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RADIAL VELOCITIES OF STARS IN THE GLOBULAR CLUSTER M4 AND THE CLUSTER DISTANCE

RUTH C. PETERSON
Astronomy and Astrophysics Board of Study, University of California, Santa Cruz, CA 95064; peterson@lick.ucsc.edu
AND
RICHARD F. REES[1] AND KYLE M. CUDWORTH[2]
Yerkes Observatory, The University of Chicago, P.O. Box 258, Williams Bay, WI 53191
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ABSTRACT

The internal stellar velocity distribution of the globular cluster M4 is evaluated from nearly 200 new radial velocity measurements good to 1 km s^{-1} and a rederivation of existing proper motions. The mean radial velocity of the cluster is 70.9 ± 0.6 km s^{-1}. The velocity dispersion is 3.5 ± 0.3 km s^{-1} at the core, dropping marginally towards the outskirts. Such a low internal dispersion is somewhat at odds with the cluster's orbit, for which the perigalacticon is sufficiently close to the galactic center that the probability of cluster disruption is high; a tidal radius two-thirds the currently accepted value would eliminate the discrepancy. The cluster mass-to-light ratio is also small, $M/L_V = 1.0 \pm 0.4$ in solar units. M4 thus joins M22 as a cluster of moderate mass and concentration with a mass-to-light ratio among the lowest known.

The astrometric distance to the cluster is also smaller than expected, 1.72 ± 0.14 kpc. This is only consistent with conventional estimates of the luminosity of horizontal branch stars provided an extinction law $R = A_V/E(B-V) \approx 4$ is adopted, as has been suggested recently by several authors.

Subject headings: globular clusters: individual (M4) — stars: kinematics — techniques: radial velocities

1. INTRODUCTION

1.1. *The Color-Magnitude Diagram and Population of M4*

M4 (NGC 6121, C1620−264) is a globular cluster of moderately low concentration very near the Sun, about 2 kpc distant (Lee 1977; Lloyd Evans 1977). It also harbors a binary millisecond pulsar, PSR 1620−26 (see Sigurdsson 1993). These facts combine to make M4 a promising target for the extensive investigation of its population and dynamical properties.

However, the cluster falls near the Sco-Oph dark clouds ($l = 351°$, $b = 16°$), and so is rather heavily reddened. Cluster membership is often problematical, and several basic parameters are somewhat uncertain. For example, Trager, Djorgovski, & King (1993) find a core radius of 50″, rather smaller than the Peterson & King (1975) value of 92″. While Peterson and King find 43ʹ.6 for the tidal radius, giving log $c = 1.45$, Trager et al. derive log $c = 1.59$, yielding 33ʹ for the tidal radius. The environment has also affected abundance determinations, because temperatures based on stellar colors are reddening-dependent. Recent estimates are converging to [Fe/H] = −1.0, one-tenth solar (e.g., Drake, Smith, & Suntzeff 1994).

To address the issues of membership and reddening, a proper-motion study was made by Cudworth & Rees (1990, hereafter CR). They produced probabilities of membership for stars down to about $V = 15.8$, the base of the subgiant branch. Most were located beyond 1ʹ.2 from the cluster center: to 6ʹ.5 and to 14ʹ.5 for stars respectively fainter and brighter than $V = 14.5$. Because of the cluster's distinctive space motion, CR obtained a clean separation between M4 cluster members and field interlopers. Armed with more accurate knowledge of membership, they inferred the reddening from the position of the edges of the instability strip, and found evidence for a gradient in reddening across the cluster from the distribution of the colors of subgiants. They also established five blue stragglers as members.

The stellar population of M4 has been remarked upon in various studies. The horizontal branch appears somewhat bimodal (Lee 1977), containing prominent red and blue branches, with a few dozen RR Lyrae stars between (Sawyer Hogg 1973; CR). Norris (1981) concluded that the cyanogen strength of red giants was bimodal as well, with CN-strong and CN-weak stars but few of intermediate strength. However, the determinations of isotopic carbon ratios by Suntzeff & Smith (1991) failed to uncover any correlation between CN band strength and $^{12}C/^{13}C$ ratio. Peterson (1985a) surveyed blue horizontal branch (BHB) stars for rotation, finding less than in the clusters M3, M5, M13, and NGC 288 (Peterson 1985b). The presence of lower-main-sequence stars has been investigated by several groups, e.g., Richer & Fahlman (1984), McClure et al. (1986), and Penny, Lubenow, & Dickens (1987).

1.2. *Dynamics and Mass-to-Light Ratio of M4*

The internal stellar dynamics of M4 were briefly investigated first by Norris (1981) for giants and by Peterson (1985a) for BHB stars. Peterson & Latham (1986, hereafter PL) included both groups, and found that the dispersion depended on spectral type: it was 3.9 ± 0.7 km s^{-1} for the 19 giants they studied, but only 1.7 ± 1.1 km s^{-1} for the nine BHB stars they took from Peterson (1985a). Due to the small sample size, these values are marginally consistent to within their mutual uncertainties. Because a "jitter" of about 1 km s^{-1} prevalent among the most luminous giants in a globular cluster (Gunn & Griffin 1979) might affect the brighter stars, PL ignored them and derived a cluster dispersion of 2.1 ± 0.7 km s^{-1} from the 16

[1] Department of Physics and Astronomy, University of Pennsylvania, 209 S. 33d Street, Philadelphia, PA 19104-6394; rick@goodricke.astro.upenn.edu.
[2] kmc@yerkes.uchicago.edu.

stars fainter than 1.2 mag from the giant-branch tip. However, this procedure led to a very low mass-to-light ratio of 0.25. PL emphasized the need for additional velocity data to decide whether this ratio was less than the solar value, which would also suggest a paucity of low-luminosity stars.

In a comprehensive examination of globular-cluster mass-to-light (M/L) ratios, Mandushev, Spassova, & Staneva (1991) adopted for M4 the PL result of 3.9 km s^{-1} from giants only, and thus derived a mass-to-light ratio of 0.86 ± 0.37. As with previous investigations of the mass-to-light ratios of globular clusters in the Milky Way (PL; Pryor et al. 1991), their study shows no dependence of M/L on concentration, metallicity, or position in the Galaxy; they do infer a possible weak dependence on overall luminosity. Their result for M4 is consistent with that of other clusters of similar absolute magnitude.

1.3. *This Work*

In this paper, we present radial velocity determinations good to 1 km s^{-1} for a total of 182 members of M4 over a wide range of magnitude and spectral type, assembling and presenting data collected over a period of nearly six years. Peterson, Seitzer, & Cudworth (1989, hereafter PSC) have provided similar data for 120 stars in the globular cluster M15, and many procedural details pertinent to this work are found there. More recently, Peterson & Cudworth (1994) have presented velocities for 130 members of M22. This work follows the latter one very closely in both motivation and methodology.

As with M22, the primary motivation for this work was to obtain the distance to the cluster from its statistical parallax, a technique which demands equality in the velocity dispersion derived from proper-motion measurements and that from radial velocities. We present here the velocity data for 182 individual stars. From these we derive the velocity dispersion and its dependence on radial distance and position angle, plus the M/L ratio found from a simple single-mass King (1966) model. We briefly describe the results of a rederivation of proper motions, and the distance obtained by matching the dispersions in radial velocities and proper motions. The latter gives a reasonable luminosity for the horizontal branch only when a large value is adopted for the ratio of extinction to reddening; other studies have independently found the need for a similar value.

2. NEW RADIAL VELOCITIES

2.1. *Star Selection*

Stars were initially chosen from photometry alone, without membership information. The astrometric measurements of CR were in progress when the radial velocity observations were begun: the sample of stars to be included in the CR study was finalized, but the results were not yet in. Consequently, most stars were taken from those in the CR sample whose preliminary photometry was consistent with the M4 color-magnitude diagram; a few giants near the center had been observed previously. The radial-velocity sample includes all CR members with $V < 13.6$, 15 of 25 members with $13.6 \leq V < 13.9$, 10 of 25 members with $13.9 \leq V < 14.2$, and 8 of 25 members with $14.2 \leq V < 14.5$. As with M22, this selection procedure tends to underrepresent the innermost and outermost regions of the cluster, where few stars were included by CR. However, unlike M22, these velocities for M4 members are unbiased with respect to proper motion.

To increase the total number of BHB stars, several BHB photometric candidates were observed that are not listed by CR; these were kindly provided by Norris (1983). They are located within 1′–3′ of the center.

2.2. *Observational Procedure*

Data were obtained at the Multiple Mirror Telescope (MMT) and the Smithsonian 1.5 m telescope (both on Mount Hopkins, Arizona) with the echelle and intensified Reticon detector in several runs from 1984 to 1989. Runs on the MMT took place on UT dates 1984 March 14–15 (data published by Peterson 1985a), 1985 February 25–26 (data published by Peterson, Olszewski, & Aaronson 1986), 1986 May 19, 1987 May 8–12 (second half nights), and 1989 April 17–21 (second half nights). The 1.5 m telescope run occurred 1985 June 3–7 (data published by PL).

