RevMexAA (Serie de Conferencias), **8**, 93–98 (1999)

YOUNG STAR CLUSTERS OF OUR GALAXY AND THE LARGE MAGELLANIC CLOUD AS TEST FOR STELLAR EVOLUTIONARY MODELS

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RESUMEN

Se comparan diagramas color-magnitud y de la función de luminosidad derivados de observaciones CCD precisas, para la secuencia principal de cinco cúmulos galácticos jóvenes y cuatro cúmulos jóvenes de la Nube Mayor de Magallanes, con diagramas sintetizados a partir de modelos recientes de evolución estelar. Se han identificado algunas brechas en la parte brillante de la secuencia principal de los cúmulos. La comparación entre los diagramas CM sintetizados y los observados indica que los modelos que consideran sobreimpulso deberían ser preferidos a los clásicos. Las funciones de luminosidad integrada sintetizadas de los modelos pueden ser ajustadas a la observada variando la pendiente de la función de masa y la fracción de binarias. Los modelos de sobreimpulso estiman, para estos cúmulos, edades mayores y puntos de quiebre en masas levemente mayores que los derivados a partir de los modelos clásicos.

ABSTRACT

A comparison of the colour-magnitude diagrams (CMDs) and the main sequence luminosity function (LF) of five young galactic star clusters and four young Large Magellanic Cloud star clusters derived from the precise CCD observations has been made with the synthetic ones derived from the recent theoretical stellar evolutionary models. Some gaps in the brighter part of the cluster main sequence have been identified. A comparison of the synthetic CMDs with the observed ones indicates that the overshoot models should be preferred over classical ones. The synthetic integrated LFs from the models can be matched with the observed ones by varying the value of mass function slope and binary fraction. In comparison to classical models, overshoot models estimate older ages but slightly heavier turn-off mass for the clusters.

Key words: **MAGELLANIC CLOUDS: GALAXIES — STAR CLUSTERS: HR DIAGRAM — STARS: EVOLUTION — STARS: LUMINOSITY FUNCTION**

1. INTRODUCTION

Colour magnitude diagrams (CMDs) of young (age less than a few hundred Myrs) star clusters are very good testing ground for stellar evolutionary models (SEMs) in order to discriminate among the possible scenarios of high-mass to intermediate-mass stars. A detailed comparison of SEMs with the narrow and well defined stellar sequences in the CMDs of the young star clusters of our Galaxy and the Magellanic Clouds (MCs) could not be done till recently, because most of the earlier CMDs (cf. Sagar & Pandey 1989) are based either on photoelectric or photographic photometry which are less accurate and limited to brighter magnitudes. The CMDs thus obtained terminate at relatively large brightness levels and hence the evolutionary features may not be brought out properly.

The present study aims to compare the CMDs of young star clusters of our Galaxy and of the Large Magellanic Cloud (LMC) with the modern stellar evolutionary models, and to identify the input physical mechanisms responsible for the observed features in the cluster CMDs. The richness of the cluster is important as we need the stars that populate it to be at various evolutionary stages. In order to identify the observational features sensitive to the core overshooting in the CMDs of star clusters, turn-off masses of stars should lie in the mass range, $1.5 - 15\ M_{\odot}$. The effects of core overshooting are difficult to identify in stars with mass less than $1.5\ M_{\odot}$, due to their very small cores, and in stars with mass above $15\ M_{\odot}$ because they loose mass in the main-sequence (MS) itself, making difficult a direct comparison between the observation and theory. Very young clusters (age $\leq 10^7$ yr) have problems of low-mass stars still in the pre-MS phase and the presence of differential reddening across the cluster. The old clusters (age $\geq 10^9$ yr) have dynamical relaxation times smaller than their ages and hence they would have lost significant number of low-mass stars due to relaxation. The intermediate age ($\sim 10^8$ yr) clusters would not have relaxed dynamically and are not generally seen to have differential reddening. In this work, we include clusters from our Galaxy, namely NGC 1907, NGC 1912, NGC 2383, NGC 2384; and from the LMC, namely NGC 6709 and NGC 1711, NGC 2004, NGC 2164, and NGC 2214. Since clusters in the LMC are rich, they populate almost all the evolutionary phases and also occupy regions of the age and metallicity domain which are not populated in our Galaxy. They therefore, extend the range of comparison between SEMs and observational data. Furthermore, their study is mandatory for understanding of star clusters in external galaxies where only integrated properties can be observed.

