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A possible scenario for the formation of the composite Large Magellanic Cloud star cluster NGC 2214

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Abstract. The total masses and relaxation times for the two stellar populations (old and young) in the star cluster NGC 2214 are estimated. The total masses are found to be comparable. While the older population may be dynamically relaxed, the relaxation time for the younger population is found to be much longer than its age. It is suggested that NGC 2214 might have resulted from two episodes of star formation in a complex of molecular clouds in the Large Magellanic Cloud. The first episode of star formation took place in a massive cloud near the centre of the cloud-complex and produced the present older population of NGC 2214. About 60 Myr after the end of star formation in the first episode, star formation in the other smaller clouds surrounding the central core was triggered by supernova explosions in massive stars of the old population giving rise to the more diffusely distributed younger population of NGC 2214.

Key words : star clusters—Large Magellanic Cloud—star formation

1. Introduction

NGC 2214 ($\alpha_{1950} = 06^h13^m11^s$; $\delta_{1950} = -68°14'36''$) is a star cluster situated to the far north-east of the bar of the Large Magellanic Cloud (LMC). The first colour-magnitude diagram (CMD) of the cluster was produced by Robertson (1974) based on BV photographic photometry. Using this CMD, Hodge (1983) assigned an age of 40 Myr to the cluster. Elson *et al.* (1987), from a study of the structural parameters of the cluster based on star counts, found that the system has properties like that of a relaxed cluster, although the two-body relaxation time ($\sim 2 - 6 \times 10^8$ yr) is much larger than its age. Bhatia & MacGillivray (1988) made a detailed study of the spatial distribution of stars in the cluster by using the COSMOS plate-scanning machine and found that the cluster has two prominent clumps. They have argued that it is a binary star-cluster in an advanced stage of merging. Recently Sagar *et al.* (1991a, b) presented the V, $(B - V)$ CCD colour-magnitude diagram of the cluster down to $V \sim 21$ mag and found that the cluster actually consists of two stellar age groups in the form of two distinct supergiant branches. The spatial distributions of the stars belonging to the two age groups are quite different.

In this paper we comment on the apparent discrepancy between the structural parameters of the cluster and its age in the light of the results on the ages and spatial distributions of the two groups of stars in the cluster by Sagar *et al.* (1991b). We estimate the total masses of the two components and their relaxation times. We also argue that the cluster may not be a case of merger as proposed by Bhatia & MacGillivray (1988) and suggest a possible scenario for the formation of this peculiar system. Present work has important implications for understnding the formation and evolution of star clusters because statistical analysis of close pairs of the LMC star clusters indicates that not all the cluster pairs could be accounted for by chance superposition of single clusters (*cf.* Bhatia & Hatzidimitriou 1988). The observed separation between the centroids of the two populations in NGC 2214 is ~ 12 arcsec (Sagar *et al.* 1991b). Following Bhatia & Hatzidimitriou (1988) and using the value of s = 12 arcsec in their equation (1) we find that the expected number of binary clusters, with separation as small as 12 arcsec, due to chance superposition is 0.02. For this calculation the average cluster density in LMC was used. In fact the cluster density in the outer regions of LMC is smaller than the average value and therefore the probability that the binary cluster NGC 2214 is a result of chance alignment of LMC star clusters is even smaller.

2. The two populations

In was found in Sagar *et al.* (1991b) that NGC 2214 consists of two stellar age groups. In the CMD the two age groups appear in the form of two well-defined supergiant branches. Their mean age based on Maeder & Meynet (1991) stellar evolutionary model are ~ 6×10^7 yr and ~ 1.7×10^8 yr respectively. The mean ages are model dependent, being larger in the case of the model by Bertelli *et al.* (1990) and smaller in the case of the model by Castellani *et al.* (1990) (*cf.* Sagar *et al.* (1991b). In further discussions we have used the values of ages derived from the Maeder & Meynet (1991) isochrones. The isochrone fitting to the CMD indicates that the age of the younger population is between 50 to 65 Myr while it is between 120 to 200 Myr for the older population. Use of isochrones given by others will change only relative numbers and not the conclusions of the present work. The older population is more concentrated towards the cluster centre while the younger shows a more extended distribution. Only stars beyond the main-sequence turn-off can be identified to belong to either of the two groups. However, we can estimate the total number and the total mass of stars in the two populations by making use of the initial mass function and the number of stars beyond the main-sequence turn-off.

