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STRUCTURAL PARAMETERS AND MASSES FOR THREE OLD LMC CLUSTERS

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ABSTRACT

This paper presents luminosity profiles for three old LMC clusters, NGC 1835, NGC 2210, and NGC 2257. King models are fitted to the profiles, the core and tidal radii are determined, and the total mass of each cluster is deduced. Total luminosities and mass-to-light ratios are also derived. For NGC 1835 a dynamical mass is determined from the cluster's velocity dispersion, obtained from a spectrum of its integrated light. Lower limits on tidal mass-to-light ratios are 0.18 ± 0.03, 0.11 ± 0.02, and 0.56 ± 0.09 for NGC 1835, NGC 2210, and NGC 2257, respectively. The velocity dispersion measurement yields a mass-to-light ratio for NGC 1835 of 0.42 ± 0.08. These values are up to 3 times larger than previous determinations. The values for NGC 1835 and NGC 2210 are still somewhat smaller than mass-to-light ratios of Milky Way globulars or of NGC 2257, and we suggest that this reflects a difference in age.

Subject headings: clusters: globular — galaxies: Magellanic Clouds — stars: evolution

I. INTRODUCTION

The globular cluster system of the LMC differs markedly from that of the Galaxy in that it contains clusters with a wide range of ages, while those in the Galaxy are all old. The question arises whether clusters of a similar age in the two galaxies differ substantially in other properties. One property of interest is the mass-to-light ratio, which contains information about stellar content, and hence conditions of formation and evolution. Masses based on velocity dispersions have been determined for 10 Milky Way globulars (Illingworth 1976); their mass-to-light ratios are all between 0.9 and 2.9, with a mean value of 1.6. Because LMC clusters are much fainter, measuring their velocity dispersions is difficult. However, tidal radii have been determined for four of the oldest (SWB types VI and VII; Searle, Wilkinson, and Bagnuolo *et al.* 1980) LMC clusters: NGC 1835, NGC 1978, NGC 2210, and Hodge 11 (Freeman and Gascoigne 1977; Chun 1978; Searle 1983). These tidal radii are used to estimate the cluster masses from the tidal field of the LMC (see § 11*b*). They all yield mass-to-light ratios between 0.1 and 0.3: an order of magnitude smaller than those of their galactic counterparts!

The aim of this paper is to verify whether the difference in M/L between LMC and Milky Way globulars is real. New photometric luminosity profiles for three old LMC clusters, NGC 1835, NGC 2210, and NGC 2257, and new mass-to-light ratios are presented. For NGC 1835, an independent mass estimate is obtained by measuring its velocity dispersion from a high-dispersion spectrum of its integrated light. The photometric observations and data reductions are described in § II, and tidal masses and mass-to-light ratios are calculated. The velocity dispersion measurements for NGC 1835 are presented in § III, and the results are summarized and discussed in § IV.

II. PHOTOMETRY: LUMINOSITY PROFILES OF NGC 1835, NGC 2210, AND NGC 2257

a) Observations and Data Reductions

The luminosity profiles presented in this section for NGC 1835 and NGC 2210 are derived from photometric drift scans, obtained using the Siding Spring 40 inch (1 m) telescope, equipped with an offset guider head, filter/aperture box, and 1P21 photomultiplier. Five 10′ east-west strips across each cluster were scanned through a V filter by offsetting the telescope tracking rate. One strip was centered on the cluster, and four were offset one and two aperture diameters north and south. The drift rate was $1'' \text{ s}^{-1}$ of time. Scans along each strip were repeated 3–5 times. Six hundred points along each strip were sampled at a rate of 1 Hz. The aperture used was 9″.81 in diameter.

The raw scans were aligned to produce a two-dimensional map of each of the two scanned regions. From these maps, mean radial luminosity profiles were constructed. For NGC 1835 in particular, this is complicated by the dense background star field. We used a modal approach in order to minimize the distortion of the profiles by the surrounding star fields.

Figure 1*a* shows a segment of a scan in the sky region far from NGC 1835. Figure 1*b* is the histogram of counts for all pixels more than 200″ from the cluster center. The count distribution is Poisson-like: the mode corresponds to sky plus unresolved field stars, while the tail comes from the brighter field stars. For regions closer to the cluster center, the mode becomes brighter, due to the extra light contributed by the cluster. We used the brightness of the mode at a given radius as a measure of the cluster's intrinsic surface brightness at that radius.

First, the sky level was determined for each cluster map by constructing histograms of counts for pixels well beyond the cluster limit, as in Figure 1*a*. The mode of the distribution was adopted as the sky level. This sky level was then subtracted from all pixels in the map. Sky-subtracted counts were converted to V magnitudes using transformations derived from observations of several standard stars. The scale of the scans was determined by measuring distances between field stars on photographic plates, and the uncertainty in the scale is negligible.

The cluster profile was obtained by plotting the magnitude at which the mode of the distribution occurs, as a function of radius. Magnitudes proved more convenient than counts for constructing histograms in annuli across the cluster. Furthermore, radial histograms at a given magnitude were better