Observing procedures were patterned after those of PL and PSC. The intensified Reticon records a single echelle order of about 50 Å, which was centered near 5200 Å to include the Mg *b* lines and several other features immediately to the red. Because the MMT points accurately and astrometric coordinates were used, identification was never a problem on that telescope, and changing from one object to the next required typically 15 s. Exposure times were about 4–5 minutes at $V = 13.2$ under good conditions. Use of the image stacker with 1″.2 apertures yielded a FWHM of 6.5 pixels for a resolution of 9 km s^{-1} or 0.16 Å. On the 1.5 m telescope, pointing was very difficult; at least one misidentification was made (see below). Exposure times averaged 15 minutes at $V = 12.5$. Resolution with a 1″ slit was 4.9 pixels = 6.5 km s^{-1} = 0.11 Å.

In discussing measurements of radial velocities made on the MMT, it is worthwhile to note that the MMT is an altitude-azimuth telescope, so properties such as flexure and atmospheric refraction depend only on zenith distance and not on hour angle. In fact, corrections for the dispersion associated with atmospheric refraction (such as those made by Peterson 1985c) are not necessary here at all, since the wavelength of the observations coincides with the peak wavelength of sensitivity of the guiding/pointing camera.

On both telescopes, giant stars were exposed typically to a level of 6–8 counts per pixel. Fewer counts were required than for M22 and M15, since the Mg *b* lines are stronger at the higher metallicity of M4. The hotter, weaker lined BHB stars were more heavily exposed, to achieve a uniform uncertainty in the velocity measurement. The standards that were observed repeatedly to establish the zero point of velocities were also more heavily exposed, to reduce the uncertainty in each measurement.

The primary standard was the twilight sky, observed at dusk and at dawn whenever possible, at both the zenith and at 65° from zenith as a check for zenith dependence. Three secondary standards in M4 were observed a total of 41 times (see Table 3). These stars, Lee 3209 ($V = 10.94$), Lee 1403 ($V = 12.13$), and Lee 1608 ($V = 13.27$), were chosen to span a wide magnitude range to minimize variability due to possible "jitter". Except as noted just below, one or more of these stellar standards was observed each night of each run to check constancy of the zero point, and sometimes several times during the night to investigate a possible dependence on zenith distance. During 1984 March 14–15, a run devoted to BHBs, no giants were observed; two of these BHBs were repeated in the 1989 April 17–21 run along with several giants from other runs, to ensure run-to-run consistency of the velocity zero point. On 1985 February 25–26, only one M4 giant standard was observed, and none on 1986 May 19; giants adopted as standards for other clusters (M15 and M22) and repeat observations of two or three additional M4 giants were used to check the zero points.

Comparison spectra were recorded with a Th-Ar lamp every half hour or so. The removal of pixel-to-pixel variations in sensitivity was done by dividing by the spectrum of a quartz lamp taken almost every afternoon or morning. While usually obtained at the zenith, these were occasionally made at a zenith distance of 65° to span the range of the zenith distances of the program observations.

2.3. *Derivation of Radial Velocities*

The data were reduced following standard practices for CfA echelle spectra, using the Nova computers on Mount Hopkins and at Steward Observatory of the University of Arizona. The appropriate flatfield exposures were divided into each object and comparison spectra. No sky or dark subtraction was performed, nor was any necessary. The sky was that of moonlight, whose cross-correlation produces a peak at zero velocity, well displaced from the velocity of typically 70 km s^{-1} of an M4 star. Wavelength calibration was accomplished using the pair of Th-Ar exposures recorded immediately before and after the program stars. These typically differed by less than 1 pixel. About 30 lines were used to construct a fifth-order solution, for which the rms error was about 0.02 Å (1.2 km s^{-1}) per Th-Ar line.

Velocities were determined by cross-correlation against various templates chosen to match the program spectra. Velocities for all stars were derived from correlations against five templates of near-solar metallicity: the four of PL (the daytime sky, a field F dwarf, and two giants) plus the star Fagerholm 141 in the open cluster M67 (Mathieu et al. 1986). For the BHB stars, whose lines are very much weaker, correlations were also performed against the four metal-poor giant templates of PSC and the four hot-star templates of Peterson (1983) developed for BHB stars. The velocity zero point for each run was established from the sky plus the standard spectra. The internal agreement during each run was typically 0.3 km s^{-1} among the sky spectra, and 0.6–0.9 km s^{-1} for the stellar standards. There is no clear evidence of variability for the latter (the observed standard deviation of 0.9 km s^{-1} for the Lee 3209 measurements exceeds the theoretical value of 0.6 km s^{-1} by an amount suggestive of "jitter" of 0.7 km s^{-1}). There is no dependence on zenith distance for either the sky or the stellar standards. The uncertainty in the zero point is about 0.5 km s^{-1} for each run, and the systematic error is of similar size (PSC).

3. RESULTS FOR RADIAL VELOCITIES

3.1. *Individual Velocities*

The velocities so derived are presented in full in Tables 1, 2, and 3, and in the AAS CD-ROM series, Vol. 4. Table 1 gives the final results for the stellar heliocentric velocity for each star that is a member of M4. Table 2 presents the same information for nonmembers in the M4 field, and Table 3 lists the individual velocity values for those stars observed more than once. Velocities in the three tables differ slightly (typically 0.2 km s^{-1}) from those of PL for the same observations of the same stars because of the additional fifth template incorporated here.

In Tables 1 and 2, the first two columns list the right ascension and declination (equinox 1950.0), which are good to 0\".1 in each coordinate for stars measured by CR. (For the stars not included by them, namely Lee 1619, 2614, 3406, 3730, and 4624, coordinates measured by R. C. P. from a single 4 m plate are listed; these are of lower accuracy, showing a systematic difference of about 0\".2–0\".3 superposed on random errors of similar size.) The next two columns give the radius in arcmin and the position angle in degrees from the center of the cluster, as measured by Shawl & White (1986) and confirmed by CR. The next two columns list the V-magnitude and $B-V$ color from CR where available, and from Lee (1977) otherwise. The next column gives the Julian date of the observation, or that of the first observation if the star was observed twice or more. The eighth and ninth columns give the measured velocity and its internal uncertainty. For all multiply observed stars, this is the weighted mean of the set of observations in Table 3. The uncertainty is derived from the ratio R of the height of the cross-correlation peak relative to a typical noise fluctuation, according to the Tonry & Davis (1979) formula $\sigma_R = K/(1 + R)$ (in km s^{-1}), with $K = 8.3$ for sharp-lined spectra obtained with the Mount Hopkins echelle spectrographs (PSC). The tenth column gives the percent probability of membership; a "-1" indicates that the star in question was not in the CR study. While these membership probabilities are from the new reductions described below, the vast majority are identical to the values of CR. The final column gives the star identification: the Lee number, where available, appears first without a prefix, and is followed by identifications from Sawyer-Hogg (1973, prefix "V" for variable); Alcaino (1975, single letter or prefix "A"); or Greenstein (1939, prefix "G").

Table 2 lists the same information as in Table 1 for nonmembers of M4. The velocities of these stars average -12.8 km s^{-1} with a dispersion of 34.5 km s^{-1}. Thus the radial velocity of M4 is quite distinct from that of the field, differing by more than 80 km s^{-1}.

One of the nonmember stars has a membership probability of 99%. It was observed twice, on the chance it might be a binary belonging to the cluster. However, the two observations agree to 1 km s^{-1} at a value more than 100 km s^{-1} away from the cluster mean. Furthermore, a binary of half-amplitude greater than 100 km s^{-1} would have a separation less than the stellar radius of a giant within two magnitudes of the giant-branch tip. We conclude that this star is a nonmember, and comment that it is not surprising to find one such star out of more than 170 with a probability that is 99%.

One member star, Lee 3413, was reported as a nonmember by PL but is recognized as a member here. This star was almost certainly misidentified at the 1.5 m telescope, which pointed especially poorly during that run, and the log notes that a wide search was made before a star was found. The velocity suggests that Lee 3303 was observed instead, and the PL measurement has been included as such in Table 3.

Table 3 presents the individual measurements for those stars observed more than once. The first column lists the Julian date of each observation, and the next two give the velocity and its internal uncertainty. The final column identifies the star by its Lee number, and this identification holds for all succeeding lines until the next identification is listed. The largest number of observations were obtained for the three standards; other stars were typically observed twice only.