2.1. Total masses

If the initial mass function is of the form $dN/dM = CM^{-x}$ then the number of stars N in the mass range M_l to M_u is given by

$$N = C \int_{M_1}^{M_u} M^{-x} \, dM \qquad \dots (1)$$

where C is a constant and x is the power index. Using theoretical evolutionary tracks given by Maeder & Meynet (1991) and the V, $(B - V)$ CMD given by Sagar *et al.* (1991a), we have determined the mass range (M_l, M_u) for the evolved cluster stars. We adopt a value of 18.6* mag for the true distance modulus of the LMC (*cf.* Sagar & Richtler 1991). The interstellar extinction in V for the cluster is taken as $3.1 \times E(B - V)$ with $E(B - V) = 0.07$ mag (Cassatella *et al.* 1987). Table 1 lists the values of M_l, M_u and the observed number of evolved cluster members, N_{evol}. For a given value of x and the observed value of N_{evol}, the value of the constant C is easily determined from equation (1) for each population. The total number of stars between any other mass limits (M_a, M_b) can be calculated from equation (1) and the total mass M_T is given by

$$M_T = C \int_{M_a}^{M_b} M^{-x+1}\, dM . \qquad \ldots (2)$$

Table 1. Total mass (M_T) estimates for the two stellar populations. N_{evol} denotes the observed number of cluster stars evolved from the main-sequence in the mass range M_l to M_u of an age group. N_{tot} is the total number of cluster members up to 0.3 solar mass. T_E is the dynamical relaxation time

Population	Radius (pc)	Age (Myr)	M_l ($M_\odot$)	M_u ($M_\odot$)	N_{evol}	N_{tot}	M_T ($10^4 M_\odot$)	T_E (Myr)
Young	24	50 to 65	6.82	7.44	23	14000	1.6	1100
Old	7	120 to 200	4.02	4.16	30	22000	2.6	200

To estimate the total mass we have used 0.3 $M_\odot$ as the lower limit in equation (2), as the mass function for low mass field stars in the solar neighbourhood is found to fall off for masses < $0.3 M_\odot$ (Scalo 1986). The value of x in the mass function for stars in NGC 2214 has been studied by Sagar & Richtler (1991). They divided the cluster in 3 concentric regions, namely: nucleus, Ring 1 and Ring 2. The old population is more or less confined to the nuclear region while Ring 1 and Ring 2 have the younger population stars. Combining the statistics of Ring 1 and Ring 2, we find the mass function slope x for the younger population to be 2.6 ± 0.3, close to the Salpeter value of 2.35. We have no information on the value of x for the older population. Therefore, we use the Salpeter value for both the populations in the following analysis. The values of M_T derived in this way are given in table 1. The uncertainty in the value of M_T depends upon the accuracy of M_l and M_u determination which depends mainly upon the photometric errors in V $(B - V)$ as well as upon the errors in reddening and distance modulus estimates. Except for the photometric error, others will produce systematic error in M_l and M_u. Due to photometric error uncertainties of ~ 50% and ~ 100% are expected in the M_T values of young and old populations respectively. The cause of larger error in the M_T value of the older population is the relatively smaller mass range in the evolved stars. An inaccuracy of $\pm$ 0.3 in x will introduce ~ 20% error in M_T value. Thus, as can be seen in table 1, the total stellar mass in the two populations is of the same order (to within a factor of 2). However, in

* Recent investigators give $18.4 \lesssim (m - M)_0 \lesssim 18.5$ for the LMC, however this small difference should not affect our results.

the old population this mass is concentrated in a compact region near the centre of NGC 2214 while the younger population is distributed over a larger region. The total mass of the cluster including both the populations is $\sim 4.2 \times 10^4 M_\odot$. Considering the uncertainties in the estimate, this is consistent with the upper limit of $4 \times 10^5 M_\odot$ on the mass of NGC 2214 given by Lupton *et al.* (1989), based on an upper limit on the stellar velocity dispersion, which could be an overestimate.

