liller (1986, hereafter PLH), which include the results of Gunn and Griffin (1979, hereafter GG). The difference is $+0.25 \pm 0.40$ in the sense PLH − MMT from six measurements good to ± 1.0 km s^{-1} each. Similarly, the difference is $+0.14 \pm 0.55$ km s^{-1} between the velocities obtained at the MMT and at the 1.5 m for five stars in common.

Though the absolute accuracy of the zero points is not of particular interest to these velocity dispersions, brief comments are in order for future reference. The zero point of the values in Table 1 is not strictly that of the standard Center for Astrophysics system (discussed at the IAU in Delhi by Stefanik, Latham, and McCrosky 1986), because different templates were employed. To check the size of the effect, all the 1.5 m data were reduced independently at the Center for Astrophysics and correlated against the standard templates. The mean difference between the two sets of correlations of the velocities of all stars in all clusters was -0.25 ± 0.17 km s^{-1}. Taking ± 0.3 km s^{-1} to be representative of the external contribution, the overall uncertainty in the zero point of the MMT values is ± 0.5 km s^{-1}, while that of the 1.5 m data is ± 0.3 km s^{-1}.

III. STELLAR AND CLUSTER VELOCITIES

The observations of each star and the velocities deduced from them are presented in Table 1. The source of the star identifications and *BV* photometry for all stars in a particular cluster is that given in parentheses following the cluster name. The r value preceding each deduced radial velocity is the ratio of the heights of the cross-correlation peak and the typical noise peak. The deduced heliocentric velocity in the next column is followed by its theoretical uncertainty, $\sigma_i = 8.3/(1 + r)$, from the formula of Tonry and Davis (1979) with the coefficient established empirically from 1.5 m and MMT echelle data by PLH. Previous measurements of individual stellar velocities are included for comparison purposes. In the Notes column, a number is the percentage probability of membership according to Cudworth, while f indicates that the star was considered a field star and its velocity was not used in forming the cluster averages. For M4, CN+ and CN− refer to stars characterized by Norris (1981) as CN-strong and CN-weak, respectively.

The velocities found for five stars from MMT data obtained on 1985 February 25–26 were incorporated as if they constituted part of this data set. The effect of the ± 0.5 km s^{-1} uncertainty in the zero point of the MMT data is negligible with respect to the empirical dispersions.

The difference in mean velocity between these determinations and other previous ones is somewhat larger than would be expected from the tabulated errors. Better agreement is found between the mean velocity for M4 of $+70.0 \pm 0.9$ km s^{-1} deduced here from 19 giants and that of $+72.3 \pm 0.9$ km s^{-1} measured from nine blue horizontal-branch (HB) stars by Peterson (1985*a*). As noted by Peterson (1985*b*), the scale of velocities determined from the blue HB stars may be high by a few km s^{-1} because of the difficulty of accurately establishing the zero point of the templates appropriate for weak-lined hot stars with respect to the (strong-lined) Sun or cool giants. Because of the demonstrated repeatability of the 1.5 m and MMT echelle velocities for giants (see PLH), we feel that these cluster velocities are the most reliable.

IV. VELOCITY DISPERSIONS AND M/L RATIOS

From the data in Table 1, mean heliocentric velocities and velocity dispersions are calculated for each cluster in Table 2. For reasons discussed below, this table shows four velocity dispersions for M4: that of all 19 giants, those found for the 12 brightest only and the seven faintest only, and that recomputed from the data of Peterson (1985*a*) for the nine blue HB stars with the inclusion of measurement and sampling errors.

For each group of stars, the intrinsic velocity dispersion $\mu_{\rm int}$ was found by subtracting in quadrature the mean theoretical uncertainty, $\langle \sigma_i \rangle$, and the uncertainty in the mean, $\sigma_{\langle V \rangle}$, from the empirical dispersion $\mu_{\rm obs}$. The square of the uncertainty in $\mu_{\rm int}{}^2$ was calculated following Seitzer (1983) as the sum $\sigma_\mu{}^2 + \sigma_N{}^2$, the errors in $\langle \sigma_i \rangle^2$ and $\sigma_{\langle V \rangle}{}^2$ being negligible. For the giants, the sampling error ($\sigma_N{}^2 = 2/N \times \mu_{\rm obs}{}^4$) dominates the error due to the uncertainty in an individual measurement ($\sigma_\mu{}^2 = 4/(N-1) \times \sigma_i{}^2 \times \mu_{\rm obs}{}^2$), since the empirical dispersion is always at least twice the mean 1 σ error in an individual measurement. The percent uncertainty in $\mu_{\rm int}{}^2$ included in that column is the same as the percent uncertainty in M/L. In the penultimate column, the uncertainty associated with $\mu_{\rm int}$ itself was found by dividing the uncertainty in $\mu_{\rm int}{}^2$ by $2\mu_{\rm int}$. The last μ value is the central velocity dispersion computed by Peterson and King (1975).