The observational data used in the present analysis are described in the next section. The results of comparison between the observations and theory and conclusions follow.

2. OBSERVATIONAL DATA

The data for the LMC star clusters NGC 1711, NGC 2004, NGC 2164, and NGC 2214 are taken from Sagar, Richtler, & de Boer (1991). The observations were obtained at the f/8.5 Cassegrain focus of the 1.54-m Danish telescope at the European Southern Observatory, La Silla, Chile using a RCA CCD chip of 320 × 512 pixels in size where one pixel corresponds to 0.″47. Other details of observations and data reductions are given in Sagar et al. (1991).

The galactic clusters NGC 1907, NGC 1912, NGC 2383, NGC 2384, and NGC 6709 have been observed with the 1.02-m and 2.34-m telescopes at the Vainu Bappu Observatory, located in Kavalur (India). At the Cassegrain focus (f/13) of the 1.02-m Carl-Ziess reflector, a CSF TH 7882 CCD chip, with a size of 384 × 576 pixels covering 137″ × 206″ of the sky was used. At the prime focus (f/3.23) of the 2.34-m Vainu Bappu Telescope, a GEC P8602 CCD chip with a size of 385 × 578 pixels and a sky coverage of 4.′0 × 6.′1, and a TH 1024AB2 CCD chip of size 1024 × 1024 pixels and 10.′75 × 10.′75 sky coverage were used. Further details of observations and data reductions are given elsewhere (Subramaniam & Sagar 1999).

3. SYNTHETIC COLOUR MAGNITUDE DIAGRAMS AND STELLAR EVOLUTIONARY MODELS

The idea is to generate a CMD having the same age and chemical composition as the observed clusters, with the help of the theoretical stellar evolutionary tracks of various masses. The computer code developed for this purpose, produces stars along the isochrone according to the time-scales predicted by the models. We know that the observed cluster CMDs show some scatter around the actual evolutionary path, and as the synthetic CMD as well as the luminosity function (LF) is used to compare with the observed ones, the factors which produce scatter in the MS as well as in the evolved region of the cluster CMDs have to be incorporated. The two main factors considered here are the binary stars in the cluster and the observational photometric errors. The presence of binaries in a cluster produces a widening of the MS, some scatter near the turn-off and in all later evolutionary stages. The attempts to find the percentage of spectroscopic binary stars in open clusters indicate that it varies between 30 – 50% (Mermilliod & Mayor 1989; Crampton, Hill, & Fisher 1976). Therefore, we assume around 30% binaries for computing the synthetic CMD. The effect of binarity in the CMD is maximum when the ratio of their masses is close to one and therefore, the mass ratio is chosen in the range of 0.75 – 1.25. The details of the algorithm can be seen in Subramaniam & Sagar (1995).

In this analysis, we use three stellar evolutionary models consisting of one classical and two overshoot models. The classical model used here is by Castellani, Chieffi, & Straniero (1990) and is referred to as model 1. It covers a mass range of 0.8 to 20 $M_{\odot}$. The model given by Schaller et al. (1992) is our model 2, covering a mass range from 0.8 $M_{\odot}$ to 120 $M_{\odot}$. Bressan et al. (1993) presented evolutionary models in the mass range from 0.6 to 120 $M_{\odot}$ and this is our model 3. Models 2 and 3 incorporate the effects due to overshooting of the convective core. The Z value considered is 0.02 for all models.

4. OBSERVED COLOUR MAGNITUDE DIAGRAMS AND GAPS ON THE MAIN SEQUENCE

The CMDs of the five galactic and four LMC star clusters analysed here are presented in Subramaniam & Sagar (1999) and Sagar et al. (1991), respectively. These papers also describe the procedures used to correct for data incompleteness and field star contamination before comparing the observed CMDs with the SEMs. Some gaps on the MS of the observed CMDs have been noticed (see Subramaniam & Sagar 1999). A gap on the MS is loosely defined as a band, not necessarily perpendicular to the MS, with no or very few stars. Böhm-Vitense & Canterna (1974) first located a gap on the MS around $(B-V)_0 = 0.27$, due to the onset of convection in the envelope of the star. Sagar & Joshi (1978) have analysed the gaps present just below the turn-off point. The gaps found in open clusters are also listed by Kjeldsen & Frandsen (1991) and some of these gaps have physical explanations.