2.2. Relaxation times

The dynamical relaxation time T_E, for the two stellar populations has been estimated using the following equation given by Spitzer & Hart (1971)

$$T_E = 8.9 \times 10^5 (N_{tot} \times R_h^3/<m>)^{1/2}/\log (0.4 \times N_{tot}) \quad \ldots (3)$$

where N_{tot} is the total number of cluster members, R_h is the radius containing half of the cluster mass in parsec and $<m>$ is the average mass of cluster stars in $M_\odot$. The values of total number of cluster stars N_{tot} and average mass $<m>$ have been determined using equations (1) and (2) with 0.3 $M_\odot$ as the lower mass limit. We have assumed that the angular value of R_h is equal to half of the cluster radius listed in column 2 of table 1. Values for the cluster radii in table 1 correspond to their angular radii of 28 arcsec for the older population (Sagar *et al.* 1991b) and 93 arcsec for the younger population (Shapley & Lindsay 1963). The values of T_E obtained in this way for the two stellar populations are given in the last column of table 1.

3. Discussion

By comparing the relaxation times for the two populations with their ages (120 to 200 Myr for the old and 50 to 65 Myr for the young population) we find that the young population is not relaxed while for the old population the relaxation time is of the same order as its age and may be relaxed. The old population thus gives NGC 2214 an appearance like that of a relaxed cluster (Elson *et al.* 1987) while the younger population is far from being relaxed and makes NGC 2214 seem young (Hodge 1983). This may explain the apparent discrepancy between the structural parameters (like that of a relaxed cluster) of NGC 2214 and its age as determined in earlier studies.

Bhatia & MacGillivray (1988) have suggested that NGC 2214 is a binary star-cluster in an advanced stage of merging at an age $\sim 4 \times 10^7$ yr. With the recognition of the existance of two distinct age groups in the cluster that are spatially segregated we think that NGC 2214 is not a case of merger. In the event of a merger one would expect the two populations to be spatially intermixed and therefore stars of the old population should also be found at large radial distances from the centre ($R > 28$ arcsec). This is contrary to the observed distribution of stars in NGC 2214. Sagar *et al.* (1991b) found that the older supergiant branch is seen only in the CMD for stars within $R = 28$ arcsec of the cluster centre. The younger supergiant branch is seen in the CMDs for stars in the inner ($R < 28$ arcsec) as well as outer regions ($R > 28$ arcsec).

What could be the origin of this peculiar cluster? It is clear that the cluster consists of two populations. Bhatia & MacGillivray (1988) noticed that the cluster has an almost spherical halo and a very elliptical core which on short exposure photographs shows a double structure. The two components of the double structure are aligned along the east-west direction, the western component being more compact. The spatial distribution of stars belonging to the two age groups has been studied by Sagar *et al.* (1991b). They found that the centroids of the old and the young population are separated by ~ 12 arcsec in the east-west direction, the older population being the more compact western one. Thus it may be concluded that the more compact old population dominates the central regions of NGC 2214 while the young population has an amorphous structure and dominates the outer spherical halo. The centroid of this younger population is separated by ~ 12 arcsec to the east from the centroid of the compact old population. This separation is much smaller than the spatial extents of the two populations which measure about 55 arcsec (old population) and 185 arcsec (young population) respectively in diameter. The probability that the two populations belong to two unrelated star clusters in the LMC that happen to align close to the line of sight by chance is very small due to the paucity of star clusters in the outer regions of this galaxy (*cf.* section 1). Therefore in the following we assume that the two populations in NGC 2214 are physically related.