For M71, the velocity dispersion of 2.8 ± 0.6 km s^{-1} found here agrees very well with Cudworth's (1985) best estimate of

TABLE 1

HELIOCENTRIC RADIAL VELOCITIES[a] FOR CLUSTER GIANTS

NGC 5466 (Cuffey 1961[c]; Buonanno et al. 1984)

Star	V (Cuffey)	B-V (Cuffey)	V (Buonanno)	B-V (Buonanno)	Disk No.	Julian Date	Exposure (min)	R	This Velocity	Other Velocity	Ref[b]	Notes
G	13.63	1.38	13.76	1.26	2650-17	6221.726	20	9.1	+110.0 ± 0.8	+101 ± 18 +106.0 ± 4	Z74 PBOO	1[d]
a	13.68	1.31	...	...	2653-5	6222.771	15	8.1	+109.6 ± 0.9	+106.5 ± 4	PBOO	
N	13.58	1.27	...	...	2650-15	6221.709	15	6.9	-12.2 ± 1.1	+47 ± 18 Field	Z74 PBOO	f
P	14.00	1.19	14.13	1.08	2652-25	6222.696	20	7.7	+108.3 ± 1.0	+118 ± 18 +107.4 ± 1.0	Z74 MMT	259
S1R2-15	13.56	1.35	13.67	1.23	2655-3	6223.714	20	8.1	+106.6 ± 0.9	+113 ± 18 Field	Z74 PBOO	53
S1R2-17	14.54	1.01	14.67	0.93	2655-6,8	6223.745	30	6.0	+106.7 ± 1.2			73
S1R2-18	14.51	0.96	14.64	0.89	2655-10,12	6223.769	30	6.0	+107.9 ± 1.2			59
S2R1-22	14.01	1.25	14.22	1.13	2650-19	6221.744	20	6.5	+103.8 ± 1.1			178
S3R1-4	14.56	1.00	14.73	0.91	2652-28,30	6222.718	30	6.7	+106.1 ± 1.1			169
S3R1-10	14.43	0.89	14.60	0.83	2650-13	6221.695	20	5.3	+107.1 ± 1.3	+125 ± 18 +106.1 ± 1.0	Z74 MMT	198
S3R1-18	14.38	0.84	14.50	0.78	Not observed at the 1.5m					+102 ± 18 +103.6 ± 1.3	Z74 MMT	217
S3R3-10	14.41	1.06	14.51	0.99	Not observed at the 1.5m					+108.1 ± 1.0	MMT	271
S4R1-16	14.75	0.91	14.91	0.83	2653-1,3	6222.744	35	5.3	+109.3 ± 1.3			113

NGC 6121 = M4 (Lee 1977)

