Forming Globular Cluster Systems in a Semi-analytic Scheme

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Abstract. We apply the semi-analytical galaxy formation code of Cole et al. to investigate the formation of globular cluster (GC) systems in hierarchical clustering scenarios. The nature of the model allows us to investigate the properties of GC systems and their parent galaxies within a cosmological framework, over a wide dynamic range of mass and time resolution. Assuming GCs form during mergers of gaseous systems, the metal-rich peak of the classical ‘bimodal’ metallicity distribution of GCs naturally falls out of our model, where such merging occurs over a wide range of redshifts. The physical origin of old, metal-poor GCs (the metal-poor peak) is harder to understand, since their formation must be decoupled from the ongoing star formation in these systems at high redshift (z ~ 5). Within the context of semi-analytic models in general, a possible solution lies in a cut-off in the GC formation efficiency at a characteristic local star formation rate.

1 Introduction

Globular cluster (GC) systems are generally regarded as ‘probes of galaxy formation’. They inhabit all luminous galaxies in the local Universe, and a number of their properties (e.g. total population, mean metallicity) scale with the mass of their host galaxy. However, the potential for GC systems in revealing insights into the formation of their hosts has been hampered by a lack of understanding of the origin of GCs, and how GC formation relates to galaxy formation in general. A number of models exist in the literature discussing the formation of GC systems and their associated galaxies (or vice versa, from a non-GC researcher viewpoint) through gaseous mergers (Ashman & Zepf 1992; Barnes 1998), singular collapse (e.g Forbes, Brodie & Grillmair 1997) or the dissipationless accretion of satellites (Forte, Martínez & Muzzio 1982; Cote, Marzke & West 1998). Whilst all these models have had important successes in explaining the observables (for example, the Ashman & Zepf model predicted the observed colour bimodality seen in many GC systems), the distinction between the processes of rapid collapse, merging and accretion is likely to be artificial in a Universe where we expect all these mechanisms to occur.

A viable route to following the evolution of galaxies and their GC systems within a cosmological framework is through semi-analytic modelling (e.g. White & Rees 1978). We have applied the fiducial semi-analytic model of Cole et al. (2000) to such a purpose, which is described in Beasley et al. (2002).
1.1 A Synopsis of the Model

'Semi-analytic models' (SAMs) deal with the evolution of both baryonic and non-baryonic matter using a number of analytical formulae and observed scaling relations. The evolution of dark matter is either dealt with using extended Press-Schechter formalism, or direct N-body numerical simulations. Gas, which is assumed to follow the distribution of dark matter, is shock-heated when dark matter haloes merge. Over time, and in the absence of further halo merging, this gas will cool and settle into a disc at the centre of the halo. Star formation is then allowed to proceed in these discs in what is termed a 'quiescent' mode. As dark matter haloes merge, they bring with them their own stellar systems, the most massive of which becomes the central galaxy and the others satellites of the new halo. If the dynamical timescales of these satellites are shorter than the timescale for halo merging, they will merge. If this is a major merger, it will lead to a burst of star formation.

1.2 Metal-rich Globular Clusters

A key aspect of our model are galaxy major mergers, which not only govern the morphology of the final galaxy (e.g. Baugh et al. 1996), but are also responsible for the formation of metal-rich globular clusters (GCs). These clusters are formed during the merger process and are characterized by their high metallicity, which is a result of the accretion of material from the progenitor galaxies. The taxonomy of these objects is ill defined, since they exhibit a range of physical sizes, gas-fractions and stellar populations. In the CDM picture, they may be classified as Searle-Zinn fragments or galaxy building blocks.
for the formation the metal-rich peak of the GC systems. We know that this latter assumption, one which was made by Ashman & Zepf (1992), is at least partially correct. Young, massive clusters have been identified in many nearby merging/interacting systems (e.g. Whitmore & Schweizer 1995), some of which are expected to evolve into long-lived GCs (e.g. Goudfrooij et al. 2001). In the SAM, each merger induces a burst of star formation, producing stars and GCs. The relative fraction of GCs formed in each burst is determined by the GC formation efficiency, $\epsilon_{\text{GC}}$ (the mass of GCs/mass of stars). This efficiency is determined from counting the total populations of metal-rich GCs in present-day ellipticals, and typically corresponds to $\sim 0.5\%$ efficiency.

The redshift distributions of major mergers for two galaxies in the model are shown in Fig. 1. Each merger corresponds to the formation of field stars and GCs. The high-luminosity elliptical undergoes $\sim 80$ mergers, the low-luminosity elliptical in the figure has undergone $\sim 10$. In this hierarchical picture, significant age and metallicity sub-structure is present in this metal-rich peak. Such sub-structure has now been detected (e.g. Forbes et al. 2001; Kissler-patig et al., this volume), and the question is now perhaps not if GCs are formed in mergers, but what fraction and when.

1.3 Metal-poor Globular Clusters

The source of metal-poor GCs (hereafter 'halo' GCs) in the model are the star forming discs which grow from gas which has cooled out of the dark matter halo. Star formation proceeds as an 'accreting box' model, fresh gas continually falls onto the discs, which is also expelled through feedback from supernovae. The star formation rate in these discs is governed by the mass of gas available divided by an efficiency $\tau_*$. The fraction of these stars which become GCs are again governed by $\epsilon_{\text{GC}}$. However, the drawback of this picture, where the progenitors of halo GCs are gaseous galaxy 'building blocks' is that in our model, these building blocks proceed to aggregate mass and form stars quiescently until they reach metallicities at or above solar. This leads to metallicity distributions for the GCs which are similar to that of the bulge stars.

