B−R Colours of Globular Clusters in NGC 6166 (A2199)

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ABSTRACT

We have analysed new R-band photometry of globular clusters in NGC 6166, the cD galaxy in the cooling flow cluster A2199. In combination with the earlier B photometry of Pritchet & Harris (1990), we obtain B−R colours for ∼ 40 globular clusters in NGC 6166. The mean B−R is 1.26 ± 0.11, corresponding to a mean [Fe/H] = −1 ± 0.4. Given that NGC 6166 is one of the most luminous cD galaxies studied to date, our result implies significant scatter in the relationship between mean cluster [Fe/H] and parent galaxy luminosity. We obtain a globular cluster specific frequency of S_N ∼ 9, with a possible range between 5 and 18. This value is inconsistent with the value of S_N ≤ 4 determined earlier by Pritchet & Harris (1990) from B-band photometry, and we discuss possible reasons for the discrepancy. Finally, we reassess whether or not cooling flows are an important mechanism for forming globular clusters in gE/cD galaxies.

Key words: stellar populations: globular clusters; galaxy clusters: cooling flows – cD galaxies.

1 INTRODUCTION

Broadband colours provide a relatively easy way to estimate metallicities of extragalactic globular clusters. The mean cluster metallicity (we will use colour and metallicity interchangeably in this paper, implicitly assuming that we are dealing with old stellar populations where age effects are not important) gives the overall level of chemical enrichment in the globular cluster system (GCS). There appears to be a relationship between mean cluster [Fe/H] and parent galaxy luminosity (e.g. Brodie 1993) in the sense that more luminous galaxies have, on average, more metal-rich globular clusters. However, recent work (e.g. Zepf, Ashman, & Geisler 1995a) has shown that there is considerable scatter about this relationship.

The cluster metallicity distribution (MD) provides far more information than the mean metallicity alone. The width of the MD is presumably indicative of the inhomogeneity of the protogalactic gas from which clusters formed and/or their subsequent chemical enrichment. In addition, multimodality in cluster MDs has been detected in several ellipticals (e.g. M87: Lee & Geisler 1993, Whitmore et al 1995; NGC 3311: Secker et al 1995; NGC 1399: Ostrov, Geisler, & Forte 1993; NGC 3923: Zepf, Ashman, & Geisler 1995a), and is most naturally explained by distinct epochs of cluster formation. The existence of spatial metallicity gradients is also interesting, since such gradients are predicted by many cluster formation scenarios, including classical dissipative collapse (e.g. Eggen, Lynden-Bell, & Sandage 1962), galaxy mergers (Ashman & Zepf 1992; Zepf & Ashman 1993), and possibly cooling flows if clusters have been forming out of the (subsonic) flow over several Gyr (e.g. Fabian 1994).

The number of early-type galaxies with measured globular cluster colours is still small (< 20). NGC 6166, the central cD in Abell 2199, is an interesting addition, given that it is one of the most luminous galaxies known (M_V ≃ −23.6 for H_0=75). It is also very X-ray luminous, together with a substantial cooling flow of 100–150 M☉/yr (Edge, 1995).
Stewart, & Fabian 1992). NGC 6166 has long been regarded as the classic multiple-nucleus galaxy, though two of the ‘nuclei’ are in fact not bound to the brightest one (Tonry 1984; Lachieze-Rey, Vigroux, & Souviron 1985; Lauer 1986). Lachieze-Rey et al. and Peletier (private communication) both find a colour gradient in NGC 6166, with δ(B−R) ≃ −0.4 from the centre out to ∼ 1 arcmin from the galaxy centre (see Figure 5). Cardiel, Gorgas, & Aragon-Salamanca (1995) also find stellar metallicity gradients from long-slit spectroscopy, and there is some evidence from Einstein and Ginga data of a metallicity gradient in the X-ray gas.

Two of us (Pritchet & Harris 1990; hereafter PH) previously detected a GCS in NGC 6166, using B-band images taken at the CFHT. The determination of the globular cluster specific frequency SN was hampered by the lack of a background frame, but PH estimated that SN ≤ 4. In this respect then, NGC 6166 is clearly unlike M87 and some other central cD/gE galaxies where SN ≃ 15–20 (e.g. Harris 1991). PH used this result, together with the large cooling flow, to argue that most globular clusters in central cD/gE galaxies do not form from cooling flows. We will return to this point in our Discussion (Section 4). The motivation for the present R-band study is two-fold: first, to confirm or not the specific frequency found by PH, and second to obtain B−R colours and thus metallicities for the brightest globular clusters in NGC 6166.