Star	M_{bol}[e]	$(V-K)_0$[e]	V	B-V	Disk No.	Julian Date	Exposure (min)	R	This Velocity	Other Velocity	Ref[b]	Notes
1403	-1.33	3.02	12.10	1.44	2650-29	6221.814	10	11.2	+72.6 ± 0.7	+67	N81	CN+
1408	...	...	11.79	1.41	2650-27	6221.805	6	10.1	+74.8 ± 0.8	+65	N81	CN+
1501	...	...	11.63	1.55	2650-31	6221.822	6	12.7	+69.9 ± 0.6			CN+
1619	...	...	11.83	1.48	2651-2	6221.832	8	14.8	+65.8 ± 0.5			CN+
2206	-1.58	3.10	11.90	1.47	2653-19	6222.876	9	13.4	+70.7 ± 0.6			
2207	...	...	10.25	1.75	2653-21	6222.880	3	10.2	-23.0 ± 0.8			f
2208	...	...	12.30	1.47	2653-17	6222.866	15	10.5	+76.7 ± 0.7			
2301	...	...	12.64	1.47	2655-25	6223.853	11	10.7	+27.6 ± 0.7	+22	N81	f
2315	...	...	12.82	1.29	2655-20	6223.837	16	10.0	+70.4 ± 0.8	+62	N81	CN-
2617	-1.71	3.33	11.90	1.48	2651-4	6221.843	5	12.8	+63.6 ± 0.6	+61	N81	CN+
3207	...	...	11.91	1.20	2651-10	6221.865	10	13.2	+73.2 ± 0.6			
3209	-2.74	3.41	10.95	1.68	2651-12	6221.872	7	11.6	+64.2 ± 0.7	+65.5 ± 0.6	MMT	
3303	-1.76	3.30	11.82	1.58	2651-6	6221.855	5	9.7	-36.7 ± 0.8	-46 ± 5	C/FPC	f
3413	-2.17	3.15	11.33	1.53	2651-8	6221.855	3	7.8	-35.5 ± 1.0			f
4201	...	...	11.67	1.38	2650-25	6221.797	6	11.2	+75.6 ± 0.7	+75.3 ± 0.5	MMT	
4310	...	...	12.01	1.38	2653-12	6222.834	10	12.5	+66.0 ± 0.6			CN-
4404	...	...	12.96	1.30	2655-18	6223.822	18	10.2	+70.8 ± 0.8	+65	N81	CN+
4413	...	...	12.62	1.30	2653-14	6222.848	16	10.5	+68.4 ± 0.7	+61	N81	CN+
4414	...	...	11.76	1.33	2650-2	6220.826	8	8.8	+65.7 ± 0.9	+67.3 ± 1.3	MMT	
					2655-16	6223.807	8	12.8	+65.7 ± 0.6			
4415	...	...	12.52	1.36	2653-10	6222.822	15	12.3	+74.8 ± 0.6	+71	N81	CN+
4416	...	...	12.89	1.30	2653-8	6222.810	20	12.6	+72.8 ± 0.6	+66	N81	CN+
4611	-3.26	4.30	11.02	2.00	2649-27	6220.801	5	9.7	+65.0 ± 0.8	+77 ± 6	K59	
4613	-3.31	4.09	10.81	1.97	2649-30	6220.809	6	9.6	+68.7 ± 0.8	+57 ± 5	K59	

NGC 6656 = M22 (Arp and Melbourne 1959)

Star	M_{bol}[e]	$(V-K)_0$[e]	V	B-V	Disk No.	Julian Date	Exposure (min)	R	This Velocity	Other Velocity	Ref[b]	Notes
I-12	-2.40	2.80	11.60	1.52	2649-10	6219.925	6	8.5	-143.0 ± 0.9			95
I-36	...	...	11.91	1.44	2649-16	6219.943	7	7.4	-139.2 ± 1.0	-133 ± 8 -179 ± 10	LE78 HH79	92
I-37	...	...	11.90	1.50	2649-14	6219.937	7	9.3	-157.3 ± 0.8			98
I-86	...	...	12.24	1.44	2656-1	6223.929	10	8.7	-140.6 ± 0.9			96
I-92	-2.63	2.95	11.48	1.56	2649-12	6219.931	6	10.5	-155.3 ± 0.7	-179 ± 5 -148 ± 10	HH79 HH79	54
II-31	-2.21	2.88	11.88	1.49	2649-8	6219.916	6	9.0	-155.4 ± 0.8	-156 ± 5	C81	97
II-96	...	...	11.54	1.57	2649-4	6219.905	5	8.8	-162.2 ± 0.9			85
III-12	-2.78	3.13	11.46	1.74	2648-31	6219.894	4	7.1	-149.0 ± 1.0	...	...	95
III-33	...	...	12.23	1.37	2655-30	6223.920	10	10.9	-146.3 ± 0.7	-160 ± 10	HH79	96
III-52	-2.77	3.12	11.49	1.68	2649-2	6219.900	5	8.0	-150.4 ± 0.9			94
IV-20	-2.13	2.96	12.04	1.48	2648-26	6219.876	7	10.6	-166.3 ± 0.7	-163 ± 5	C81	28
IV-72	...	...	11.29	1.32	2648-29	6219.887	2	7.4	-39.2 ± 1.0	-35 ± 8	LE78	0,f
IV-88	...	...	12.18	1.47	2655-28	6223.911	12	9.5	-144.1 ± 0.8			90

TABLE 1—(*continued*)