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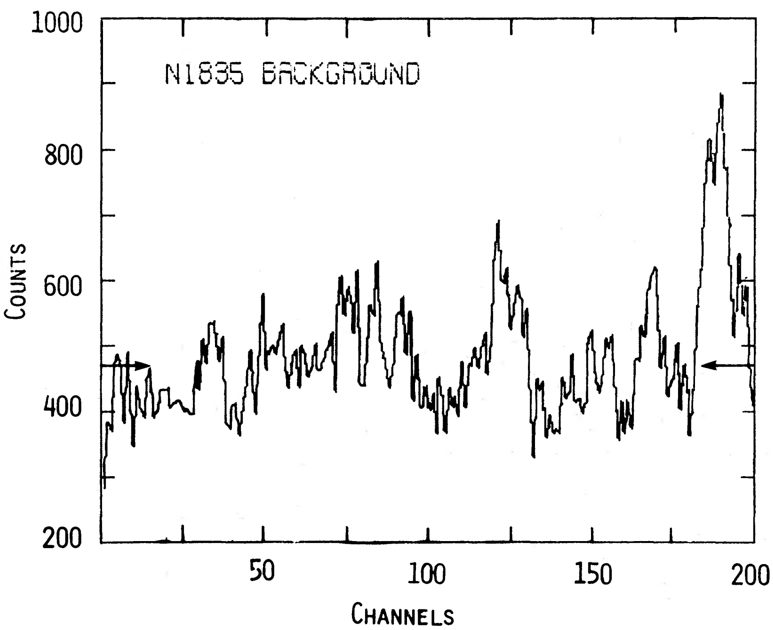

FIG. 1*a*

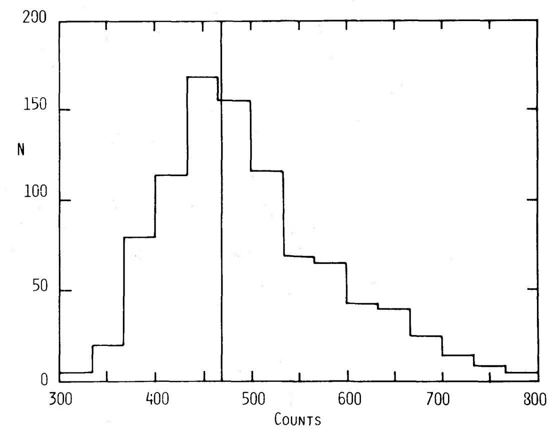

FIG. 1*b*

FIG. 1.—Sky region of NGC 1835 map: (*a*) instrumental counts in radial interval 100″–300″. The level of the background mode in Fig. 1*b* is marked on the ordinate. (*b*) Histogram of instrumental counts in an annulus at 200″–300″. The mode at 470 counts corresponds to sky plus unresolved stars, while the tail comes from brighter field stars.

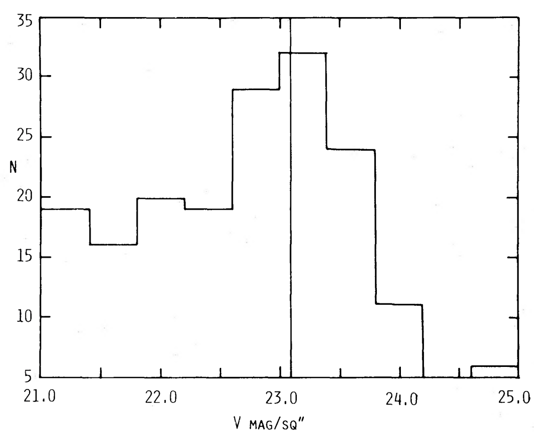

FIG. 2*a*

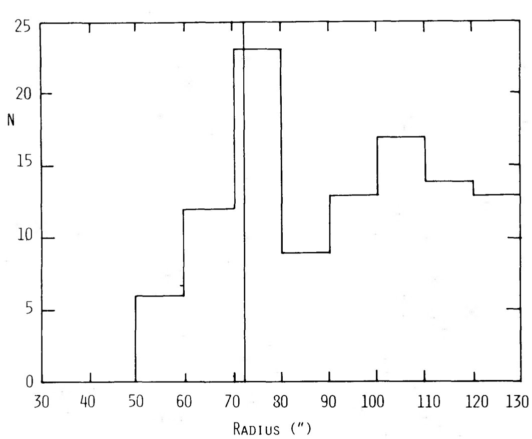

FIG. 2*b*

defined over the entire profile than magnitude histograms at a given radius. Examples of magnitude and radial histograms are shown in Figures 2*a* and 2*b*. Like the magnitude histograms, the radial histograms are Poisson-like; the mode at the smallest radius corresponds to the mode in the magnitude histograms. This correspondence is demonstrated in Figure 3 for NGC 1835: surface brightnesses determined from magnitude histograms and from radial histograms are in excellent agreement.

This modal procedure permits accurate determination of a cluster's intrinsic surface brightness distribution in the presence of background fluctuations and allows profiles to be traced to a much fainter level than other methods: the histograms are still well defined at $V = 26$ for both NGC 1835 and NGC 2210, whereas previous profiles (Chun 1978) peter out at $V = 24$. We

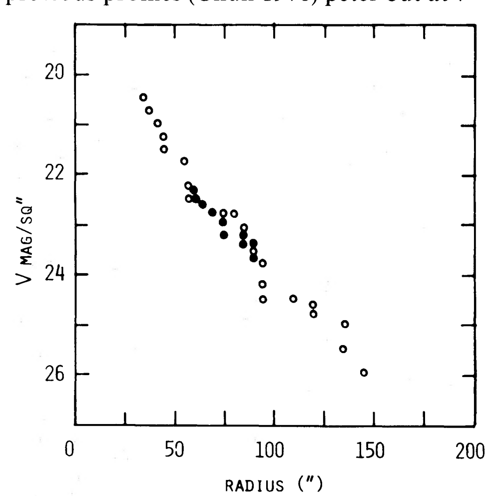

FIG. 3

FIG. 2.—Histograms of NGC 1835 data points: (*a*) points in a 20″ wide annulus at radius 85″, binned in magnitude; (*b*) points in a magnitude interval $V = 22.5$–23.0, binned radially.

FIG. 3.—Profile for NGC 1835 obtained from the modal procedure described in the text. The solid circles come from histograms binned radially in a given magnitude interval, and the open circles come from histograms binned in magnitudes in a given radial interval. Note the good agreement.