There are no gaps on the observed MS of the LMC star clusters. However, gaps are noticed in the observed MS of three of the five galactic star clusters here considered. The details of these gaps are given in Table 1. The probability for these gaps to be accidental is estimated using the method adopted by Hawarden (1971) and the probability values obtained are also tabulated. All the gaps listed in the table have very low probability to be accidental and hence are expected to be real gaps. The cluster MS of NGC 1912 is seen to be clumpy with many gaps and the prominent one is listed in the Table 1, which lies just below the MS turn-off point and seems similar to the gaps discussed by Sagar & Joshi (1978). Another gap in the MS of this cluster is located near $M_V \sim 1.5$. It is similar to the A-bend and A3-group found by Kjeldsen & Frandsen (1991). Two gaps are noticed in NGC 2383, the first of which may be like the Mermilliod gap (Mermilliod 1976), but with $(B-V)_0$ values differing by 0.1 mag. The first gap seen in the case of NGC 6709 is similar to the A-group and the second one is similar to the M11-gap (Kjeldsen & Frandsen 1991). The gap found in NGC 1912 and the second gap in NGC 2383 are not similar to any of the gaps mentioned in Kjeldsen & Frandsen (1991).

TABLE 1

THE DETAILS OF THE GAPS NOTICED IN THE MAIN-SEQUENCE OF THE GALACTIC STAR CLUSTERS

Cluster	M_V (mag)	$(B-V)_0$ (mag)	Width in M_V (mag)	Width in $(B-V)_0$ (mag)	Probability (%)
NGC 1912	−0.90	0.00	0.10	0.10	9
NGC 2383	−0.10	0.00	0.15	0.05	12
	0.35	0.05	0.05	0.05	8
NGC 6709	1.15	0.00	0.15	0.05	2
	1.50	0.10	0.10	0.10	4

4.1. Age Determination

The age of the clusters is determined by comparing the cluster sequence with the isochrones from the models. The isochrones corresponding to the model 3 are taken from Bertelli et al. (1994). The isochrones for the models 1 and 2 are computed and converted from the $\log(L/L_\odot)$ vs $\log(T_{\rm eff})$ plane to the M_V, $(B-V)_0$ plane. The details of the comparison and fitting of the isochrones to the cluster sequence are given by Subramaniam & Sagar (1999) for the galactic star clusters, and by Subramaniam & Sagar (1995) for the LMC star clusters. The ages of the clusters as found from the three models are tabulated in Table 2. Except for NGC 2384, all the other four galactic clusters are of intermediate age while all LMC star clusters are younger than ~ 100 Myr. The classical model finds younger age for the clusters compared to the overshoot models. In clusters older than 40 Myr, models 2 and 3 find the same age while for the younger clusters, model 3 finds older age compared to model 2.

TABLE 2

AGE AND TURN-OFF MASS OF THE STAR CLUSTERS DETERMINED FROM THE MODELS

	Ages in Myr from models			Turn-off masses in solar mass from models		
Cluster	1	2	3	1	2	3
Galactic						
NGC 1907	280	400	400	...	...	...
NGC 1912	160	250	250	3.9	3.4	3.5
NGC 2383	280	400	400	3.2	2.8	2.9
NGC 2384	13	16	20	14.3	11.6	11.3
NGC 6709	220	320	320	3.4	3.0	3.2
LMC						
NGC 1711	22	28	35	9.7	8.3	8.3
NGC 2004	12	14	18	14.3	12.3	11.4
NGC 2164	35	50	60	7.5	6.4	6.4
NGC 2214	37	50	60	7.3	6.4	6.4

5. COMPARISON OF OBSERVED COLOUR MAGNITUDE DIAGRAMS WITH SYNTHETIC ONES

In order to compare the theoretical stellar evolutionary models with present observations, we produced synthetic CMDs from the SEMs discussed above. The number of stars in the brighter part of the cluster sequence is used to fix the proportionality constant in the mass function. The computer code used to construct synthetic CMDs using SEMs is described in Subramaniam & Sagar (1995). A comparison of the observed distribution of stars in the CMD of a star cluster with that of synthetic CMD produced from different SEMs tells us about the reliability of the physical assumptions involved in theoretical calculations. To do this we compare the features as well as the integrated luminosity function (ILF) of the observed CMDs with the synthetic ones.