Star	M_{bol}^{e}	$(V-K)_0^{e}$	V	B-V	Disk No.	Julian Date	Exposure (min)	R	This Velocity	Other Velocity	Ref^{b}	Notes
					NGC 6838 = M71 (Cudworth 1985a)							
A	...	...	10.70	0.53	2654-11	6222.984	2.5	10.7	-27.1 ± 0.7	-17 ± 7	PS83	0,f
					2656-15	6223.986	4	9.7	-27.0 ± 0.8			
B,V2	-3.13	4.66	12.08	1.87	2654-9	6222.980	7.2	5.5	-18.9 ± 1.3			95
					2656-13	6223.982	5.5	4.7	-19.2 ± 1.5			
A4	-2.35	3.55	12.20	1.69	2651-19	6221.902	6	10.3	-25.4 ± 0.7	-25	C80	94
A9	-1.38	3.37	12.94	1.57	2651-24	6221.931	12	11.2	-24.8 ± 0.7			86
I	...	...	12.42	1.57	2656-11	6223.976	8.2	10.4	-15.5 ± 0.7			93
S	-1.34	3.12	12.94	1.51	2651-22	6221.920	12	10.7	-23.7 ± 0.7			81
1-21	-1.08	2.84	13.02	1.49	2651-28	6221.956	15	12.7	-21.5 ± 0.6			95
1-29	-3.39	5.6	12.76	1.84	2651-17	6221.896	8	9.4	-23.6 ± 0.8			90
1-36	...	...	12.79	1.25	2651-30	6221.964	10	8.5	-22.2 ± 0.9	-24 ± 11	GN78	64
1-45	-2.18	3.60	12.36	1.76	2654-2	6222.948	12	9.2	-22.8 ± 0.8	-22	C80	94
					2654-4	6222.958	12	9.8	-23.2 ± 0.8	-29 ± 14	GN78	
										-22 ± 18	GN78	
1-46	-2.31	3.64	12.29	1.75	2656-9	6223.968	12	8.8	-23.2 ± 0.9	-26	C80	93
										-16 ± 10	GN78	
1-53	...	...	12.97	1.61	2652-1	6221.974	10	9.6	-25.1 ± 0.8			95
					2654-7	6222.972	15	9.5	-24.2 ± 0.8			
1-56	...	...	13.14	1.38	2656-7	6223.958	20	11.7	-20.9 ± 0.7			96
1-64	...	...	13.10	1.53	2653-26	6222.908	17	12.5	-17.2 ± 0.6	-24 ± 40	HS78	95
					2656-4	6223.943	6	7.7	-17.4 ± 1.0	-9 ± 40	HS78	
1-66	...	...	13.01	1.40	2653-28	6222.919	15	13.1	-20.0 ± 0.6			81
1-77	-1.89	3.57	12.65	1.73	2651-26	6221.941	12	9.7	-27.1 ± 0.8	-16 ± 19	GN78	73
1-113	-2.25	3.81	12.43	1.80	2653-24	6222.895	10	10.3	-21.5 ± 0.7	-29 ± 11	GN78	95
										-21 ± 18	GN78	

[a] In km s^{-1}.

[b] References to other velocity determinations—C/FPC = Cohen, cited by Frogel, Persson, and Cohen 1983; C80 = Cohen 1980; C81 = Cohen 1981; GN78 = Gratton and Nesci 1978; HH79 = Hesser and Harris 1979; HS78 = Hartwick and Sargent 1978; K59 = Kinman 1959; LE78 = Lloyd Evans 1978; MMT = Peterson, Olszewski, and Aaronson 1986; N81 = Norris 1981; PBOO = Pilachowski *et al.* 1983; PS83 = Pilachowski and Sneden 1983; Z74 = Zinn 1974.

[c] Cuffey's $P-V$ colors have been converted to $B-V$ according to his formula $B-V = 0.92 \times (P-V) + 0.16$.

[d] Alternate identifications from Buonanno *et al.* 1984.

[e] M_{bol} and $(V-K)_0$ from Frogel, Persson, and Cohen 1983, except M71 from Frogel, Persson, and Cohen 1979.

3.1 ± 0.7 km s^{-1} based on proper motions of stars within 100″ from the cluster center. He noted that the statistically significant increase in velocity dispersion exhibited by stars outside this radius is probably not meaningful because of the greater likelihood of contamination by nonmembers. This conclusion is also supported by our radial velocity results, as seen below.