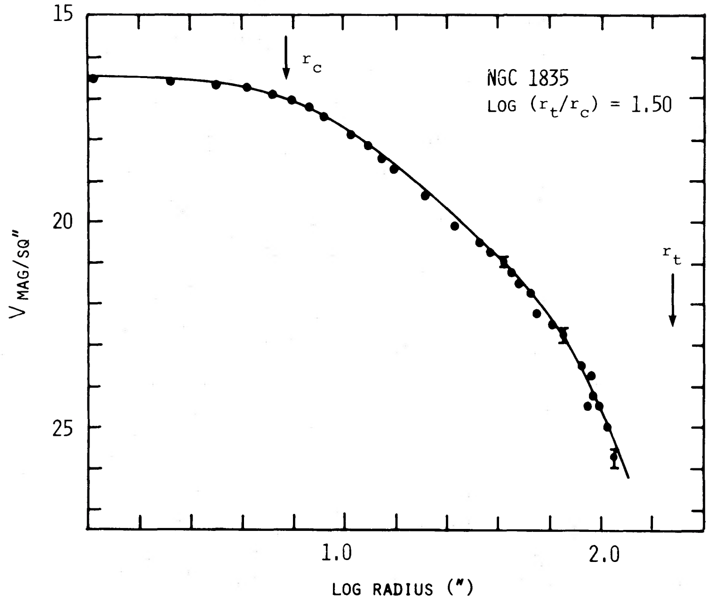

FIG. 4*a*

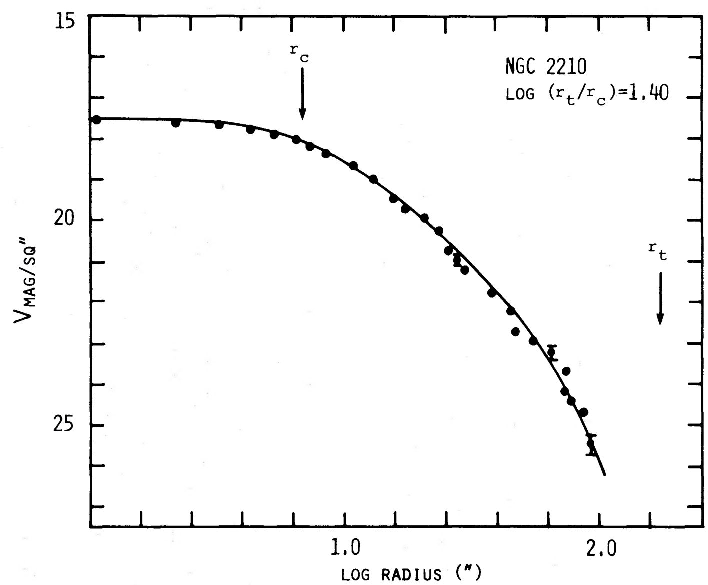

FIG. 4*b*

FIG. 4.—Surface brightness profiles for (*a*) NGC 1835, (*b*) NGC 2210, and (*c*) NGC 2257. The solid curves are King (1966) models which best fit the data. The arrows mark the positions of the adopted core and tidal radii. The error bars for (*a*) and (*b*) are as described in the text. Those for (*c*) are as in Illingworth and Illingworth (1976). Points with no error bars have negligible errors. The solid circles are from drift scans, and the open circles are from star counts. The broken horizontal line represents the background level for the star counts.

TABLE 1

CORE AND TIDAL RADII

Cluster	log (r_t/r_c)	r_c(arc sec)	r_c(pc)	r_t(arc sec)	r_t(pc)	Source
			A. This Paper			
NGC 1835......	1.50	6.0 ± 0.3	1.6 ± 0.1	190 ± 10	51.6 ± 2.5	This paper
NGC 2210......	1.40	7.1 ± 0.4	1.9 ± 0.1	178 ± 9	47.5 ± 2.4	This paper
NGC 2257......	1.10	27.5 ± 1.4	7.3 ± 0.4	347 ± 17	92.5 ± 4.6	This paper
			B. Previous Results			
NGC 1835......	1.50	4.95	1.3	157	41.8	Chun 1978
NGC 2210......	1.50	6.48	1.7	205	54.7	Chun 1978

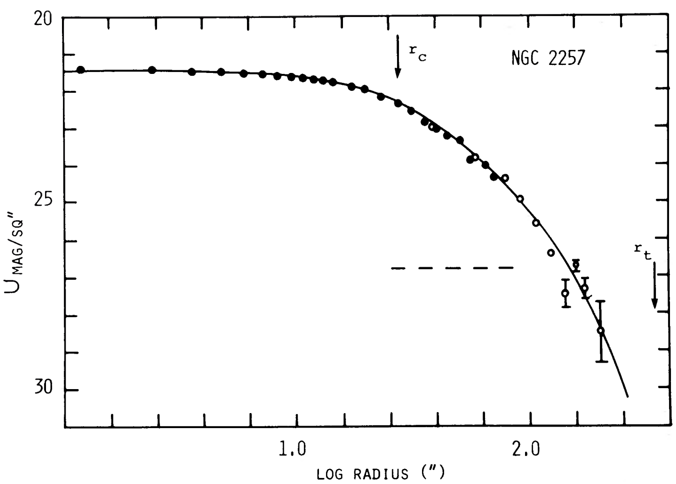

FIG. 4*c*

feel this is a powerful method for determining tidal radii, particularly for globular clusters such as those in the inner regions of the LMC or the Galaxy, where luminosity profiles may be distorted by crowded star fields.