It is evident, from the presence of two age groups, that there have been two episodes of star formation in NGC 2214. The first episode of star formation produced the old population (age 200 to 120 Myr). About 60 Myr after the end of star formation in this episode a second episode of star formation gave rise to the younger population (age ~ 65 to 50 Myr). As found above the total number and mass of stars formed in the two episodes is of the same order. However, their spatial distribution is different. We suggest here that NGC 2214 resulted from two major episodes of star formation in a large complex of molecular clouds. Such complexes of clouds (containing a few 10s to ~ 100 clouds) are common in the Galaxy, *e.g.* the cloud complexes in Orion, Taurus and Ophiuchus; and also exist in the LMC, *e.g.* the 30 Dor complex. The first episode of star formation might have taken place in one or a few massive clouds near the centre of the cloud complex with a high star formation efficiency, giving rise to the present old population in NGC 2214. The present younger population which is more diffusely distributed around the old population was then produced in a second episode of star formation in the other clouds of the complex surrounding the one in which the first star formation episode took place. The second star formation episode could have been triggered by a large number of supernova explosions in massive (mass $\geq 6.6\ M_{\odot}$ according to Maeder & Meynet 1989) evolved stars, which could have been formed towards the end of the first star formation episode of the central compact cluster, after about 60 Myr. Using equation (1) and the observed number of evolved stars for the old population, we estimate that ~ 300 stars could have exploded as supernovae. The spatial distribution of the stars in the younger population results from the spatial distribution of the other less massive clouds of the complex which surrounded the central massive cloud. In this model the centroids of the two populations need not coincide because the cloud in which the first star formation episode took place could be a little off centre in the cloud complex. The mass spectrum of clouds in the complexes (see *e.g.* Bhatt *et al.* 1984) is such that most of the mass lies in the largest of the clouds. Therefore even though the number of clouds in the other regions of the complex is large their combined mass may be comparable with that of the single most massive central one. Thus, the total masses of the two populations of stars in NGC 2214 could be comparable as is observed. Also the star formation efficiency in the second episode could be smaller as it takes place in a thinly populated volume, so that the stellar mass produced is comparable even if the cloud mass were a little more.

It is interesting to note that in galactic open clusters also, evidence for the existence of different age subgroups has been recently found by Strobel (1992), the cause of which could be sequential star formation.

4. Conclusions

We have estimated the total masses and relaxation times for the two stellar populations in NGC 2214. The total mass of the young population is comparable with that of the older population. The relaxation time for the younger population is much larger than its age but the relaxation time for the older population is comparable with its age.

It is suggested that NGC 2214 formed from two episodes of star formation in a complex of molecular clouds. The first episode of star formation took place in a massive cloud near the centre of the complex producing the old population. About 60 Myr after the end of star formation in this episode a second episode of star formation in other smaller clouds surrounding the central one was triggered by supernovae in evolved massive stars of the old population and gave rise to the more diffusely distributed younger population of NGC 2214.

In order to verify the above scenario, accurate radial velocity and chemical composition measurements are needed which will throw light on the kinematical properties of the two stellar populations and any possible enrichment of heavy elements in the stars of the younger population that formed in the second episode of star formation triggered by supernovae.

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References

Bertelli G., Betto, R., Bressan A., Chiosi C., Vallenari A., 1990, A & AS, 85, 845.

Bhatia R. K., Hatzidimitriou D., 1988, MNRAS, 230, 215.

Bhatia R. K., MacGillivray, H. T. 1988, A & A, 203, L5.

Bhatt H. C., Rowse, D. P., Williams I. P., 1984, MNRAS, 209, 69.

Cassatella A., Barbero, J., Geyer, E. H. 1987, ApJS, 64, 83.

Castellani V., Chieffi, A., Straniero, O., 1990, ApJS, 74, 463.

Elson R. A. W., Fall, S. M., Freeman, K. C., 1987, ApJ, 323, 201.

Hodge P. W., 1983, ApJ, 264, 470.

Lupton R. A., Fall S. M., Freeman K. C., Elson R. A. W., 1989, ApJ, 347, 201.

Maeder A., Meynet G., 1989, A & A, 210, 155.

Maeder A., Meynet G., 1991, A & AS, 89, 451.

Robertson J. W., 1974, A & SA, 15, 261.

Spitzer L. Jr., Hart M. H., 1971, ApJ, 164, 399.

Sagar R., Richtler T., 1991, A & A, 250, 324.

Sagar R., Richtler T., de Boer K. S., 1991a, A & AS, 90, 387.

Sagar, R., Richtler T., de Boer K. S., 1991b, A & A, 249, L5.

Scalo J. M., 1986, Fundam. Cosmic Phys. 11, 1.

Shapley H., Lindsay E. M., 1963, IAJ, 6, 74.

Strobel A. 1992, A & A, 253, 374.