Our intrinsic dispersions are line-of-sight values averaged equally over all the stars observed. In principle, a small upward correction should be applied for comparison with the theoretical central velocity dispersions of Peterson and King (1975), to account for the spread in radial distance of the stars observed. Judging from Figure 4 of GG, this correction would be 20% if all stars were at 10 core radii r_c, and 10% at $5r_c$. No corrections were applied because mean distances were always less than this. In M22, all stars are within $2.5r_c$, and all but one within $2r_c$. In NGC 5466, 10 are within $2.5r_c$, and all are within $4r_c$. In M71, eight are within $2r_c$ (100″) and eight beyond. Their internal dispersions are 3.2 and 2.5 km s^{-1}, respectively, the same to within the errors. Likewise in M4, no downward trend in intrinsic dispersion as a function of central distance is observed. Five giants fall within $3r_c$, seven from 3 to $4r_c$, and seven more from 4 to $6r_c$. For the 12 stars within $4r_c$, the intrinsic dispersion is 3.8 km s^{-1}, and it is 3.9 km s^{-1} for the fourteen stars farther than $3r_c$.

However, the mean dispersion of 3.9 ± 0.7 km s^{-1} measured from the giants does differ significantly from that found by

TABLE 2

HELIOCENTRIC CLUSTER VELOCITIES AND VELOCITY DISPERSIONS[a]

Cluster	N	This Velocity	Other Velocity[b]	$\langle\sigma_i\rangle^2$	$\sigma_{\langle V\rangle}^2$	σ_μ^2	σ_N^2	μ_{obs}^2	μ_{int}^2	μ_{int}	μ_{PK}[c]
NGC 5466	12	+107.2 ± 0.6	+119.8 ± 2.5	1.1	0.4	1.6	3.0	4.2	2.8 ± 2.1 (76%)	1.7 ± 0.6	1.9
NGC 6121:											
All giants	19	+70.0 ± 0.9	+64.2 ± 4.5	0.4	0.8	1.5	27.6	16.2	14.9 ± 5.4 (36%)	3.9 ± 0.7	4.4
Bright giants	12	+68.7 ± 1.2	...	0.4	1.4	2.3	47.0	16.8	15.0 ± 7.0 (37%)	3.9 ± 0.9	...
Faint giants	7	+72.4 ± 1.1	...	0.5	1.1	2.6	17.5	7.8	6.2 ± 4.5 (72%)	2.5 ± 0.9	...
Blue HBs	9	+72.3 ± 0.9	...	2.2	0.6	6.5	7.4	5.8	2.9 ± 3.7 (130%)	1.7 ± 1.1	...
NGC 6656	12	−150.8 ± 2.5	−152.5 ± 2.6	0.7	6.2	19.6	1014.9	74.7	74.6 ± 32.2 (43%)	8.5 ± 1.9	8.5
NGC 6838	16	−22.1 ± 0.8	−19.3 ± 0.9	0.6	0.6	1.5	10.7	9.3	8.1 ± 3.5 (43%)	2.8 ± 0.6	2.5

[a] In km s^{-1}.

[b] From Webbink 1981.

[c] From Peterson and King 1975.

Peterson (1985*a*) from nine blue HB stars. (The value given there of 1.9 ± 0.3 km s^{-1} should be 1.7 ± 1.1 km s^{-1}, according to this more complete error analysis.) Six HB stars fell within $3r_c$, and all are within $5r_c$, so that their central distance does not seem to be a factor. Rotation of the cluster as a whole is not obvious from either set of data. We are unable to check whether the dispersion depends on CN strength, since only two CN–weak stars are included in the total sample. A trend does emerge, however, when the giants are grouped according to visual magnitude. For the 12 stars with $10.8 \leq V \leq 12.0$, the internal dispersion is 3.9 ± 0.9 km s^{-1}, but for the seven stars with $12.1 \leq V \leq 13.0$, it is 2.5 ± 0.9 km s^{-1}. There is but one chance in six that the two groups of giants have the same velocity dispersion, but the dispersion of the faint giants agrees with that of the HB stars.

The most plausible explanation for this is to ascribe it to the small jitter in velocities first identified by GG among the brightest M3 giants. They were forced to invoke an extra ±0.8 km s^{-1} variation in the velocity of the giants within 1 mag of the tip of the giant branch to explain the repeatability of their measurements of these stars. The effect has been confirmed from an extended set of M3 observations by PLH, and has been shown by Mayor *et al.* (1984) to exist among bright giants in 47 Tucanae as well. There is no explicit evidence for velocity variations among the three giants with MMT measurements made 97–100 days before, but a single pair of observations good to ±1 km s^{-1} is not likely to reveal them.