Figures 4*a* and 4*b* show the luminosity profiles for NGC 1835 and NGC 2210. The estimated error in the modally determined points ranges from 0.1 for the brighter points to 0.25 for the fainter ones, and is represented by the size of the points or by typical error bars in the outer parts. The brightest points ($V < 20$) are mean values with negligible errors.

NGC 2257 is a more diffuse cluster than the other two, and it was possible to do star counts from a 74 inch (1.9 m) telescope plate (kindly lent to us by Dr. S. C. B. Gascoigne) to determine the luminosity profile in the outer parts. Our method follows that of Illingworth and Illingworth (1976). For the inner parts of the profile, we used a U scan obtained with a 15''4 aperture on the 40 inch telescope. The composite profile for NGC 2257 is shown in Figure 4*c*.

King (1966) models, convolved with a circular apertures of the appropriate diameter, were fitted by eye to the data. The best fitting models are shown as solid lines in Figures 4*a*–4*c*. The adopted structural parameters are listed in Table 1*a*; previously determined values are listed in Table 1*b*. For NGC 2210, where the background fluctuations are insignificant, the modal procedure gives structural parameters in excellent agreement with those derived earlier by more straightforward methods. For NGC 1835, the procedure gives a slightly larger tidal radius, which we believe is more realistic.

b) *Masses and Mass-to-Light Ratios*

The tidal radii were transformed to masses according to (King, 1962)

$$M = r^3(4\Omega^2 - \kappa^2) , \qquad (1)$$

where r_t, Ω, and κ, are the cluster's tidal radius, and the LMC's angular velocity and epicyclic frequency at the cluster's position. The adopted distance to the LMC was 55 kpc. The rotation curve used is the same as that adopted by Chun (1978). Distances of clusters from the center of the LMC were taken from Freeman, Illingworth, and Oemler (1983, hereafter FIO). The clusters were assumed to be in circular orbits, because even the old clusters in the LMC appear to form a disk-like system (FIO).

Total magnitudes were derived for the clusters using the fitted King models and King's (1962) table of integrated surface brightness profiles. The zero point was taken from the drift scan data. As a check on these total magnitudes, aperture measurements were synthesized from the drift scans and compared with published values (van den Bergh and Hagen 1968; Bernard and Bigay 1974; Bernard 1975). NGC 1835 and NGC 2210 show excellent agreement for aperture diameters less than about 40'', while for larger apertures our values are brighter by up to 0.2 mag for NGC 1835, and 0.1 mag for NGC 2210. We believe that our values are more likely to be correct, because of the large amount of sky data that the drift scans provide, and because of our detailed modal analysis. Large-aperture measurements of objects in dense star fields are very difficult.

For NGC 2257 we made *UBV* measurements with the 40 inch telescope through an aperture 47''5 in diameter. Our values are $V = 13.26$, $B - V = 0.57$, and $U - B = -0.02$, all uncertain by 0.03 (s.e.). The integrated U magnitude agrees with this direct measurement to within 0.1 mag.

The total magnitudes, luminosities, masses, and mass-to-light ratios are listed in Table 2*a*, and previous values are listed in Table 2*b* for comparison. No correction for galactic absorption has been made for values of L and M/L given in either table. Quoted errors are from uncertainties in tidal radii only, and not from other sources such as potential fields and distance estimates.

III. SPECTROSCOPY: VELOCITY DISPERSION OF NGC 1835

a) *Observations and Data Reductions*

The spectra discussed here were obtained at the Coude focus of the Mount Stromlo 74 inch telescope, using the PCA image intensifier and CCD detector. The wavelength region observed was 5150 Å to 5250 Å, and the dispersion was 9.2 Å mm^{-1}. The sigma for the instrumental profile is 8 km s^{-1}.

TABLE 2

LUMINOSITIES AND TIDAL MASSES

Cluster	V_t	$L(\times 10^5)$	$M(\times 10^4)$	M/L	Source
		A. This Paper			
NGC 1835......	9.52 ± 0.05	4.02 ± 0.18	7.3 ± 0.7	0.18 ± 0.03	This paper
NGC 2210......	10.36 ± 0.05	1.85 ± 0.08	1.9 ± 0.2	0.11 ± 0.02	This paper
NGC 2257......	11.48 ± 0.05	0.66 ± 0.03	3.7 ± 0.4	0.56 ± 0.09	This paper
		B. Previous Results			
NGC 1835......	9.81	2.94	4.4	0.15	Chun 1978
NGC 2210......	10.50	1.56	2.7	0.17	Chun 1978