3.2. *Radial and Angular Dependence*

Plots of the individual velocities are shown in Figures 1–4. Figure 1 plots the velocities for each member against its radial distance from the cluster center. The typical uncertainty in

TABLE 1

VELOCITIES FOR M4 MEMBERS

RA (1950)	Dec (1950)	Radius (′)	θ (°)	V	B−V	Date (2440000+)	Velocity (km s^{-1})	σ (km s^{-1})	%	Lee, Other
16:19:35.02	-26:27:44.3	12.99	256.1	13.83	0.45	7634.90	70.47	1.77	99	1103
16:20:05.96	-26:25:15.4	5.72	263.5	13.69	1.27	6925.82	75.25	0.86	99	1402,K
16:20:09.81	-26:26:26.4	5.16	249.2	12.13	1.46	6221.81	72.76	0.20	99	1403,C
16:20:12.82	-26:26:37.9	4.62	244.0	13.42	0.92	7635.89	73.88	0.96	99	1404,A230
16:20:13.45	-26:27:07.4	4.73	237.9	13.40	0.92	7635.89	70.39	1.13	99	1405,A227
16:20:14.31	-26:27:15.6	4.65	235.2	13.84	1.23	6924.82	67.28	0.97	99	1406,A226
16:20:14.69	-26:27:29.5	4.72	232.3	13.33	1.08	6924.91	77.54	1.34	99	1407,A225
16:20:12.56	-26:27:30.1	5.11	235.5	11.82	1.41	6221.80	74.67	0.73	99	1408,B
16:20:10.22	-26:29:07.2	6.54	226.4	11.08	1.75	7634.86	69.01	0.89	99	1411,A219
16:20:16.79	-26:30:13.6	6.50	210.1	10.38	1.63	6926.85	67.55	0.95	99	1412,V4,ALX
16:20:27.30	-26:29:21.3	4.83	190.8	13.50	1.26	6925.86	72.91	0.88	99	1416,A188
16:20:15.63	-26:29:27.4	5.99	216.0	13.64	0.44	7634.88	73.82	1.30	99	1426
16:20:12.45	-26:25:11.8	4.27	262.1	11.70	1.53	6221.82	69.90	0.60	99	1501,A243
16:20:17.04	-26:25:02.3	3.23	262.3	12.98	1.15	6926.93	74.57	0.91	99	1504,A416
16:20:15.96	-26:25:43.8	3.62	252.0	13.47	1.27	6925.86	74.84	0.86	99	1506,A237
16:20:18.92	-26:26:34.9	3.41	234.6	13.13	1.30	6926.89	75.01	1.09	99	1509,A404
16:20:19.40	-26:26:43.8	3.42	231.6	13.12	1.32	6926.89	69.07	1.11	99	1510,A403
16:20:21.15	-26:26:31.8	2.99	229.9	12.82	1.35	6925.85	72.68	0.73	99	1512,A396
16:20:19.64	-26:27:32.1	3.93	221.8	10.76	1.84	6925.90	78.27	0.58	99	1514
16:20:23.58	-26:28:01.2	3.83	207.0	13.56	0.48	7634.92	74.55	1.12	99	1517,A210
16:20:20.42	-26:25:17.6	2.54	254.3	13.40	0.84	7635.84	71.88	1.21	99	1603,A414
16:20:20.25	-26:25:31.1	2.65	249.9	12.45	1.45	6924.90	75.82	0.87	99	1605,A413
16:20:22.62	-26:25:41.7	2.24	240.9	13.27	1.32	6923.89	69.34	0.34	95	1608,A412
16:20:23.55	-26:26:09.7	2.34	228.3	13.54	0.86	7635.86	71.96	1.17	99	1610,A410
16:20:24.33	-26:25:57.0	2.07	229.5	13.15	1.30	6926.82	71.12	1.14	99	1611,A411
16:20:22.94	-26:26:32.5	2.70	224.2	13.36	1.29	6924.92	72.06	1.09	99	1614,A395
16:20:26.07	-26:26:27.3	2.19	212.6	12.18	1.38	6925.91	67.96	0.73	99	1617,A399
16:20:27.35	-26:26:15.5	1.88	208.5	11.83	1.48	6221.83	65.80	0.50	-1	1619
16:20:29.24	-26:26:18.1	1.76	195.6	13.59	1.26	6925.84	73.11	0.99	99	1621
16:20:29.98	-26:26:07.2	1.54	191.5	13.46	1.32	6925.87	77.89	0.80	99	1622,A511
16:20:30.91	-26:26:41.3	2.08	182.7	13.55	0.91	7635.86	64.59	1.32	99	1623,A510
16:20:29.69	-26:27:23.1	2.80	187.6	12.79	1.45	6927.82	65.99	0.77	99	1625,A385
16:20:29.37	-26:27:09.1	2.58	189.9	15.38	0.63	7633.88	72.64	2.24	99	1626,A388
16:20:25.77	-26:24:52.2	1.28	258.1	12.02	1.36	6926.83	72.71	0.90	99	1701,A523
16:20:27.86	-26:24:48.9	0.81	255.0	12.80	1.20	6927.82	72.00	0.93	99	1705,A525
16:20:28.75	-26:25:03.9	0.74	231.8	13.26	1.10	6923.89	69.93	1.12	99	1713,A521
16:20:30.25	-26:25:39.8	1.09	193.1	13.57	0.46	7634.88	80.48	1.46	96	1726,A519
16:20:30.66	-26:24:38.4	0.16	257.9	12.70	1.14	6927.84	71.53	0.87	99	1734
16:19:36.64	-26:24:17.2	12.25	271.5	13.25	1.34	6927.89	70.26	0.94	99	2117
16:20:14.03	-26:15:05.5	10.28	337.8	13.84	0.46	7634.91	71.43	1.51	99	2204
16:20:08.51	-26:15:00.7	10.87	331.9	13.61	0.94	6569.82	66.98	0.78	99	2205
16:20:00.47	-26:16:44.6	10.47	318.7	11.90	1.51	6221.88	70.48	0.50	99	2206
16:19:46.10	-26:21:24.9	10.63	287.5	12.34	1.51	6222.87	76.70	0.70	99	2208,D
16:20:25.91	-26:16:28.7	8.22	351.5	13.06	1.38	6927.85	74.03	0.82	99	2305,A54
16:19:58.63	-26:22:29.4	7.63	286.1	13.06	1.43	6927.85	74.08	1.05	99	2314,F
16:19:53.98	-26:21:47.3	8.83	288.6	12.86	1.29	6223.84	70.40	0.80	99	2315,E
16:20:28.39	-26:19:24.1	5.25	352.7	13.08	1.30	6926.91	68.20	0.99	99	2404,A294
16:20:26.89	-26:20:07.4	4.59	347.4	10.84	1.69	6926.86	69.58	1.17	99	2406,V13
16:20:18.68	-26:19:24.9	5.92	331.3	12.68	1.39	6569.86	66.14	0.48	99	2410,A284
16:20:17.71	-26:19:49.6	5.67	327.4	13.57	1.25	6923.94	72.79	1.32	99	2411,A283
16:20:13.65	-26:20:12.6	5.92	318.0	13.38	0.97	6569.85	70.47	1.32	99	2413,A276
16:20:08.00	-26:22:45.5	5.55	289.5	14.35	1.13	6923.86	70.27	1.15	99	2418,A259
16:20:12.85	-26:22:50.1	4.51	293.2	13.10	1.31	6926.90	74.20	1.36	99	2419,A257
16:20:10.51	-26:23:48.7	4.73	279.7	12.54	1.45	6925.93	66.91	0.74	99	2422
16:20:07.96	-26:23:55.9	5.28	277.4	13.60	1.29	6925.84	75.26	0.91	99	2425,A248
16:20:05.52	-26:24:07.0	5.80	274.9	13.47	0.92	6569.84	72.66	0.76	99	2426,G
16:20:29.78	-26:20:53.3	3.73	354.6	13.64	1.27	6925.83	75.95	0.91	99	2501,A301
16:20:28.91	-26:20:53.7	3.75	351.6	13.41	1.00	6569.87	63.70	0.85	99	2502,A300
16:20:17.38	-26:21:36.2	4.34	313.8	14.33	1.22	6923.87	69.03	1.14	99	2506,A270
16:20:20.94	-26:22:27.8	3.17	312.6	13.71	1.23	6925.81	75.38	0.70	99	2508,A436
16:20:18.46	-26:22:44.9	3.43	302.8	14.05	1.20	6924.85	74.23	1.00	99	2509,A258
16:20:19.97	-26:23:03.3	2.98	301.3	12.76	1.36	6927.81	77.79	0.84	99	2511,A434