To allow for possible jitter, it seems wise to recompute the internal velocity dispersion for M4 by averaging the results for the faint giants and the HB stars. This produces $\mu_{\text{int}} = 2.1 \pm 0.7$ km s^{-1}, a factor of 2 less than predicted by Peterson and King (1975). The statistical uncertainty in the inferred $M/L = 0.25$ is about 70%.

Without additional observations to establish jitter as a factor among M4 stars, we are unable to say definitively that the mass-to-light ratio of M4 is less than solar. Pursuing this is important, with ramifications for the mass function which might support the suggestion of Richer and Fahlman (1984) that the number of low-mass stars is reduced in M4.

Unanswered questions relevant to all clusters include the degree of rotation of each and the variation of velocity dispersion with radius. As seen above, a substantially larger sample is required to address these issues. Furthermore, since only one observation was obtained for the vast majority of stars, no allowance has been made here for the presence of binaries. Although their effect is clearly small (at least in the clusters with the lowest velocity dispersions), and binaries seem to be very rare among M3 giants (PLH), their complete absence is by no means assured. Despite these apparent shortcomings, however, our central velocity dispersions are sufficient to have significant consequences for the occurrence of dark matter, as we now discuss.

V. SUMMARY AND DISCUSSION

Clearly $M/L = 1 \pm 1$ at the center of all four of these low-concentration clusters. Illingworth's (1976) result that mass-to-light ratios are essentially solar at the center of concentrated globular clusters is thus extended to low-concentration ones.

Since Illingworth's study, very detailed modeling of several individual clusters has become available from accurate radial velocity measurements of large numbers of stars. For the massive globular cluster 47 Tucanae, Mayor *et al.* (1984) find a central velocity dispersion of 9.7 ± 0.9 km s^{-1}, in accord with Illingworth's value of 10.5 ± 0.5 km s^{-1} and an M/L of 1 at the center. However, Freeman (1985) has emphasized that the total M/L ratio is larger, because the relaxation time of this concentrated, massive cluster is short enough to establish thermal equilibrium in the center, so that mass-segregation effects may be important. Because the brightest and heaviest stars are more centrally concentrated, the M/L ratio increases with increasing distance. (Note that Larson 1984 argues the reverse, but only for $r \leq r_c$.) Assuming thermal equilibrium, Da Costa and Freeman (1985) deduce an overall $M/L = 4.0$ for 47 Tucanae. They see the need for some dark matter—30% to 40% of the total cluster mass—which, if in the form of stars, is distributed as are the cluster giants. Their preferred candidate is an excess of white dwarf remnants, which implies an initial mass function enriched in massive stars.

Other total M/L values are now available, also based on detailed models incorporating measurements of the velocity dispersion with radius out to $> 10r_c$. For M3, GG find M/L near 3, with no need for an excess of dark remnants: a normal initial mass function in a multicomponent model explains the situation. Similarly for ω Centauri Seitzer (1983) deduced $M/L = 2.6 \pm 20\%$, a result of which Larson (1984) was apparently unaware. Seitzer noted that relaxation effects should not be nearly as important as in M3, since ω Centauri, although more massive, is much less concentrated. The clusters considered here are less massive than ω Centauri and also of low concentration, so relaxation effects should be no more important.

Thus, while M/L may vary with radius, $M/L = 4$ seems an upper limit to the mass-to-light ratios found to date for any globular cluster. In contrast, M/L ratios of 40–100 are being deduced from measurements of individual stars in the dwarf spheroidal galaxies Draco and Ursa Minor by Aaronson and Olszewski (1986). If this result survives additional observational scrutiny (see, e.g., Cohen 1983 and Seitzer and Frogel 1985), it suggests basic dynamical differences between dwarf spheroidals and globular clusters, despite their overlap in metallicity, mass, and age. According to Kormendy (1985), however, the structure of even the least concentrated globular clusters bears little resemblance to that of the dwarf spheroidals, so that dissimilar M/L ratios may not be surprising. Also, all globular clusters with measurements of M/L are rather close to the Sun, while the dwarf spheroidals are at much greater galactocentric distances.

Nonetheless, the overall result that $0.5 \leq M/L \leq 4$ for all globular clusters studied to date does place a significant constraint on the presence and distribution of dark matter. A successful mechanism for predicting its strong presence in dwarf spheroidals should provide for its virtual absence from globular clusters in the vicinity of the Sun, whatever their mass or concentration.

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