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CORE EXPANSION IN YOUNG STAR CLUSTERS IN THE LARGE MAGELLANIC CLOUD

REBECCA A. W. ELSON
Harvard-Smithsonian Center for Astrophysics; Bunting Institute, Radcliffe College; and Institute for Advanced Study
KENNETH C. FREEMAN
Mount Stromlo Observatory
AND
TOD R. LAUER
Princeton University Observatory
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ABSTRACT

We have measured the core radii of 18 rich star clusters in the Large Magellanic Cloud (LMC) with ages 10^7–10^9 yr. Data for an additional 17 clusters with ages 10^6–10^{10} yr are available in the literature. The combined sample shows that the core radii increase from ~ 0 to ~ 5 pc between $\sim 10^6$ and 10^9 yr, and then begin to decrease again. The expansion of the cores is probably driven by mass loss from evolving stars. Models of cluster evolution show that the rate of increase in core radius is sensitive to the slope of the initial mass function. The observed core radius–age relation for the LMC clusters favors an initial mass function with slope slightly flatter than the Salpeter value.

Subject headings: clusters: dynamics — clusters: globular — galaxies: Magellanic Clouds

I. INTRODUCTION

In the past few years much effort has been expended investigating the later stages of globular cluster evolution, and in particular the phenomenon of core collapse (see Elson, Hut, and Inagaki 1987 for a review). However, the processes through which a core is initially established in a cluster, and the evolution of that core prior to gravitational collapse, remain largely unexplored. We have obtained CCD images of 18 of the richest clusters in the Large Magellanic Cloud (LMC), with ages $\sim 10^7$–10^9 yr, to provide a sequence of "snapshots" to investigate the evolution of the inner parts of these globular-like clusters. A brief synopsis of our data and results is presented here. Full details are in Elson (1989).

II. OBSERVATIONS

The objects in our sample, listed in Table 1, are representative of the richest LMC clusters with ages $\sim 10^7$–10^9 yr. CCD images of each cluster in the B and V passbands were obtained on 1988 January 12–14, using the 1 m telescope at Siding Spring Observatory, and the MSSSO coated GEC chip no. 2. At f/8 the image scale was 0″.56 pixel^{-1}. Integration times were short to avoid saturation (200 s in V and 400 s in B), and this gave limiting magnitudes of $B \approx V \approx 18$. Data were reduced with VISTA (Lauer, Stover, and Turndrup 1983) and FIGARO.

Surface brightness profiles were derived for each cluster from the B and V images, using standard methods for determining cluster centers and for estimating surface brightness within concentric annuli (Djorgovski 1987; Newell and O'Neil 1978). There was no significant difference between the V and B profiles, and only the V profiles are discussed here. The profiles of young clusters populated with massive stars are noisy. To reduce the errors in the estimated core radii, the bright stars in each frame (typically with $V \leq 16.5$) were subtracted by fitting point-spread functions, and a profile was rederived from the "cleaned" image. Examples of original and cleaned profiles are shown in Figure 1. Even in the cluster centers there was no difficulty in identifying the bright stars. Removing them reduced the errors in the core radii by 40% on average, typically without altering the derived values of the core radii by more than 5%.

Finally, a value of the background density, determined from each cluster frame as far as possible from the cluster, was subtracted from each profile. In the case of some extended clusters, these backgrounds may be contaminated with a few cluster stars; however, core radii derived before and after background subtraction did not differ significantly.

III. RESULTS

Models of the form

$$\mu(r) = \mu_0(1 + r^2/a^2)^{-\gamma/2} , \qquad (1)$$

chosen for mathematical convenience, were fitted to the profiles using a least-squares procedure. The models of King (1962) reduce to equation (1) at small radii, and the parameter a is related to the core radius r_c of the equivalent King model by

$$r_c = a(2^{2/\gamma} - 1)^{1/2} . \qquad (2)$$

Equation (1) provides an excellent fit to the profiles of the older clusters in our sample, while some of the younger clusters have a slightly sharper "shoulder" at the core radius. (Note that the models are fitted only in the inner regions of the clusters where tidal effects are negligible.) Values of r_c for each cluster, derived from the cleaned V frames, are listed in Table 1.

Since some of the clusters in our sample have small cores, seeing effects should be considered in determining the true core radii. Schweizer (1981) examines the effect of seeing on fitting King models to the profiles of elliptical galaxies, and his Table II gives values of true and apparent core radius for models with concentrations ($= \log r_t/r_c$) of 2.25 and 2.75, and both Gaussian and modified Gaussian seeing disks. We corrected our "apparent" core radii using the Gaussian FWHM of the seeing disk measured in each frame (listed in Table 1), and