2 DATA AND ANALYSIS

The data for this study were obtained by D. Carter in August 1988 during the commissioning of the 4.2m William Herschel Telescope (WHT) in La Palma. The observations consist of a series of 12 × 300 sec dithered exposures for a field centred on NGC 6166 (Figure 1), and a field offset ∼ 10 arcmin from the galaxy (the ‘background’ field). Data were taken in the Kron-Cousins R-band using a GEC CCD (0.27 ″/pixel, R/N ∼ 9 e−, 1.7 × 2.6 arcmin). After the usual pre-processing (bias subtraction, flat-fielding), the galaxy and background frames were median-combined into a single effective exposure of 3600 sec each; the FWHM on the combined image is 0.9″ for the galaxy and background fields, and the effective field size is 1.5 × 2.4 arcmin for each field. The STSDAS ISOPHOTE and BMODEL routines were then used to fit and subtract most of the smooth halo light of NGC 6166. The area within 15″ of the galaxy centre, and smaller areas around other galaxies and bright stars in the frame, were masked out and not used in the following analysis; the central masked region includes the superposed ‘multiple nuclei’.

Detection and photometry of objects in the combined galaxy and background fields were done with the IRAF version of DAOPHOT. Image moments were also calculated to allow rejection of non-stellar images in a uniform way (e.g. Butterworth & Harris 1992). 46 and 181 objects with reliable classifications were rejected as non-stellar in the background and galaxy frames, respectively, to R ∼ 26–26.4 (the precise magnitude limit is difficult to determine, since our photo-

Figure 1. R image of NGC 6166, with North to the top and East to the left. The galaxy has been fit and subtracted using the STSDAS ISOPHOTE package within IRAF. The center of NGC 6166 has been marked with an ‘X’; the object just North-West of the galaxy center is a superposed cluster galaxy.

metric calibration applies only to stellar objects). From the deep R-band galaxy counts of Smail et al. (1995), we expect ∼ 250 galaxies in each of the galaxy and program fields to R = 26, within our ∼ 3 arcmin2 field (which includes a correction for the masked-out regions). The agreement with the numbers of rejected objects in each field is as good as can be expected, given the uncertainties as well as possible small-scale clustering of background galaxies. A further check of our image classification comes via a comparison with PH. There are only 13 objects (out of 372 total) from our final ‘stellar’ R list that were classified by PH as extended objects from their B photometry. Visual examination shows that about half of these 13 objects do appear to be stellar in our R frame. In any case, these results show that the image classification has been performed reliably in both the B and R datasets.

Variable extinction due to dust causes an uncertainty in the zero point as determined from the R band standards. However, we have refined the zero point using surface photometry of NGC 6166 and NGC 6173 (for the background field) by R. Peletier (private communication). The uncertainty in this zero point is of order 0.1 mag. Finally, determination of photometric incompleteness and errors was done by using ADDSTAR to put in groups of 100 PSF stars at several magnitudes, and rerunning DAOPHOT exactly as for the original frame. The 50% completeness level occurs at R ∼ 24.85 (25.15) for the galaxy (background) field; the magnitude scale error is ∼ 0.14 (0.05) mag at this level, while the rms uncertainty reaches ∼ 0.30 (0.20) mag. Before correcting for incompleteness, we find 304 objects classified as stellar to R=25.0 in the galaxy field (at R=25.0 the completeness is ∼ 35% in the galaxy field). We have looked for possible variations of the photometric completeness with distance from the galaxy center, by adding in 1000 stars and determining the completeness in 25-pixel wide annuli with mean radii of 100, 150, and 200 pixels (∼ 0.5, 0.75 and 1 arcmin); this experiment was run for three different magnitudes corresponding to completeness levels between 0.3 to 0.9. There is no trend for a variation of the completeness with radius, and no statistically significant differences in the completeness levels at the 3 radii, at any magnitude.