A key to forming halo GCs from these building blocks is to disconnect GC formation from the more general star formation occurring at early epochs, and in Beasley et al. (2002) it is was necessary to truncate their formation at $z \sim 5$. A physically reasonable way of achieving this truncation is to tie $\epsilon_{\text{GC}}$ to the local star formation rate (SFR) (e.g. Larsen & Richtler 2000). Hence, GCs are only allowed to form above a given SFR threshold, whereas field stars may form irrespective of this criterion. In the fiducial model of Cole et al., such a SFR criterion fails for the halo GCs because the SFR peaks rather late, yielding halo GCs which are too metal rich.

We show the mean SFR in discs for three different assumptions about $\tau_*$ in Fig. 2. Nomenclature for the different star formation schemes comes from Somerville, Primack & Faber (2001), whose motivation was to explain the observed characteristics of Lyman-break galaxies at $z \geq 2$. Star formation schemes such as the ‘accelerated quiescent’ mode (see Kauffmann, White & Guideroni
Fig. 2. Mean instantaneous star formation rates for three different assumptions about $\tau_\ast$. In the fiducial model of Cole et al. (2000), the star formation history follows the quiescent lines. The upper limits represent the observed ‘maximal dust correction’ from Somerville, Primack & Faber (2001). The values in Fig. 3 are illustrative only, since both the exact form and normalisation of these SFRs are not strongly constrained observationally (e.g. Steidel et al. 1999).

Although initially promising, how well such a scheme can be made to work in the broader context of galaxy formation and cosmology (e.g. M. Santos, these proceedings) remains to be seen. Importantly, the effects of other influences, such as the UV ionising background in SAMs (e.g. Benson et al. 2002), and its relation to GC formation (e.g. Cen 2001) must be accounted for.

1.4 The GC-Spheroid Connection

In our model, the entire metal-rich peak of the GC systems is created during merger-induced star formation. The metal-poor peak reflects the mass spectrum and accretion history of the galaxy progenitors. Since reproducing the ‘bimodal’ metallicity distribution function (MDF) is regarded as a key problem in GC
Fig. 3. Resultant metallicity distributions of metal-poor GCs for different star formation rate thresholds in the SAM (broken lines). The solid line corresponds to the observed halo GCs in the Virgo elliptical NGC 4649 (Forte et al., in preparation).

research, we should ask the question how well does the SAM reproduce the MDF of the spheroid stars?

Until recently, this question was unimportant since no MDFs of elliptical galaxies were observed. However, recent observations of individual stars in the nearby elliptical NGC 5128 (e.g. Harris & Harris 2002), have made this an important test. Such a comparison is shown in Fig. 4 for four model ellipticals compared to the stellar data of Harris & Harris (2002). The galaxies have been chosen to be similar to the luminosity and from similar environments to NGC 5128, but otherwise have been chosen arbitrarily. The agreement is surprisingly good, considering that the models were not intended for making such detailed comparisons.

We argue that such results demonstrate the utility of semi-analytic models in understanding the formation and evolution of GC systems in a cosmological context.

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Fig. 4. Metallicity distribution functions for four model ellipticals (open histograms) compared to the NGC 5128 distributions from Harris & Harris (2002). In each panel, $M_B$ refers to the B-band absolute magnitude of the model galaxy, and $\sigma$ refers to its halo velocity dispersion.

References

1. Ashman, K., Zepf, S.E., 1992, ApJ, 384, 50
2. Barnes, J.E., 1998, in "The Evolution of Galaxies on Cosmological Timescales", eds. Beckmen, J.E. & Mahoney, T.J., ASP Conference Series, v. 187, pp. 293
3. Baugh, C.M., Cole, S., Frenk, C.S., 1996, MNRAS, 283, 1361
4. Beasley, M.A., Baugh, C.M., Forbes, D.A., Sharples, R.M., Frenk, C.S., 2002, MNRAS, 333, 383
5. Benson, A.J., Lacey, C.G., Baugh, C.M., Cole, S., Frenk, C.S., 2002, MNRAS, 333, 156
6. Cen, R., 2001, ApJ, 560, 592
7. Cole, S., Lacey, C.G., Baugh, C.M., Frenk, C.S., 2000, MNRAS, 319, 168
8. Cote, P., Marzke, R.O., West, M.J., 1998, ApJ, 501, 554
9. Forbes, D.A., Brodie, J.P., Grillmair, C.J., AJ, 1997, 113, 1652
10. Forte, J.C., Martinez, R.E., Muzzio, J.C., 1982, AJ, 87, 1465
11. Goudfrooij, P., Mack, J., Kissler-Patig, M., Meylan, G, Minniti, D., 2001, MNRAS, 322, 643
12. Harris, W.E., Harris, G.L.H., 2002, AJ, 123, 3108
13. Kauffmann, G., White, S.D.M., Guiderdoni, B., 1993, MNRAS, 264, 201
14. Larsen, S.S., Richtler, T., 2000, A&A, 354, 836
15. Somerville, R.S., Primack, J.R., Faber, S.M., 2001, MNRAS, 320, 504
16. Steidel, C.C., Adelberger, K.L., Giavalisco, M., Dickinson, M., Pettini, M., 1999, ApJ, 519, 1
17. White, S.M., Rees, M.J., 1978, MNRAS, 183, 341
18. Whitmore, B.C., Schweizer, P., 1995, AJ, 109, 960