TABLE 1—*Continued*

RA (1950)	Dec (1950)	Radius (′)	θ (°)	V	B–V	Date (2440000+)	Velocity (km s^{-1})	σ (km s^{-1})	%	Lee, Other
16:20:13.85	-26:23:08.3	4.19	290.6	13.87	1.19	6923.93	72.87	1.69	99	2515,A256
16:20:17.08	-26:23:46.6	3.30	284.6	13.82	1.24	6924.87	74.88	1.28	99	2516,A424
16:20:17.30	-26:24:11.9	3.17	277.4	11.82	1.46	6925.92	66.65	0.67	99	2519,A423
16:20:28.27	-26:21:56.5	2.75	345.5	13.36	0.52	5774.94	72.10	1.40	99	2602,A450
16:20:28.29	-26:22:25.7	2.28	342.5	13.90	1.21	6923.81	76.05	1.12	99	2603
16:20:26.65	-26:22:42.5	2.17	331.0	12.58	1.20	6926.93	72.80	0.79	99	2607
16:20:25.46	-26:22:14.8	2.70	330.8	12.25	1.44	6926.82	77.29	0.81	99	2608,A442
16:20:23.81	-26:22:14.6	2.90	324.5	14.29	1.12	6924.84	69.73	1.32	99	2609,A454
16:20:21.02	-26:22:55.8	2.86	305.9	14.00	1.23	6923.85	72.57	1.01	99	2611,A435
16:20:23.70	-26:22:52.0	2.44	315.5	13.68	0.44	5774.97	70.00	2.00	99	2613
16:20:24.30	-26:22:52.0	2.35	317.8	13.39	0.50	5775.00	71.20	1.30	-1	2614
16:20:25.67	-26:22:53.5	2.13	323.4	13.21	0.55	5775.99	73.90	1.80	99	2616,A440
16:20:25.05	-26:23:32.9	1.76	306.9	11.82	1.60	6221.84	63.62	0.42	99	2617,A529
16:20:23.91	-26:23:37.1	1.94	300.7	14.06	1.20	6924.88	71.26	1.22	99	2618,A430
16:20:22.04	-26:23:43.1	2.27	293.1	14.03	1.23	6924.81	69.88	1.20	99	2620,A427
16:20:22.93	-26:23:47.3	2.06	293.5	13.29	1.28	6923.91	71.35	1.06	99	2621,A428
16:20:23.34	-26:24:02.5	1.88	287.5	13.04	1.36	6569.94	63.98	0.56	99	2623,A429
16:20:22.99	-26:24:26.7	1.88	274.9	14.37	1.14	6923.88	66.53	1.51	99	2624
16:20:22.84	-26:24:34.2	1.91	271.1	12.52	1.45	6924.93	68.18	0.88	99	2626,A524
16:20:20.56	-26:24:14.1	2.44	278.8	13.63	1.31	6925.84	77.18	1.04	99	2627,A421
16:20:19.97	-26:23:30.6	2.77	293.3	13.13	0.91	7634.87	72.55	1.22	99	2630,A433
16:20:31.30	-26:23:14.4	1.37	359.5	13.36	0.94	7636.90	73.82	0.81	99	2701,A536
16:20:30.07	-26:23:24.3	1.24	346.6	14.61	0.75	7633.84	68.56	1.84	75	2706
16:20:27.38	-26:23:28.1	1.44	322.0	12.49	1.43	6924.90	69.83	0.81	99	2711,A530
16:20:29.42	-26:23:33.3	1.14	337.7	14.03	1.18	6923.93	73.14	1.26	99	2712,A534
16:21:10.67	-26:20:23.3	9.76	64.4	13.35	1.21	6927.88	71.38	1.05	99	3204
16:21:15.66	-26:19:42.0	11.07	63.7	13.29	1.20	6927.88	66.20	1.04	99	3205
16:21:04.63	-26:18:01.5	9.94	48.5	11.87	1.23	6221.87	73.20	0.60	99	3207
16:20:59.08	-26:17:09.2	9.70	39.8	10.94	1.66	6124.00	66.26	0.46	99	3209
16:21:04.95	-26:24:03.2	7.54	85.8	13.22	0.48	5775.97	74.20	1.40	99	3301
16:21:09.55	-26:23:11.0	8.67	80.5	13.25	0.94	7636.87	69.22	1.14	99	3302,A114
16:20:55.31	-26:20:20.9	6.85	51.5	13.20	0.73	7633.83	68.96	0.69	99	3306,A88
16:20:52.64	-26:19:28.6	7.00	42.9	13.19	0.48	5776.02	73.99	0.99	99	3307,A79
16:20:52.55	-26:18:33.6	7.69	38.1	13.20	0.89	7636.86	66.82	0.78	99	3310,A75
16:20:41.99	-26:16:41.4	8.27	16.7	13.24	0.47	5776.03	75.40	1.50	99	3315,A64
16:20:57.10	-26:24:38.2	5.77	90.3	13.43	1.18	6924.93	73.57	1.06	99	3401
16:20:55.52	-26:24:37.4	5.41	90.2	13.23	0.49	7636.91	67.11	1.54	99	3402,A365
16:21:00.20	-26:23:33.5	6.54	80.8	13.01	1.25	6927.87	70.33	1.02	99	3404,A112
16:20:50.55	-26:22:46.7	4.67	67.0	13.97	1.13	6923.83	71.26	1.38	-1	3406,A346
16:20:48.96	-26:21:11.6	5.22	49.1	13.47	1.25	6925.86	78.59	0.95	99	3412,A327
16:20:55.44	-26:21:02.6	6.47	56.5	11.33	1.52	7634.84	67.16	0.70	99	3413,A95
16:20:34.89	-26:18:46.8	5.88	7.7	13.07	1.31	6926.92	74.17	0.80	99	3419,A308
16:20:50.71	-26:24:24.8	4.34	87.4	13.12	1.24	6926.90	71.07	1.20	99	3501,A358
16:20:44.88	-26:24:03.6	3.08	79.8	14.25	1.12	6924.86	76.78	1.12	99	3502,A484
16:20:48.20	-26:23:30.0	3.93	73.6	13.27	1.02	6569.87	64.72	0.96	99	3503,A349
16:20:43.81	-26:22:52.8	3.28	58.2	13.61	1.26	6924.93	73.20	1.06	99	3506,A339
16:20:46.20	-26:22:30.6	3.93	57.8	13.42	1.23	6925.88	65.94	0.84	99	3507,A335
16:20:44.93	-26:22:23.7	3.76	54.0	13.69	1.20	6925.83	68.59	1.04	99	3508
16:20:45.70	-26:21:56.5	4.17	50.3	13.97	1.13	6923.84	71.22	1.05	99	3509,A329
16:20:40.19	-26:21:28.3	3.71	32.3	13.16	0.47	5775.95	67.99	0.96	99	3511,A321
16:20:39.07	-26:21:11.8	3.82	26.9	13.46	1.27	6925.86	68.75	0.87	95	3513,A318
16:20:45.07	-26:21:31.8	4.35	45.0	14.93	0.60	7633.86	67.73	2.80	99	3521,A328
16:20:38.58	-26:24:24.9	1.63	83.2	12.70	1.10	6927.84	75.16	0.86	99	3601,A552
16:20:43.55	-26:24:08.6	2.77	80.4	13.52	1.23	6925.85	75.24	0.92	99	3606,A485
16:20:40.00	-26:23:10.3	2.41	53.5	11.82	1.47	6925.92	74.90	0.95	99	3612,A468
16:20:36.84	-26:23:13.4	1.85	41.6	13.58	1.25	6925.85	64.74	1.14	99	3618,A472
16:20:34.67	-26:23:03.7	1.71	25.7	13.39	1.02	6926.82	69.11	1.54	99	3619,A474
16:20:37.70	-26:22:50.9	2.26	38.9	13.72	1.31	6925.81	67.66	0.89	99	3620,A465
16:20:38.74	-26:22:31.8	2.66	38.5	12.67	1.34	6569.89	71.38	0.57	99	3621,A464
16:20:37.29	-26:22:12.8	2.74	29.1	13.38	0.95	6569.89	70.39	0.71	99	3622,A461
16:20:35.94	-26:21:52.9	2.91	20.7	11.78	1.56	6925.91	70.22	0.73	99	3624,A459
16:20:34.54	-26:22:19.9	2.38	17.4	13.20	1.33	6926.82	69.41	1.00	99	3627