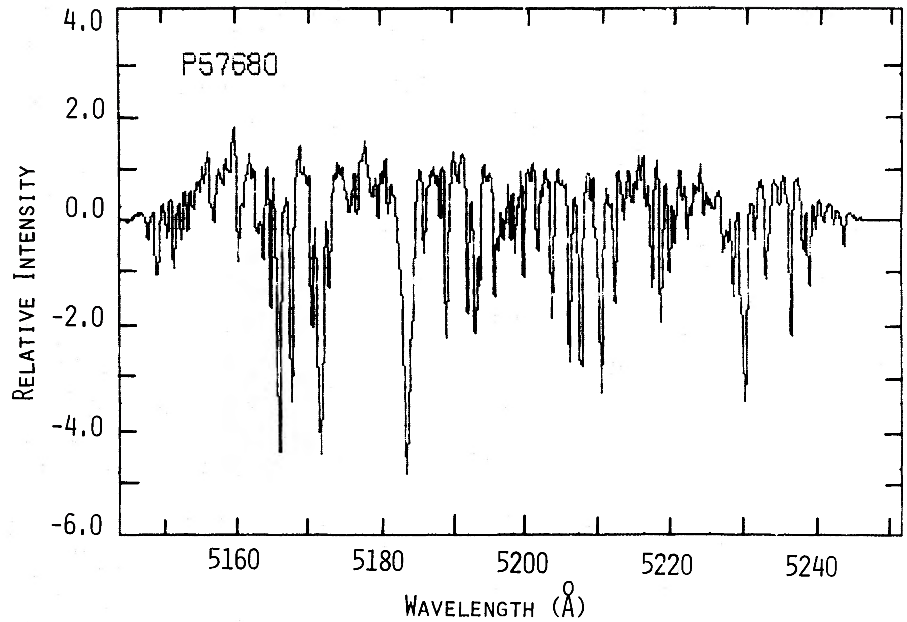

Fig. 5a

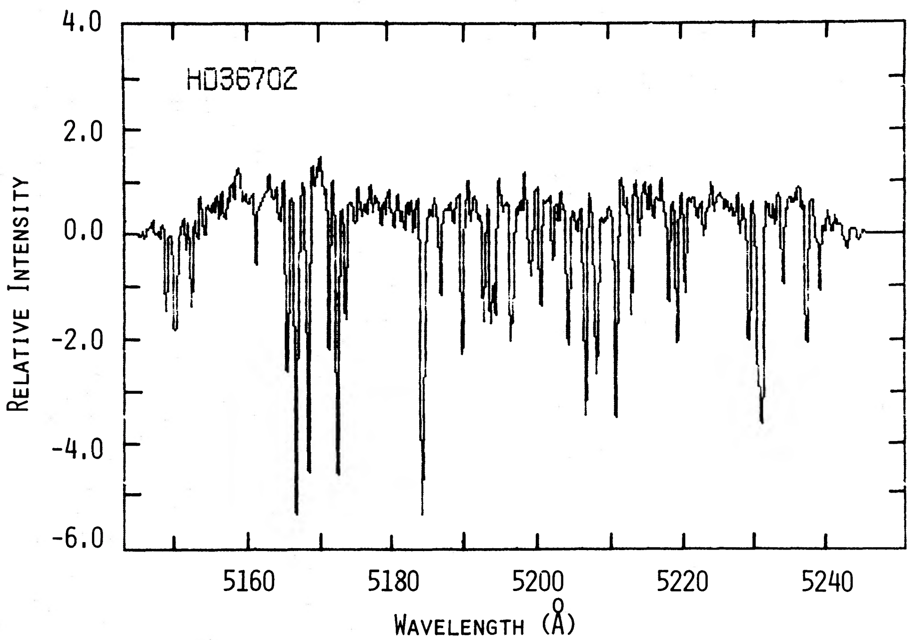

Fig. 5b

Fig. 5.—Direct spectra of two template stars and the two clusters in the wavelength region 5150 Å to 5250 Å: (*a*) P57680, (*b*) HD 36702, (*c*) NGC 1835, and (*d*) NGC 2808. Radial velocity shifts have been removed. The spectra have been divided by a smooth continuum and masked at the ends. The prominent lines at 5167A, 5173A, and 5184A are Mg I.

In addition to NGC 1835, spectra were obtained for the galactic globular cluster NGC 2808 and a total of seven template stars over the course of two observing runs. The spectra were transformed to a wavelength scale using Fe-Ar arc exposures, and sky-subtracted. Spectra of two template stars and of the clusters are shown in Figures 5*a*–5*d*.

Velocity dispersions for the two clusters were determined using a fourier method. This is outlined briefly here: full details can be found in Illingworth (1973), Illingworth (1976), and Illingworth and Freeman (1974). The spectra of the clusters and those of the template stars, convolved with Gaussians of appropriate widths, are Fourier transformed. Broadening the spectra has the effect of steepening their fourier power spectra. The cluster velocity dispersion can therefore be determined by finding the convolved template spectrum whose Fourier power spectrum slope best matches that of the cluster. This method has several advantages over direct comparisons: it makes use of the entire spectrum, it is not so dependent on finding template stars with the same relative line strengths, and it is more sensitive to small velocity changes than direct comparisons. In our experience this method is better than fourier quotient methods for measuring small velocity dispersions (comparable