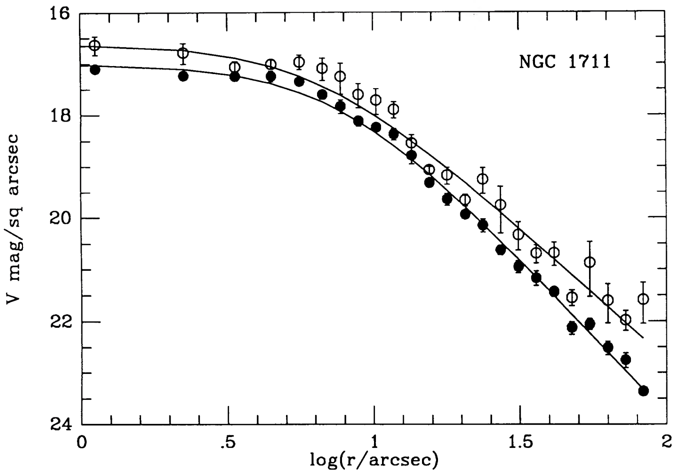

FIG. 1.—Surface brightness profiles in V for NGC 1711. The open circles are derived from an image where no background has been subtracted and no bright stars have been removed. The filled circles are from the same data after removing the bright stars from the frame and subtracting a background from the profile. The solid curves are models from eq. (1), with $r_c = 6.3 \pm 1.0$ (*filled circles*) and 6.7 ± 0.5 (*open circles*).

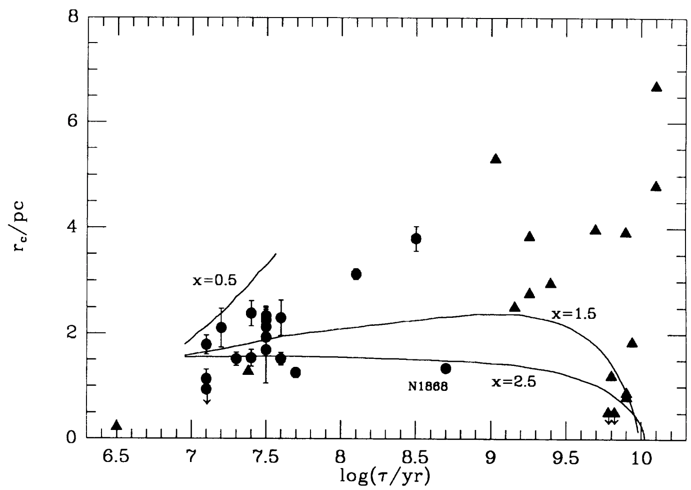

FIG. 2.—Core radius vs. age for the clusters in Table 1 (*circles*; r_c from col. [5]), and Table 2 (*triangles*). Solid curves are from Fokker-Planck models of clusters with power-law IMFs with the slopes indicated (the Salpeter IMF has $x = 1.35$).

Schweizer's models with concentration 2.25 and a Gaussian seeing disk with FWHM = 1".77. Since the values of these parameters are not necessarily identical to those for our clusters, corrections are only approximate. In general, clusters with $2r_c$/FWHM ≥ 3 have resolved cores, and corrections for seeing are small. For our sample, the true core radii (listed in Table 1) are typically 10%–20% smaller than the apparent core radii. Only one cluster, NGC 2002, has an unresolved core.

Color-magnitude diagrams were derived for each cluster from the B and V frames, using E region standards (Graham 1982) to calibrate the photometry. Ages for the clusters were then estimated from the main-sequence turnoffs using isochrones constructed from the stellar evolution models of Becker (1981) and Brunish and Truran (1982) for stars with $3 \leq m/M_{\odot} \leq 15$. These ages are listed in Table 1.

Figure 2 shows core radius plotted against age for the clusters in Table 1, and for 17 additional clusters with published core radii, listed in Table 2. The cores show a general increase

TABLE 1

CORE RADII FROM THIS WORK

Name (1)	log τ (yr) (2)	r_c (3)	FWHM (4)	r_c (pc) (5)
N1711.........	7.3	6".7 ± 0".5	2".2	1.5 ± 0.1
N1755.........	7.4	7.1 ± 0.6	3.2	1.5 ± 0.2
N1818.........	7.2	9.4 ± 1.4	3.5	2.1 ± 0.4
N1831.........	8.5	15.7 ± 0.9	3.3	3.8 ± 0.2
N1850.........	7.5	10.2 ± 0.7	3.1	2.3 ± 0.2
N1855.........	7.4	10.7 ± 0.9	4.1	2.4 ± 0.2
N1866.........	8.1	13.6 ± 0.4	4.4	3.1 ± 0.1
N1868.........	8.7	6.0 ± 0.3	2.0	1.4 ± 0.1
N1872.........	7.7	5.6 ± 0.4	2.0	1.3 ± 0.1
N2002.........	7.1	≤3.5	3.9	≤0.9
N2004.........	7.1	5.6 ± 0.7	3.7	1.1 ± 0.2
N2100.........	7.1	8.2 ± 0.7	3.9	1.8 ± 0.2
N2156.........	7.5	7.1 ± 2.4	1.8	1.7 ± 0.6
N2157.........	7.6	9.6 ± 1.3	2.2	2.3 ± 0.3
N2159.........	7.5	8.1 ± 1.0	2.0	1.9 ± 0.3
N2164.........	7.6	7.4 ± 0.4	4.6	1.5 ± 0.1
N2172.........	7.5	10.0 ± 1.4	5.3	2.1 ± 0.4
N2214.........	7.5	10.5 ± 0.7	5.3	2.3 ± 0.2

Col. (1).—NGC number.