TABLE 1—*Continued*

RA (1950)	Dec (1950)	Radius (′)	θ (°)	V	B–V	Date (2440000+)	Velocity (km s^{-1})	σ (km s^{-1})	%	Lee, Other
16:20:34.41	-26:22:27.3	2.26	17.7	12.40	1.28	6927.85	70.19	0.94	99	3628
16:20:31.87	-26:22:33.9	2.04	3.3	13.33	0.85	7635.85	74.05	1.18	99	3629,A446
16:20:33.47	-26:21:43.4	2.92	9.3	14.08	1.22	6923.85	65.87	1.28	99	3632,A457
16:20:31.66	-26:21:41.8	2.91	1.4	13.42	0.52	5774.95	71.70	1.50	99	3633,A455
16:20:36.88	-26:24:34.1	1.24	88.2	12.78	1.34	6927.82	65.62	0.84	99	3701,A553
16:20:36.75	-26:24:25.6	1.22	81.6	12.18	1.39	6925.93	72.46	0.92	99	3702,A549
16:20:36.01	-26:24:21.0	1.07	76.2	12.53	1.39	6569.90	71.53	0.51	99	3705,A548
16:20:35.39	-26:24:15.3	0.97	68.7	12.70	1.33	6569.90	69.32	0.61	99	3706,A547
16:20:34.19	-26:24:10.9	0.76	56.3	13.67	1.17	6925.82	66.83	0.98	99	3718,A582
16:20:34.47	-26:23:41.9	1.15	37.6	12.97	1.32	6927.82	73.81	0.97	99	3721,A545
16:20:31.71	-26:23:46.1	0.84	5.5	13.44	1.27	6925.88	75.92	0.82	99	3726,A577
16:20:32.52	-26:23:23.9	1.24	12.2	12.21	1.47	6926.86	66.86	1.57	-1	3730,A538
16:20:33.44	-26:23:14.2	1.45	18.9	13.15	0.49	7636.88	71.59	1.38	99	3732,A541
16:20:32.35	-26:23:10.0	1.46	8.8	13.19	0.91	7634.89	70.18	1.37	99	3733,A475
16:20:46.41	-26:37:36.1	13.42	165.5	12.94	1.29	6927.86	69.16	0.85	99	4105
16:20:54.41	-26:32:53.7	9.76	148.1	11.71	1.38	6124.00	75.42	0.40	99	4201
16:21:11.75	-26:25:33.9	9.10	96.0	13.04	1.25	6927.87	66.63	0.90	99	4206,A119
16:20:35.72	-26:32:06.6	7.57	172.6	13.46	1.20	6927.88	71.77	1.06	99	4305,A163
16:20:52.27	-26:32:05.8	8.83	148.0	12.06	1.40	6222.83	66.00	0.60	99	4310,A156
16:20:56.69	-26:28:58.2	7.16	127.5	12.62	1.38	6927.85	68.27	0.89	99	4313,A130
16:21:05.83	-26:27:54.5	8.39	113.1	13.56	0.36	7635.88	67.18	1.57	99	4316,A126
16:20:34.06	-26:28:58.6	4.41	172.1	13.69	1.29	6925.82	77.75	0.97	99	4401,A196
16:20:36.68	-26:30:27.1	5.97	168.5	12.97	1.29	6223.82	70.30	0.62	99	4404,A195
16:20:40.35	-26:29:59.9	5.76	159.5	14.34	1.14	6923.88	68.23	1.02	99	4405,A150
16:20:43.79	-26:29:47.8	5.89	151.8	13.37	0.93	7636.89	74.34	0.82	99	4406,A147
16:20:45.89	-26:29:13.8	5.65	144.8	13.08	0.43	7636.90	71.80	1.36	99	4408,A149,Z8
16:20:40.11	-26:29:09.3	4.95	156.7	13.45	0.92	7635.90	68.04	1.03	99	4409,A197
16:20:49.99	-26:29:27.1	6.39	139.3	13.34	0.93	7636.88	72.64	0.89	99	4412,A143
16:20:54.14	-26:28:44.0	6.56	128.9	12.65	1.30	6222.85	68.40	0.70	99	4413,A131
16:20:49.57	-26:27:47.3	5.17	127.9	11.80	1.33	6124.01	65.95	0.30	99	4414,A142
16:20:49.41	-26:27:19.9	4.88	124.0	12.57	1.38	6222.82	74.87	0.46	99	4415,A140
16:20:49.68	-26:26:57.3	4.73	119.8	12.91	1.34	6222.81	73.40	0.50	99	4416,A138
16:20:53.34	-26:25:30.0	5.00	100.3	12.67	1.36	6925.93	67.65	0.86	99	4421
16:20:41.05	-26:27:01.0	3.24	138.0	13.52	1.27	6925.85	72.80	1.05	99	4507,A376
16:20:41.77	-26:26:43.1	3.15	132.1	12.94	1.30	6569.92	67.54	0.57	99	4508,A375
16:20:42.76	-26:26:48.2	3.37	130.7	12.98	1.31	6926.93	69.81	0.75	99	4509,A374
16:20:45.64	-26:27:03.3	4.03	127.4	11.62	1.59	6925.91	66.12	0.56	99	4511
16:20:45.43	-26:25:56.9	3.43	113.0	14.28	1.15	6924.83	68.13	1.00	99	4514,A372
16:20:43.85	-26:25:47.3	3.04	112.9	13.80	1.21	6924.94	65.40	0.93	99	4515,A373
16:20:46.02	-26:25:24.1	3.38	103.6	13.47	1.27	6925.87	70.87	0.99	99	4516,A493
16:20:31.76	-26:26:38.2	2.03	177.4	13.64	1.30	6925.83	68.17	1.00	98	4601,A509
16:20:32.39	-26:26:58.7	2.38	174.4	13.10	1.41	6926.92	65.05	1.01	99	4602
16:20:32.96	-26:26:53.6	2.31	171.0	13.48	1.25	6925.87	70.37	0.95	99	4603
16:20:36.37	-26:27:02.0	2.67	155.2	13.47	0.86	7635.85	65.93	1.03	99	4607,A379
16:20:34.31	-26:26:22.9	1.89	159.5	10.93	1.94	6220.80	65.08	0.60	99	4611,A515
16:20:35.13	-26:26:09.8	1.77	151.5	10.85	1.87	6220.81	68.61	0.71	99	4613,A516
16:20:37.67	-26:25:28.3	1.66	121.4	13.41	0.88	7635.88	73.35	1.13	99	4621,A495
16:20:38.13	-26:25:10.2	1.62	110.4	13.93	1.20	6923.82	65.73	1.28	99	4623,A498
16:20:39.12	-26:24:57.7	1.78	101.5	12.71	1.35	6569.91	78.06	0.77	-1	4624
16:20:39.56	-26:25:14.4	1.94	109.0	13.16	0.88	7636.86	70.78	0.86	99	4626,A500
16:20:39.88	-26:25:05.9	1.97	104.4	14.28	1.11	6923.90	69.90	1.43	99	4627,A501
16:20:42.20	-26:25:31.5	2.60	110.7	12.19	1.42	6926.87	69.82	1.05	99	4630,A492
16:20:43.70	-26:25:10.4	2.82	101.6	13.49	0.38	7635.87	74.77	1.66	99	4632,A491,Z6
16:20:34.80	-26:25:07.4	0.93	123.8	13.28	1.29	6925.90	72.15	1.28	99	4716,A558
16:20:36.12	-26:25:07.8	1.19	116.1	13.46	1.10	6925.88	61.94	1.05	99	4717,A557
16:20:22.79	-26:24:18.4	1.94	278.9	15.52	0.72	7633.89	67.04	2.17	99	A420
16:20:18.11	-26:10:19.3	14.59	348.3	12.96	1.39	6927.86	67.06	0.78	99	G273
16:21:20.62	-26:15:20.7	14.41	50.0	12.99	1.21	6927.87	70.02	1.06	99	G311

NOTE.—Table 1 appears in the AAS CD-ROM series, Vol. 4.

TABLE 2

VELOCITIES FOR M4 NONMEMBERS

RA (1950)	Dec (1950)	Radius (′)	θ (°)	V	B–V	Date (2440000+)	Velocity (km s^{-1})	σ (km s^{-1})	%	Lee, Other
16:19:57.31	-26:16:32.1	11.11	316.7	10.27	1.72	6222.88	-23.00	0.80	2	2207
16:20:30.20	-26:16:57.8	7.65	358.1	12.63	1.53	6223.85	27.60	0.70	0	2301,A55
16:20:01.51	-26:21:52.0	7.22	292.3	13.57	0.93	6569.83	-55.47	0.86	0	2312,H
16:20:11.18	-26:24:19.7	4.53	273.5	13.25	0.88	6569.85	36.73	0.94	0	2423,A246
16:21:16.13	-26:24:34.2	10.03	89.8	12.70	1.41	6927.86	-56.53	0.72	0	3201
16:21:13.74	-26:20:52.6	10.20	68.5	13.32	1.20	6927.88	20.49	1.11	0	3203
16:21:02.49	-26:21:23.8	7.68	65.3	11.79	1.60	6221.85	-36.10	0.80	0	3303,A98
16:20:53.89	-26:23:02.8	5.28	72.8	13.46	1.17	6925.87	19.72	0.77	0	3405,A110
16:20:39.73	-26:19:37.9	5.32	20.7	14.21	1.22	6924.87	-5.43	1.05	0	3416,A312
16:20:55.95	-26:36:25.7	13.04	155.0	13.00	1.41	6927.86	-21.56	0.94	0	4110
16:20:46.22	-26:25:52.4	3.56	110.8	12.49	1.14	6927.84	-46.78	0.80	99	4513

NOTE.—Table 2 appears in the AAS CD-ROM series, Vol. 4.

each point is 1.0 km s^{-1}, and is independent of type or magnitude except at the faintest magnitudes (see Table 1 and § 2.2).

Figure 2 presents the same velocities plotted against position angle on the sky. No global rotation is evident. In Figure 3, a similar plot is made for just those stars within 4′ (5 core radii) of the cluster center. Figure 4 plots those stars in the annulus 4′–8′. No rotation is evident in either subgroup, at a level of roughly $v \sin i = 3$ km s^{-1}. There is no evidence for rotation in the proper motions, which also appear equal in the radial and tangential directions (see below). This is in keeping with the shape of the M4 cluster, whose axial ratio was found to be 1.00 ± 0.01 by White & Shawl (1987). However, rotation with an amplitude of -0.9 ± 0.4 km s^{-1} at a position angle of 100° is suggested by taking the difference of the median velocity of stars interior to 15′ on either side of the cluster center. Such a rotation would lead to a value of 0.25 for the ratio of the maximum rotational velocity divided by the velocity dispersion, and is consequently negligible for the dynamics of the cluster. Even smaller is the rotation introduced by projection effects by the cluster motion perpendicular to the line of sight. Given the cluster's space motion as found below, we would expect stars located 10′ from the cluster center in either direction along the path of the cluster's orbit to be displaced by 0.5 km s^{-1} from the cluster mean. We have too few stars at such large projected distances to detect this.

3.3. *Mean Velocity and Velocity Dispersion*

The mean velocity of M4 is calculated from 180 values of Table 1 (excluding the two known variables) to be 70.9 km s^{-1}, with an internal uncertainty of $\sigma_v = 0.27$ km s^{-1}, and an external uncertainty of 0.6 km s^{-1} dominated by the zero point. The mean velocity agrees well with the result 70.7 ± 0.7 km s^{-1} found from the 28 members tabulated by Peterson (1985a) and PL. The uncertainty in the mean follows from the observed 1 σ

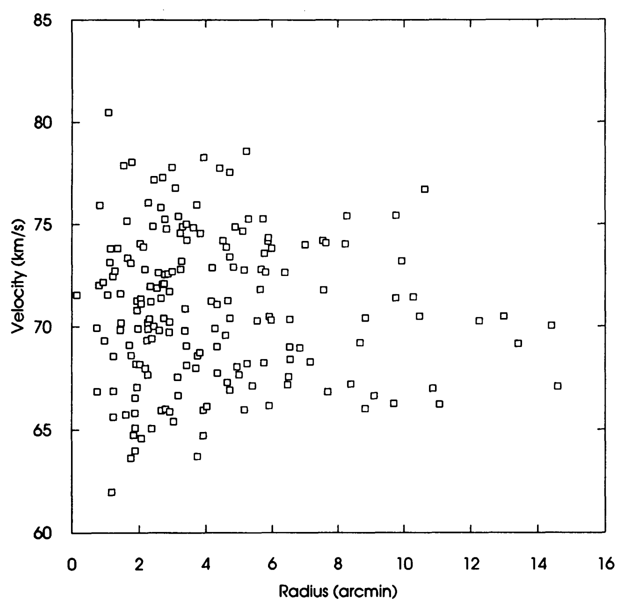

FIG. 1.—Radial velocities of each individual star are plotted against its distance from the cluster center. The uncertainty in each point is typically 1 km s^{-1}. Fig. 1 also appears in the AAS CD-ROM Series, Vol. 4.