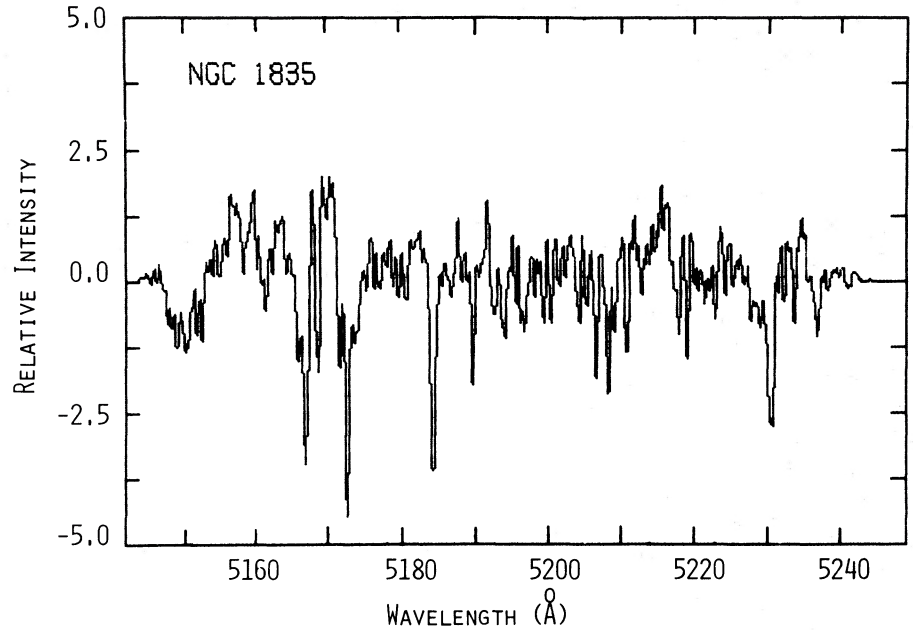

Fig. 5c

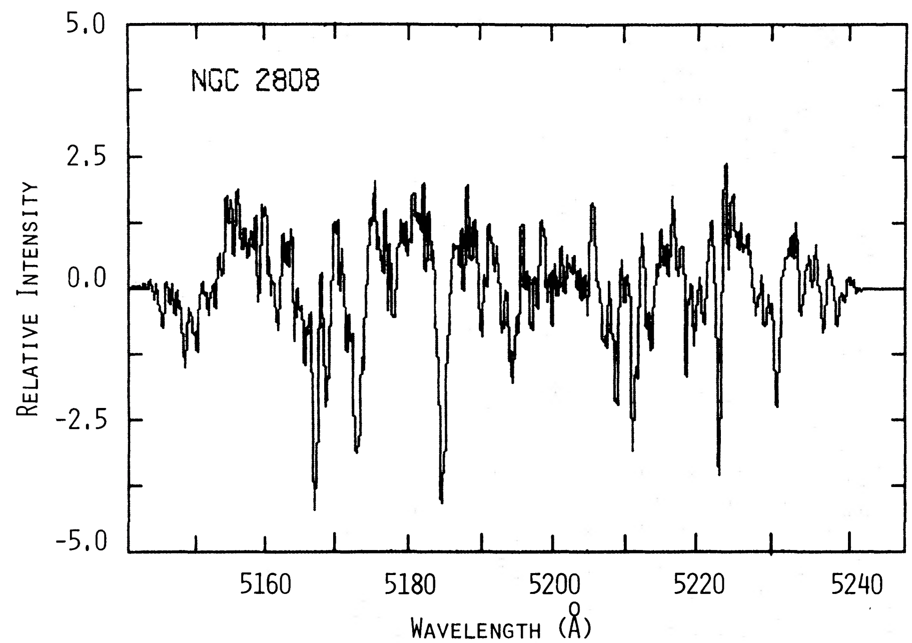

Fig. 5d

with the instrumental sigma), because detailed effects are more apparent (see van der Kruit and Freeman 1984).

Power spectra of two metal-weak template stars chosen for comparison with NGC 1835 are shown in Figures 6*a* and 6*b*. These two stars have very different distributions of line strengths (see Figs. 5*a* and 5*b*) and illustrate the problems associated with using template stars of different temperatures and metallicities to measure small velocity dispersions. Comparing Figures 6*a* and 6*b*, we see that two regions of the power spectrum are relatively unaffected by the difference in line strengths: these regions have frequencies from 0.35 to 0.57 cycles $Å^{-1}$ and from 0.8 to 1.2 cycles $Å^{-1}$. On the other hand, the low frequency end (frequency <0.35 cycles $Å^{-1}$), which comes primarily from line spacings and from widths of the strongest lines (e.g., Mg I), varies from template to template, and is of no use in determining cluster velocity dispersions. Similarly, the size of the hump between 0.57 and 0.8 cycles $Å^{-1}$ depends on the number of lines of intermediate strength, and also varies from one template to another. We will use the two unaffected regions (0.35–0.57, 0.8–1.2 cycles $Å^{-1}$), which come from the widths of the majority of lines, to measure the cluster dispersions; the mismatch of power spectra at the low frequency end and in the hump does not affect our results (see Figs. 7, 8*a*, and 8*b*).

The power spectra are noise subtracted: the effect of this is small due to the large number (~ 1800) of counts per pixel in the original spectra of both the template stars and the clusters.