5.1. Comparison of Features

A comparison between the observed and the synthetic CMDs will help in identifying the model which produces an evolutionary track which is the closest to the observed one. Here, we compare the features of the synthetic CMDs with the observed ones specially in the evolved part of the cluster sequences. The synthetic CMDs for the clusters which best match the observations are shown in Subramaniam & Sagar (1995) for the LMC star clusters and in Subramaniam & Sagar (1999) for the galactic star clusters. In general, the evolved parts of the CMDs of the galactic star clusters are better reproduced by models 2 and 3, which include the effects due to core overshooting. In the case of LMC star clusters, evolved parts of the CMD are more closely reproduced with model 3. It is interesting to note that even though the amount of convective core overshooting is the same in models 2 and 3, the number of blue supergiants and the evolved parts of the CMDs of the LMC are better matched with model 3. This may be due to the differing input physics and computational techniques involved in the two models. In all the galactic clusters and one LMC star cluster (NGC 2004), the brighter end of the MS is not populated up to the observed value by any of the synthetic CMDs. In order to populate them, one has to consider somewhat younger ages for the clusters. This may indicate that if these stars are in the normal phase of evolution then they are younger than the bulk of the stars in the cluster. Another possibility is that they are not in the normal stellar evolutionary phase and they may be contact binaries and/or blue stragglers.

5.2. Comparison of ILFs

Chiosi et al. (1989) show that the ILF of MS stars normalized to the number of evolved stars can be used to differentiate among different evolutionary scenarios, since it is just the ratio of core H to He burning lifetimes which is very much affected by the mixing scheme used. Here we compare the observed ILFs of MS, normalised to the number of evolved stars with those estimated from the synthetic CMDs. This is not attempted in the case of the galactic star cluster NGC 1907, because estimates of field star contamination are not available for it.

The synthetic CMDs are constructed for varying values of the MF slope, x, and the ILFs are calculated in each case. The results are listed in Table 3 and discussed in detail by Subramaniam & Sagar (1999) for the four galactic star clusters and by Subramaniam & Sagar (1995) for the LMC star clusters. The values of the percentage of binary stars used are also given in the table. The results given in Table 3 indicate that the synthetic ILFs derived using a proper combination of mass function slope and binary fraction can fit the observed ILFs. Thus it can be seen that the comparison of ILFs does not show a clear view on which model should be preferred.

TABLE 3

BEST FIT PARAMETERS FOR SYNTHETIC ILF'S

	Model 1		Model 2		Model 3	
Cluster	x	BF	x	BF	x	BF
Galactic						
NGC 1912	2.0	30	1.7	30	2.0	30
NGC 2383	1.3	20	1.3	30	1.3	25
NGC 2384	1.0	0	1.0	0	0.8	0
NGC 6709	2.0	20	1.7	45	2.0	35
LMC						
NGC 1711	1.9	30	1.6	30	1.35	30
NGC 2004	1.65	30	1.35	30	1.35	0
NGC 2164	1.35	30	1.35	20	1.05	30
NGC 2214	1.35	30	1.35	20	1.35	5

6. CONCLUSIONS

We have compared the CMDs and LFs derived from good quality CCD data comprising the LMC star clusters NGC 1711, NGC 2004, NGC 2164, and NGC 2214; and the galactic star clusters NGC 1907, NGC 1912, NGC 2383, NGC 2384, and NGC 6709, those having turn-off masses in the range $2.8-15\ M_{\odot}$, with the synthetic CMDs produced using the stellar evolutionary models from Castellani et al. (1990), Schaller et al. (1992), and Bressan et al. (1993). Therefore, this study covers the range of intermediate to high mass stars. The details of the analysis and results have been published elsewhere (Subramaniam & Sagar 1995, 1999). The main results of the present investigation are:

1. Classical models make the clusters younger with turn-off masses slightly heavier in comparison to the models incorporating overshooting of the convective core.

2. In general, the overshoot models reproduce better the observed features than the classical models.

3. The synthetic ILF derived from a model strongly depends on the value of the mass function slope, and slightly on the binary fraction, whereas the observed ILFs are affected by the uncertainty in the number of evolved stars. A comparison of the synthetic with the observed ILFs does not favour any model specifically. In order to constrain the models from the comparison of the synthetic ILFs with the observed ones, reliable estimates of the mass function slope and binary fraction are desired.

Ram Sagar wants to thank the workshop organizers for financial support.

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