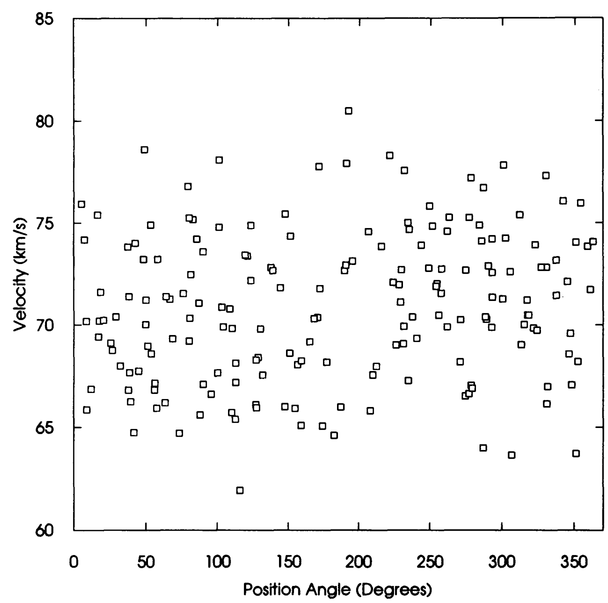

FIG. 2.—Radial velocities of each individual M4 star are plotted against its position angle. No sinusoidal trend is apparent, but the difference of -2.2 km s^{-1} in mean velocity between stars with position angles between 10° and 190° and the remaining stars hints at rotation with an apparent amplitude of 0.9 ± 0.4 km s^{-1}. Fig. 2 also appears in the AAS CD-ROM Series, Vol. 4.

TABLE 3

Duplicate Velocities

Date (2440000+)	Velocity (km s^{-1})	σ (km s^{-1})	Lee ID	Date (2440000+)	Velocity (km s^{-1})	σ (km s^{-1})	Lee ID
6221.81	72.60	0.70	1403	6124.00	65.50	0.60	3209
6923.81	72.80	0.74		6221.87	64.20	0.70	
6923.86	72.64	0.69		7633.82	66.33	0.59	
6923.92	72.98	0.71		7634.82	66.87	0.72	
6924.81	73.11	0.61		7635.83	66.58	0.62	
6924.88	72.61	0.77		7635.84	66.49	0.56	
6924.89	70.21	1.34		7635.89	67.54	0.72	
6924.95	72.77	0.75		7636.85	66.61	0.65	
6925.81	73.46	0.61		7636.85	66.73	0.60	
6925.84	72.21	0.62		7636.88	65.76	0.56	
6925.91	72.34	0.62		6221.85	-36.70	0.80	3303
6926.81	72.36	0.73		6221.86	-35.50	1.00	
6926.85	72.45	1.89		7633.83	68.69	1.17	3306
6926.87	73.34	1.60		7635.84	69.22	0.97	
6926.93	72.92	0.62		5776.02	74.30	1.30	3307
6927.81	73.43	0.54		7636.91	73.68	1.51	
6927.87	73.61	0.60		5775.95	67.90	1.40	3511
7633.82	72.75	0.51		7634.92	68.07	1.34	
7633.88	71.50	0.58		6569.89	70.74	0.67	3621
7634.83	72.90	0.90		6926.88	72.01	0.94	
7635.83	72.33	0.72		6569.89	69.64	1.01	3622
7635.87	72.56	0.65		7636.92	71.13	0.94	
7636.85	72.15	0.52		6569.90	71.84	0.62	3705
7636.89	72.91	0.51		6924.92	71.22	0.88	
6221.80	74.80	0.80	1408	6569.90	69.39	0.71	3706
6926.84	74.04	1.80		6926.88	69.20	1.12	
6926.83	76.91	2.59	1509	6124.00	75.30	0.50	4201
6926.89	75.01	1.09		6221.80	75.60	0.70	
6923.89	68.73	1.11	1608	6223.82	70.80	0.80	4404
6923.94	69.19	1.08		6926.93	69.77	0.98	
6924.84	69.40	0.91		6124.01	67.30	1.30	4414
6925.83	69.21	0.78		6220.83	65.70	0.90	
6925.88	68.63	0.70		6223.81	65.70	0.60	
6926.91	69.86	0.91		6926.87	66.38	1.46	
6927.83	70.33	0.86		6222.82	74.80	0.60	4415
6569.82	67.59	1.04	2205	6927.84	74.96	0.78	
7635.89	66.37	1.15		6222.81	72.80	0.60	4416
6221.88	70.70	0.60	2206	6927.83	74.76	0.90	
6923.95	70.26	0.86		6569.92	67.06	0.73	4508
6569.86	66.42	0.62	2410	6927.83	68.01	0.91	
6926.88	65.85	0.75		6927.84	-46.34	1.38	4513
6569.84	72.32	1.10	2426	7634.86	-47.23	1.00	
7635.90	73.00	1.05		6220.80	65.00	0.80	4611
6221.84	63.60	0.60	2617	6926.85	65.16	0.90	
6925.94	63.65	0.65		6220.81	68.70	0.80	4613
6569.94	63.57	0.70	2623	6926.84	68.28	1.57	
6926.92	64.39	0.88					

Note.—Table 3 appears in the AAS CD-ROM series, Vol. 4.

deviation $\sigma_o = 3.64$ km s^{-1} of an individual velocity about the mean. After allowance for the mean observational uncertainty $\sigma_i = 1.0$ km s^{-1}, this yields a true mean 1 σ internal velocity dispersion $\sigma_{\rm int} = 3.5 \pm 0.2$ km s^{-1}, according to the prescription of PL.

As was the case with the smaller sample of PL, the velocity dispersion of the horizontal branch stars does not seem to be as large as that of the giants. The 19 BHB stars show $\sigma_{\rm int} = 2.7 \pm 0.7$ km s^{-1}, while the 21 red HB stars yield 2.6 ± 0.6 km s^{-1}. In contrast, the 20 giants brighter than $V = 13$ (1.7 mag from the tip) produce a dispersion $\sigma_{\rm int} = 3.6 \pm 0.8$ km s^{-1}. The difference is marginally significant for each separate group of HB stars, and more so for the combined HB sample. It might be attributed to a "jitter" among the brighter giants; however, the size required to bring the two groups into agreement would then be about 2.5 km s^{-1}, rather larger than the 1.0 km s^{-1} found by Gunn & Griffin (1979) for tip M3 giants. Furthermore, those stars below the horizontal branch show an internal dispersion identical to that of the giants. The 50 stars with $13.4 \geq V \geq 14.5$ and $B-V \geq 1.1$ give $\sigma_{\rm int} = 3.7 \pm 0.5$ km s^{-1}. All these estimates allow for the uncertainty due to the size of the sample, which dominates the other sources of uncertainty in all cases. We cannot tell yet whether the HB stars as a whole have a lower internal velocity dispersion than do giants as a whole; velocities for a larger sample of HB stars are needed.

The central dispersion found from stars within 3′ is likewise

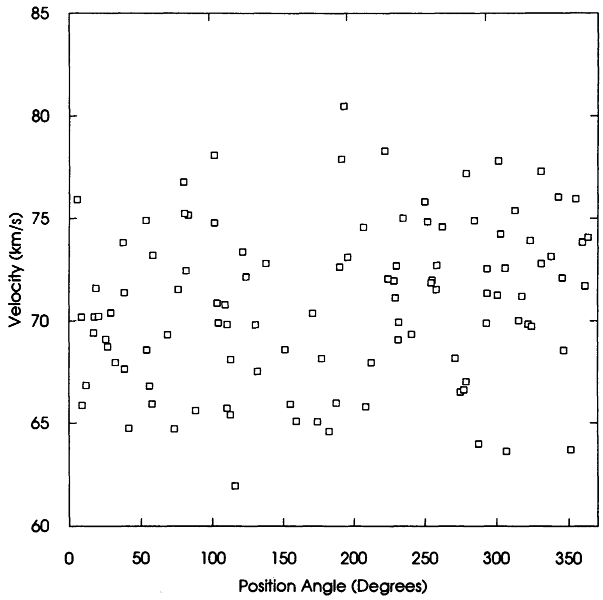

FIG. 3.—A plot as in Fig. 2 is shown for those stars within 4′ of the cluster center. Fig. 3 also appears in the AAS CD-ROM Series, Vol. 4.