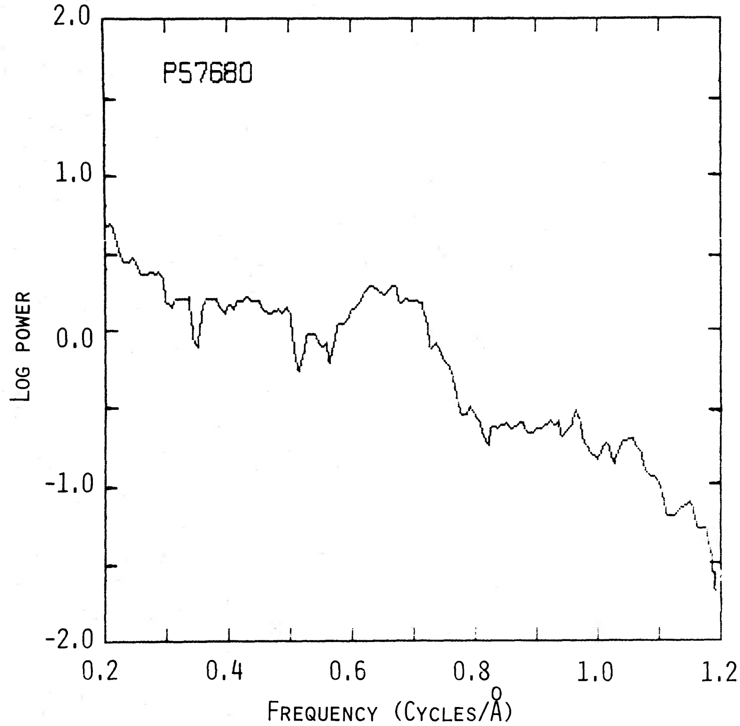

Fig. 6*a*

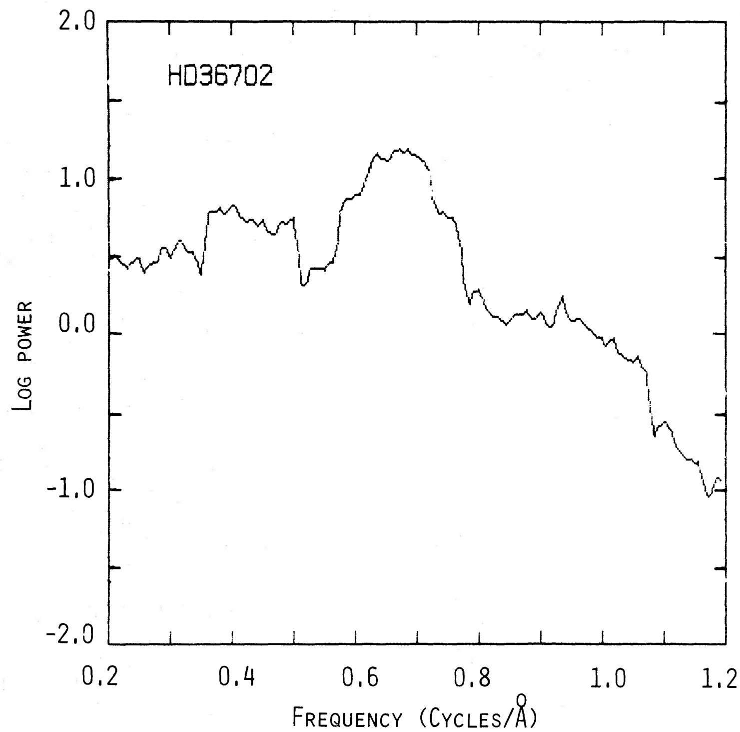

Fig. 6*b*

Fig. 6.—Power spectra of two template stars: (*a*) P57680 and (*b*) HD 36702. Note the difference at the low-frequency end and in the hump, corresponding to differences in the direct spectra, as explained in the text.

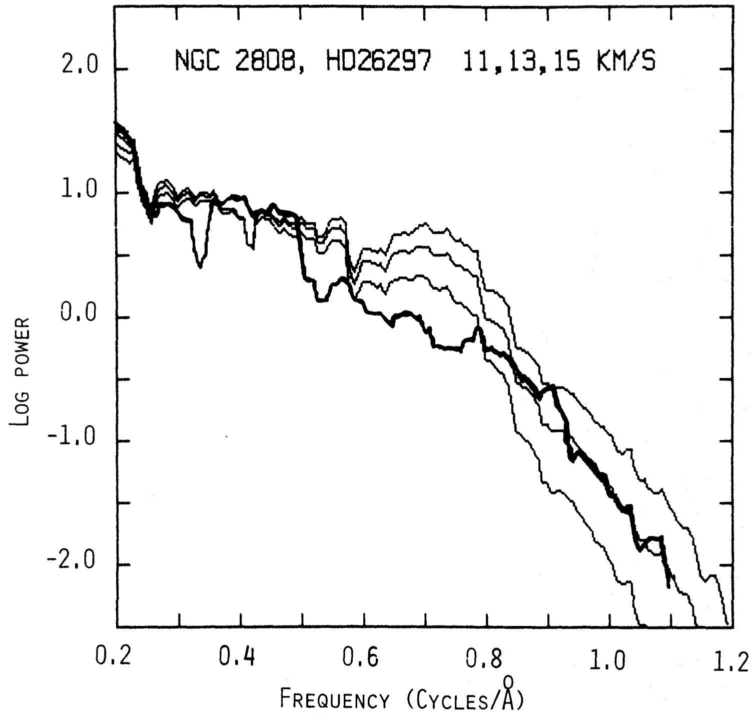

FIG. 7.—Power spectrum of NGC 2808 superposed on that of HD 26297, convolved with Gaussians whose widths correspond to velocity dispersions of 11, 13, and 15 km s^{-1}. The match is confined to the two regions of the power spectra as explained in the text.

i) *NGC 2808*

In Figure 7 the power spectrum of NGC 2808 is shown superposed on that of HD 26297. The velocity dispersion for NGC 2808 thus determined is 13 km s^{-1}, which is in excellent agreement with Illingworth's (1976) value of 14 km s^{-1}.

ii) *NGC 1835*

In Figures 8*a* and 8*b* the power spectrum of NGC 1835 is shown superposed on those of two template stars, P57680 and HD 36702. The stellar spectra have been convolved with Gaussians whose widths correspond to velocity dispersions of 2, 5, and 8 km s^{-1}. The best fitting velocity dispersion is 5 km s^{-1} in both cases, with an estimated standard error of 0.5 km s^{-1}.

The velocity dispersion is converted into a mass according to (Illingworth 1973)

$$M = 167 r_c \mu v^2 , \qquad (2)$$

where r_c is the core radius derived in § II, $\mu(=24.1)$ is taken from Table II of King (1966), and v is the line-of-sight velocity dispersion. The result is $M = 1.61 \pm 0.16 \times 10^5$. This agrees to within a factor of 2 with the value obtained in § II using the cluster's tidal radius, confirming that tidal radii measurements can supply fairly accurate mass estimates, even for distant clusters in crowded star fields. With the luminosity derived in § II, the dynamical mass yields a mass-to-light ratio of 0.42 ± 0.08.

IV. DISCUSSION

For the three old clusters studied here, the M/L values (0.12–0.59) are about 2–5 times smaller than those found by Illingworth for Milky Way globulars. We note that the tidal masses, particularly for the outer clusters NGC 2210 and NGC 2257, may be underestimated by up to a factor of 4 for NGC 2210, and 18 for NGC 2257, if these clusters are in radial rather than circular orbits. It seems likely however that the orbits of even the oldest LMC clusters are not far from circular (FIO).