Col. (2).—Age from color-magnitude diagrams derived from same data as the cluster profiles. Typical uncertainties are $\Delta \log \tau \approx \pm 0.1$.

Col. (3).—Core radius in arcsec from cleaned V frame. Uncertainties are the formal errors from fitting eq. (1).

Col. (4).—FWHM of Gaussian seeing disk in arcsec.

Col. (5).—Core radius in pc. Values are from col. (3) and are corrected for seeing as described in the text. Conversions from arcsec to pc assume a distance to the LMC of 55 kpc.

TABLE 2

PUBLISHED CORE RADII

Name (1)	log τ (yr) (2)	r_c(pc) (3)	R_g(kpc) (4)
N1466	(9.9)	2.9	8.8
N1718	9.3	2.8	3.5
N1754	(9.8)	1.2	2.8
N1786	(9.9)	0.8	2.6
N1835	(9.9)	0.9	1.5
N1847	7.4	1.3[a]	1.3
N1852	(9.7)	4.0	1.8
N1978	9.4	3.0	3.1
N2005	(9.8)	≤0.5	0.7
N2019	(9.8)	≤0.5	1.3
N2155	9.3	3.8	5.5
N2209	9.0	5.3[b]	5.5
N2210	9.9	1.8	4.8
N2257	10.1	6.7	9.0
H11	10.1	4.8	5.0
H14	9.2	2.5	...
30 Dor	6.5[c]	0.2[d]	1.6

Col. (1).—Cluster name.

Col. (2).—Cluster age, from Elson and Fall 1988; values in parentheses are derived from s values from Elson and Fall 1985 with the age calibration from Elson and Fall 1988, except as noted.

Col. (3).—Core radius in pc. Values are from Mateo 1987, except as noted.

Col. (4).—Galactocentric distance in the plane of the LMC, in kpc from Elson 1986. All conversions from arcsec to pc assume a distance to the LMC of 55 kpc.

[a] Value from Nelson and Hodge 1983.

[b] Value from K. C. Freeman, unpublished.

[c] Value from Braunswurth and Feitzinger 1983.

[d] Value from Moffat, Seggewiss, and Shara 1985.

in radius up to $\sim 10^9$ yr, after which they begin to decrease again. A likely explanation for the increase is that the cores of the younger clusters are expanding due to mass loss from stellar evolution. The solid curves in Figure 2 are from Fokker-Planck models kindly provided by Martin Weinberg (see Chernoff and Weinberg 1990). They represent the evolution of a cluster with $W_0 = 7$, $M_{\rm initial} = 6 \times 10^4\ M_\odot$ (typical of the masses determined by Elson, Fall, and Freeman 1987), at a distance of 3 kpc from the center of the LMC (the mean distance of the clusters in Table 1). Models calculated for clusters with three different power-law IMFs are shown ($\Phi \propto m^{-(1+x)}$, where $x = 0.5$, 1.5, and 2.5). (The models with $x = 0.5$ disrupt after $\sim 4 \times 10^7$ yr.) The data for the LMC clusters appear to favor an IMF with $x \approx 1.0$; however, the scatter is consistent with cluster-to-cluster variations in IMF slope. For example, the core radius and age of NGC 1868 are consistent with an IMF for this cluster with $x \approx 2.5$.

Mechanisms other than stellar evolution that could produce expansion in a cluster, for example the formation of binary stars or a central back hole, are often discussed in the context of post–core collapse evolution. These mechanisms are not likely to be relevant here: core collapse occurs on a time scale greater than the two-body relaxation time, and the clusters in Table 1 are all younger than their relaxation times, which are typically $\sim 10^9$ yr (Elson, Fall, and Freeman 1987). Finally, the trend of core radius with age in Figure 2 is unlikely to arise from correlations between core radius and cluster mass, and cluster mass and age (e.g., if more massive clusters with larger cores formed in the past). There is no correlation between core radius and mass nor mass and age for ten of the clusters in the present sample.

The decrease in core radius at ages greater than 10^9 yr may indicate the onset of core collapse. Clusters at large galactocentric distances are expected to collapse later than those at smaller galactocentric distances (Chernoff and Djorgovski 1989). Of the six clusters with $r_c \geq 4$ pc, five are further than 5 kpc from the center of the LMC, while of the remaining eight clusters, with $r_c \leq 3$ pc, all but one are closer than 4 kpc to the center. It would be interesting to see whether models of clusters at larger galactocentric distances are consistent with the data in Figure 2.

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Rebecca A. W. Elson: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

Kenneth C. Freeman: Mount Stromlo Observatory, Private Bag, Woden P.O., A.C.T. 2606, Australia

Tod R. Lauer: Princeton University Observatory, Peyton Hall, Princeton, NJ 08540