3.5 ± 0.3 km s^{-1}. Indeed, the velocity dispersion shows a minimal trend with radial distance from the center. Figure 5 shows this trend as defined by binning stars radially and calculating the observed dispersion σ_o for each bin. In the figure, the vertical error bar is the uncertainty in the mean for each group, while the horizontal error bar indicates its radial extent by plotting the 1 σ value of the radial coordinates, i.e., the range over which two-thirds of the stars in the group fall. A marginal decline of dispersion with radius is seen: it is no greater than 25%, and is consistent with zero, in going from 1′ to 10′ radial distance (1.2 to 12 core radii). The plot of Gunn & Griffin (1979) for M3 shows a similar range of values—no change over ten core radii for a light-particle-dominated model, and a drop

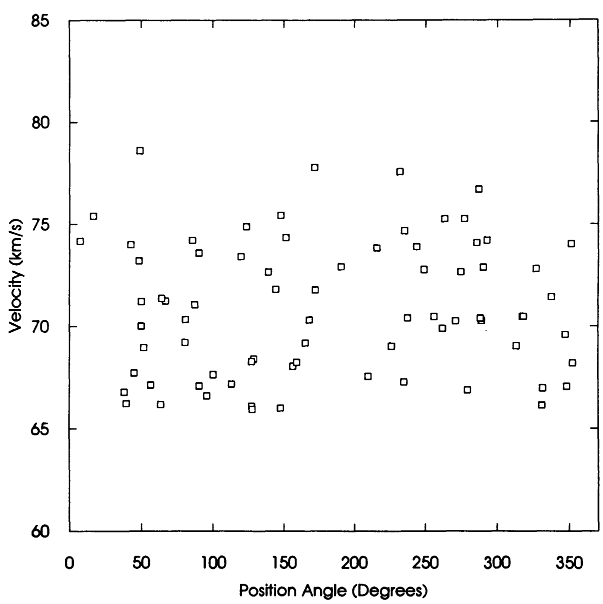

FIG. 4.—A plot as in Fig. 2 is shown for those stars from 4′ to 8′ from the cluster center.

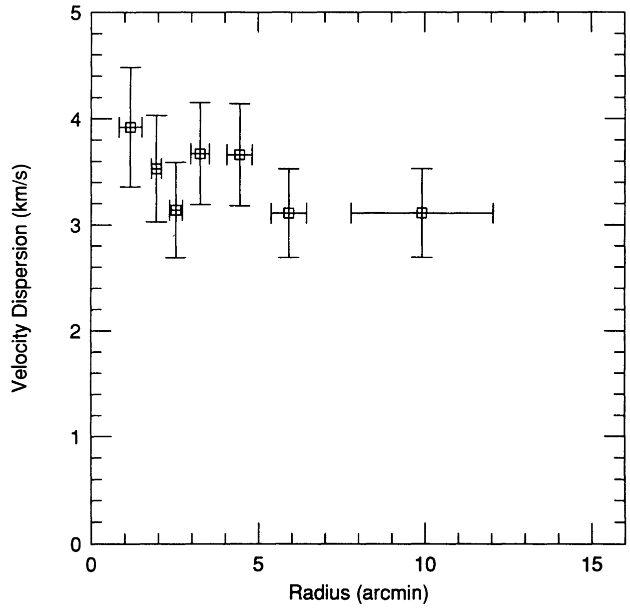

FIG. 5.—The radial dependence of the M4 velocity dispersion is shown. Each point is the dispersion calculated from all stars except variables which fall within a given radial annulus. The horizontal bars show the radial extent of two-thirds the stars in each bin. The vertical bars are true 1 σ error bars, calculated following the method of PL. They are dominated by the sample size of typical 25 stars per bin.

of about 20% for the best-fitting anisotropic model, each of which reproduces the luminosity profile. Any falloff should occur at a somewhat smaller number of core radii for a cluster such as M4 with a lower concentration than M3.

An updated central mass-to-light ratio may be derived from our velocity dispersion and the revised cluster parameters of Trager et al. (1993). Pryor & Meylan (1993) have tabulated such results for many clusters; they also use multimass King models to account more directly for mass segregation. This allows them to calculate explicitly the population central mass-to-light ratio for their assumed multimass distribution in the presence of mass segregation, and they find that the central M/L_V reaches a minimum of 1.2 at a concentration of 1.7, near that of M4. For M4 itself, they deduce a central value of $M/L_V = 1.5$. For reasons not obvious they adopted a high central dispersion, 4.2 km s^{-1}, from our 182 velocities, the 19 of PL, and 23 from Rastorguev & Samus (1991). A similar situation holds for M22, where they adopted 9.0 km s^{-1} while listing our value of 6.6 km s^{-1} from 130 stars within 3.5 core radii. We see nothing in our data in either case that indicates a rise within the central few core radii, nor is any rise expected in an isothermal model, with or without moderate mass segregation. Correcting the Pryor and Meylan M4 and M22 values for the dispersions we observe yields $M/L_V = 1.0$ for both clusters. An uncertainty of 0.4 is estimated here when model as well as observational uncertainties are taken into account. While there is no discrepancy with the theoretical estimate, clearly the M4 and M22 values fall at the low end of theoretical expectations.

The M4 and M22 M/L_V values are also low observationally, i.e., compared to those observed for other clusters. We see this in the tabulation of Pryor and Meylan, and also in the Mandushev et al. compendium. Correcting the Mandushev et al. value to our dispersion from the 3.9 km s^{-1} they adopted reduces it by 25% to a value matching the lowest value listed by them in any other cluster. As we noted for M22 (Peterson & Cudworth

1994), M4 is now found to be a cluster of modest concentration with a very low M/L_V ratio, suggesting that concentration is not the dominant factor in determining M/L_V.

We might ask whether we are being misled by an extreme form of mass segregation not anticipated by the models, for example the embedding of the cluster in a dark halo which begins outside the radial extent of our measurements. We have developed an indirect test of such a scenario (Peterson 1995) based on the deeper cluster potential well that this would imply. In any such circumstance where the cluster mass-to-light ratio rises outward from the domain where velocities are measured, the true escape velocity will be higher than the nominal escape velocity as determined from the measurements, and some stars with such velocities might appear even in an interior sample. Here, however, no star with a velocity exceeding the nominal escape speed is evident. Among the members in Table 1, the most extreme radial velocity is that of Lee 1726, which lies 9.6 km s^{-1}, 2.7 σ_{int} higher than the mean. Similarly, among the stars with the most reliable proper motions, none has a three-dimensional velocity more than 5 σ from the cluster mean.

4. PROPER MOTIONS

4.1. *New Proper Motion Reductions*

The PDS scans used by CR have been rereduced using the improved Yerkes central-overlap reduction code, as described by Peterson & Cudworth (1994) and Rees (1993). The two Yerkes reflector plates that were used by CR contributed relatively little to the results and were not included in the new reductions, leaving a total of 36 plates. No new photometric reductions were carried out here, unlike for M22 (Peterson & Cudworth 1994).

New cluster membership probabilities have been derived from the new proper motions, using the standard Yerkes sofware described by Cudworth (1985). Only 51 of the 527 stars showed any change in membership probability, and only 13 of these had changes larger than 5%. These are listed in Table 4, along with the membership probabilities found in this study (P_{new}), by CR (P_{CR}), and the change $\Delta P(=P_{new} - P_{CR})$. The largest changes in P are for stars with intermediate membership probabilities, and none are so large as to drastically alter the likelihood of any given star belonging to the cluster. The conclusions of CR regarding cluster properties based on membership and regarding individual stars are consequently unaltered.

The new membership probabilities are included in Tables 1–3. They and the new proper motions are listed in Table 5, in a format identical to that of Table 3 of CR, which it supersedes. Table 5 appears in full in the AAS CD-ROM series, Vol. 4; the first 20 stars are listed here. Table 5 is also available electronically from any of the authors.

TABLE 4

STARS WITH REVISIONS IN PROPER MOTIONS GREATER THAN 5%

Star	P(new)	P(CR)	ΔP
L4118	80	70	10
L4622	95	90	5
L4518	91	83	8
L4425	99	91	8
L1422	55	75	-20
Y308	84	79	5
A189	93	81	12
A463	57	44	13
A281	78	64	14
A353	86	70	16
A280	91	80	11
A202	56	63	-7
Y226	28	41	-13

4.2. *Absolute Proper Motion and Space Velocity*

CR derived an absolute proper motion and space velocity for M4. This was revised slightly by Cudworth & Hanson (1993) using an improved method of reduction from relative to absolute proper motion. In both cases a cluster distance of 2.0 kpc was used in calculating the space velocity. The improved proper motions derived here have no significant effect on the absolute proper motion of the cluster, but the smaller distance derived below will change the space velocity. We have therefore recalculated the space velocity assuming a distance of 1.7 kpc (with an uncertainty of 10%), but otherwise using the same data as Cudworth and Hanson. The result is $(\Pi, \Theta, Z) = (-59 \pm 3, 63 \pm 16, 9 \pm 6)$ km s^{-1}, in the Galactic rest frame. This is in a left-handed coordinate system where Π is outward, Θ in the direction of Galactic rotation, and Z toward the north Galactic pole, all as seen from the cluster. These values agree with the previous determinations to within their mutual uncertainties.

The only change of possible astrophysical significance is that the cluster is now found to have a somewhat larger velocity in the direction of Galactic rotation. It is still clear, however, that it is in a very eccentric orbit. Allen & Santillan (1993) used the original CR space velocity to calculate the orbit of M4 and found it was chaotic: despite the cluster's current position in the disk and its small Z velocity, integration over many orbits showed that it can reach z distances up to 4 kpc. They derived an orbital eccentricity of 0.88, so that the Galactocentric distance ranges from 0.5 to 6.9 kpc.