Furthermore, the colors of NGC 1835 and NGC 2210 suggest that they are somewhat younger than Milky Way globulars: about 9×10^9 years old (R. A. W. Elson and S. M. Fall, in preparation). Our *UBV* colors for NGC 2257 imply an age of about 1.7×10^{10} years, which is comparable to ages of Milky Way globulars. Since the mass-to-light ratio of a cluster increases as the cluster ages, NGC 1835 and NGC 2210 should have mass-to-light ratios somewhat smaller than those of Milky Way globulars and NGC 2257. Models (cf. Struck-Marcel and Tinsley 1978) predict a difference of a factor of 2 between clusters 10^{10} and 2×10^{10} years old. (Note that these models are for solar abundance populations; the difference could be exaggerated for low-metallicity clusters.) On these grounds, it is not unreasonable to expect NGC 1835 and NGC 2210 to have values of M/L 2–4 times smaller than those of galactic globulars and NGC 2257.

We conclude that (i) the mass-to-light ratio of the older cluster, NGC 2257, is consistent with those of Milky Way globulars, given the uncertainty in its tidal mass; (ii) even after including the uncertainty in the tidal masses, the M/L values for the two somewhat younger clusters, NGC 1835 and NGC 2210, are about a factor of 2 smaller than those of Milky Way globulars. We suggest that this is probably the result of the difference in age.

We note that the old LMC cluster Hodge 11 has a measured tidal mass-to-light ratio of 0.28 ± 0.05 (a preliminary value of 0.2 was given by Freeman and Gascoigne 1977). This M/L value could be underestimated by up to a factor of 5 if the

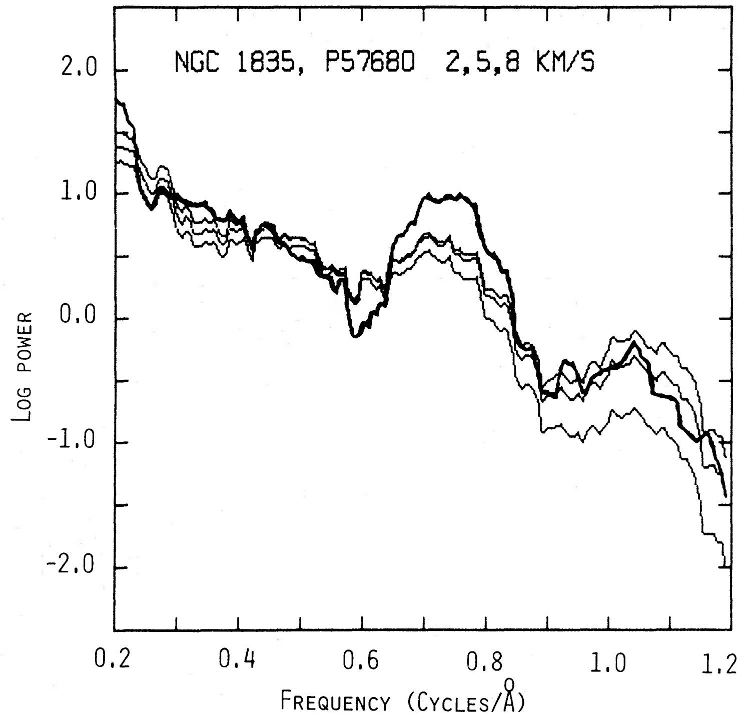

FIG. 8a

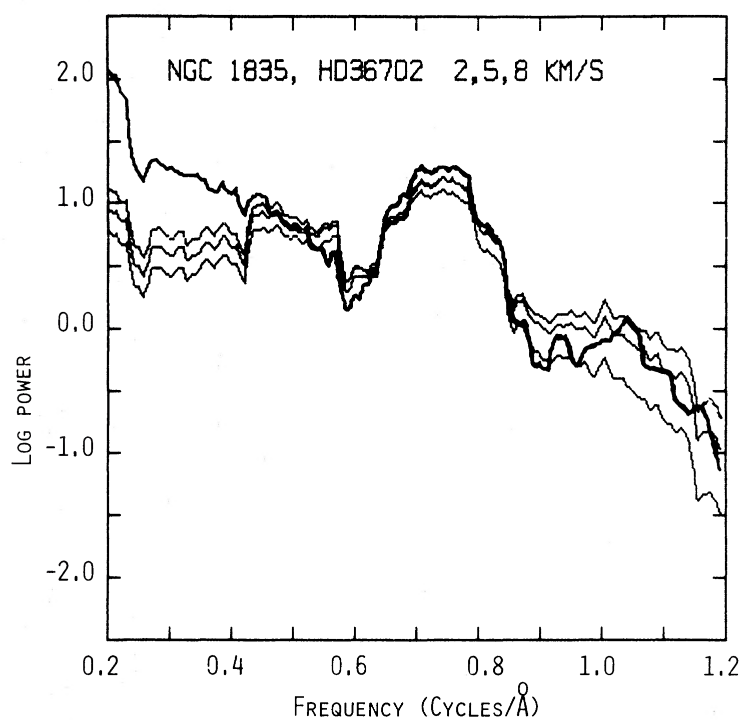

FIG. 8*b*

FIG. 8.—Power spectrum of NGC 1835 superposed on power spectra of two template stars convolved with Gaussians whose widths correspond to velocity dispersions of 2, 5, and 8 km s^{-1}: (*a*) P57680 and (*b*) HD 36702. The match is confined to the two regions of the power spectra as explained in the text.

cluster's orbit is radial rather than circular. From Freeman and Gascoigne's *UBV* colors, the age of the cluster is comparable to that of the Milky Way globulars. Given the uncertainties in the tidal M/L values, this cluster neither supports nor contradicts our above conclusions.

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