The smaller distance and consequent increase in velocity in the direction of Galactic rotation will raise the perigalactic distance to about 1 kpc, not enough to change the fact that the cluster goes quite near the Galactic nuclear bulge. The low-velocity dispersion we find is therefore rather surprising: the cluster's binding energy is low for such an orbit. The disruption probability depends on the ratio of the cluster's mean density to that of the Galaxy at cluster perihelion, discussed immediately below, and the timescale for disruption goes inversely as the orbital period of the cluster. Thus the shorter distance that we find for M4 helps by increasing the cluster's perigalactic distance and orbital period. However, together these effects are still not large enough to reverse the prediction of probable cluster disruption within a Hubble time (Oh & Lin 1995). The survival probability of the cluster would be improved if its actual tidal radius is somewhat smaller than supposed, as we now discuss.

Given enough time, disruption will occur when the mean cluster density is less than a few times the mean density of the Galaxy at the cluster's perihelion. This can be seen from the discussion of tidal disruption by Binney & Tremaine (1987). They estimate the "tidal radius" of a cluster in a circular orbit as the Lagrangian point between two objects. Their equation (7-84) gives it as the cube root of one-third the ratio of the masses of the cluster and the Galaxy, times the distance between cluster and Galaxy. Dividing each side of this equa-

TABLE 5

PROPER-MOTION DATA SUPERSEDING TABLE 3 OF CUDWORTH & REES (1990)

Names	X (arcsec)	Y	μ_x (milliarcsec century^{-1})	ϵ_x	μ_y	ϵ_y	V	B–V	P (%)
2207	-457.3	483.0	-414	33	81	31	10.27	1.72	2
1412,V4,ALX	-195.2	-338.6	39	21	162	28	10.38	1.63	99
A,4501,Z3	51.3	-202.9	3039	24	430	23	10.41	0.87	0
1514	-157.0	-177.1	-25	11	23	12	10.76	1.84	99
2406,V13	-59.7	268.0	9	16	79	20	10.84	1.69	99
A516,4613	50.9	-94.5	11	23	45	19	10.85	1.87	99
A515,4611	40.0	-107.6	61	18	126	14	10.93	1.94	99
3209	372.9	446.2	-47	29	-7	34	10.94	1.66	99
A219,1411	-283.4	-272.2	53	20	64	24	11.08	1.75	99
4101	40.3	-835.8	-600	46	3180	57	11.17	0.57	0
3105	472.5	535.3	2266	27	1585	43	11.22	0.61	0
A95,3413	323.7	212.7	55	25	-50	32	11.33	1.52	99
3111	188.5	791.3	1058	29	1617	48	11.36	0.51	0
A293,2405,Z1	-39.2	285.8	1825	10	1065	11	11.47	0.80	0
2307	-222.6	469.5	68	18	-97	29	11.56	1.72	99
4511	191.9	-148.1	24	18	-81	13	11.62	1.59	99
L2	500.0	706.1	104	33	1481	27	11.66	1.12	0
A243,1501	-253.6	-36.6	-23	14	-4	15	11.70	1.53	99
4201	309.4	-498.8	-26	27	76	25	11.71	1.38	99
A459,3624	61.8	162.4	36	21	-65	21	11.78	1.56	99

tion by the cluster distance and by the cluster radius, cubing the result, and multiplying by the Galactic mass expresses the result in terms of mean densities: the mean cluster density equals three times the mean density of the Galaxy internal to the cluster's distance.

Binney and Tremaine list several reasons why this should not be taken too literally. The tidal truncation probably occurs over a range of radii, since the surface of zero velocity is nonspherical and trapped orbits (albeit few) occur outside the Lagrangian point, Also, the host potential has finite extent, and the cluster orbit may be eccentric. These points were investigated explicitly by Oh, Lin, & Aarseth (1992) and Oh & Lin (1992) using N-body simulations. They find that the maximum extent of bound stars after 30 galactic orbits never exceeds such a "tidal radius" by 40% under various assumptions for the Galactic potential (point and logarithmic), the distribution of stellar orbits (isotropic and anisotropic), and the eccentricity of the cluster orbit (circular and with eccentricity 0.5). For eccentric orbits, the relevant distance in the Binney and Tremaine expression is the perigalactic distance, as expected since that is where the disruptive force is the strongest.

We can then estimate what tidal radius to expect for M4. Correcting the mass derived by Pryor & Meylan (1993) for our central dispersion of 3.5 km s^{-1} yields a cluster mass 4.3×10^4 $M_\odot$. Estimating the Galactic mass interior to 1 kpc as 10^{10} $M_\odot$ gives 1.1×10^{-2} for the cube root of one-third the ratio of the cluster mass to the Galactic mass. Taking 1 kpc for the (revised) perigalactic distance of M4, the cluster tidal radius becomes 11 pc. At a cluster distance of 1.72 kpc (see below), this corresponds to 22′.

This is two-thirds the value listed by Trager et al. (1993) for the tidal radius. Given the uncertainties in estimating an expected tidal radius, this discrepancy isn't severe, but is nonetheless uncomfortable. The Trager et al. value of 33′, 10′ smaller than that of Peterson and King, was derived from a surface brightness profile obtained by combining all available measurements (see Trager, King, & Djorgovski 1995). The outermost part of the profile rests on the star counts of King et al. (1968), and extends beyond 20′ with no sign of tidal truncation. However, the outermost values are based on a 48 inch Schmidt plate with background set by extrapolation. Since the background in the M4 field is high, the outer profile is uncertain because the cluster disappears more quickly into the background. Furthermore, there is a substantial dust lane to the west; this and the reddening gradient suggest that the background varies strongly with direction about the cluster center. These factors make it difficult to trust a tidal radius derived from photometry or star counts. For an unequivocal answer, the limiting radius should be redetermined from velocity measurements of a reasonable sample of outlying stars. This should be straightforward, given the difference of more than 80 km s^{-1} between the cluster radial velocity and the mean of the field stars noted in § 3.1 above.

5. CLUSTER DISTANCE

Rees (1995) has used the new proper motions and the radial velocities of this paper to derive an astrometric distance to the cluster; we briefly summarize these procedures here. The proper motions and radial velocities were related via an anisotropic King-type dynamical model. In this context the model is acting essentially as an interpolating function between the proper motions and radial velocities, rather than as an attempt to best describe the dynamical state of the cluster. In this spirit, the innermost data of the adopted surface brightness profile (Kron, Hewitt, & Wasserman 1984) were ignored to avoid uncertainties due to small number statistics. As a result, the projected model core radius (118″) does not agree well with those typically found by others. Also, the central model dispersion was found to be 3.8 km s^{-1}, slightly higher than that found in this paper. However, given the large degree of overlap between the proper motion and radial velocity samples, the derived distance is fairly independent of the details of the model. The derived distance for M4 is 1.72 ± 0.14 kpc.

Until recently such a distance would have been considered extremely small, but independent investigations within the past year support such a value. Most distance determinations discussed by CR fall in the range 1.9–2.1 kpc. Taken at face value, a shift to 1.7 kpc would imply a shift of nearly 0.5 mag in distance modulus. However, M4 lies behind the Sco-Oph dark cloud complex, for which there is considerable evidence for a unusually high value of $R = A_V/E(B-V)$ (see Vrba et al. 1993, who find a range of R of 3.15 to 5.25 for stars within a few degrees of M4). Liu & Janes (1990), assuming $R = 3.8$, found a distance of 1733 ± 5 pc from a Baade-Wesselink analysis of four M4 RR Lyraes (the quoted uncertainty seems to reflect only the agreement of the averaged distances of the four stars without taking into account the uncertainties in the individual distances). Dixon & Longmore (1993) concluded, after examining various photometric data in the literature, that $R \approx 4$ and a distance of 1.75 kpc are most consistent with the data (implying a metallicity of $[Fe/H] = -1.1$, in accord with Drake et al. 1994).

6. SUMMARY

We have presented radial velocities good to 1 km s^{-1} for 182 members of the cluster M4 in a radial annulus of 1′–14′. Coupled with proper motions updated from the values of CR using improved Yerkes software, and a simple model for M4 acting as an interpolating function for radial velocities and proper motions, we derive a distance of 1.72 ± 0.14 kpc. This distance is smaller than previously believed, and is consistent with a normal horizontal-branch luminosity provided a larger than average ratio $R = 4$ is adopted of reddening to absorption, as is independently indicated by several recent studies.

The radial velocities show a velocity dispersion of 3.5 ± 0.3 km s^{-1} at the center, decreasing minimally within 14′. A larger sample of velocities for horizontal branch stars is required to establish whether their velocity dispersion is less than that of giant-branch stars, which is marginally indicated by the present data. Rotation, if present, has an amplitude less than 1 km s^{-1}, and so is negligible for the dynamics of the cluster.

The dispersion implies a mass-to-light ratio of $M/L_V = 1$ in solar units, one of the lowest mass-to-light ratios known for a globular cluster. It is also lower than expected from the cluster orbit, which carries the cluster sufficiently close to the galactic center that the cluster is subject to disruption. A tidal radius two-thirds the size of that currently indicated from star counts would resolve this dilemma. Indeed, no star in this sample shows a radial velocity greater than the nominal escape speed. Given the strong and variable background absorption and the anomalous extinction ratio, velocity studies of the outer regions are needed to determine the limiting radius unambiguously.

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