3 RESULTS

3.1 Radial Profile of Globular Cluster System

The radial profile of the NGC 6166 GCS is presented in Figure 2, with Log (number density) vs Log (radius in arcmin); the solid line is the best-fit least-squares line. To produce this Figure, we have put the 304 stellar objects to R=25.00 into bins of width 25.0 pixels (6.75″), and corrected each
Figure 2. The Radial Density Profile of the NGC 6166 GCS. Log Density is plotted against Log Radius (Arcmin). The solid line is the least-squares fit, with a slope of \(-0.95\).

bin for photometric incompleteness. Finally, we have subtracted the density of background objects to R=25.00 (26 ± 3 per arcmin\(^2\)), as determined from our background field. The NGC 6166 GCS appears to be one of the shallowest found to date, with a best-fit slope of \(-0.95 \pm 0.1\), though this is based on a small number of clusters. This result is consistent with the finding by Harris (1993) of a correlation between GCS profile slope and parent galaxy luminosity, in the sense that the GCS exhibits a flatter profile in more luminous galaxies.

3.2 Globular Cluster Luminosity Function

The NGC 6166 globular cluster luminosity function (GCLF) is shown in Figure 3 (filled squares), as Log(Number) vs. apparent R mag. The data have again been background-subtracted, and corrected for photometric incompleteness; the completeness is shown above the x axis. The open circles in Figure 3 represent the M87 GCLF, taken from McLaughlin, Harris, & Hanes 1994, converted from V to R assuming \(V-R = 0.55\), and shifted by \(\Delta(m-M)=4.3\) mag (error bars are omitted for clarity). No vertical scaling has been applied to either dataset.

3.3 Globular Cluster Specific Frequency

We have computed a local globular cluster specific frequency \(S_N\) for NGC 6166, i.e. within our CCD field (corresponding to a radius of \(\sim 40\) kpc for \(H_0=75\)), excluding masked-out regions around the centre of NGC 6166 and other bright objects in the field. The total number of clusters over all magnitudes is determined by assuming that the NGC 6166 GCLF is intrinsically the same as that of the Virgo gEs (e.g. same absolute peak magnitude and dispersion). From Lucey et al (1991), \(\Delta(m-M) = 0.7 \pm 0.1\) between Coma and A2199, and from Bower, Lucey, & Ellis (1992), the offset between Coma and Virgo is 3.69 mag, giving \(\Delta(m-M)_{A2199-Virgo}=4.4\). On the other hand, the redshift ratio gives a difference of 4.2, and we adopt the average of these two estimates as \(\Delta(m-M)_{A2199-Virgo}=4.3 \pm 0.1\). Within our CCD field, there are 385 ± 40 stellar objects to R=25.2 after correction for photometric incompleteness and background subtraction, or to B=26.45 ± 0.1 assuming B–R=1.25 (see next section). This limiting magnitude corresponds then to B=22.15 ± 0.15 at Virgo. Given that the GCLF of the Virgo gEs peaks at B=24.7 ± 0.3 (Harris et al 1991), we are 2.55 ± 0.34 mag short of the peak in the NGC 6166 GCLF. Assuming that the dispersion is 1.4 ± 0.1, again as found for the Virgo gEs (Harris et al 1991), we find the total number of clusters over all magnitudes to be 11,000 with a possible range between 6200 and 22,000. The large uncertainty in
N_{tot} is almost entirely due to the uncertainties in the peak magnitude and dispersion in the adopted Virgo GCLF, amplified by the fact that we sample such a small fraction ($\sim 3.5\%$) of the NGC 6166 GCLF.

The total galaxy magnitude in the CCD field is determined by simply adding up all of the counts within the frame (with stellar objects subtracted, and again excluding the masked-out regions), subtracting the background sky, and using our photometric calibration to convert to true R. This yields $R=12.27 \pm 0.1$. From RC3, $(B-V)_{0,T}=0.91 \pm 0.05$, and from Peletier’s unpublished photometry, $(B-R)=1.35 \pm 0.05$. Thus $(V-R)=0.44 \pm 0.07$, and $V=12.71 \pm 0.12$. Next we find the A2199 distance using $\Delta (m-M)_{A2199-V_{irgo}}=4.3$ (above), and the Virgo distance of $17 \pm 2$ Mpc from the recent Cepheid result of Freedman et al (1994), which gives then the A2199 distance as $35.45^{+0.26}_{-0.29}$. Thus, $M_V=-22.74^{+0.31}_{-0.31}$.

Finally, the globular cluster specific frequency is given by:

$$S_N = N_T 10^{0.4(M_V-T)} (1)$$

or $S_N=9$ with a possible range between 5 and 18, where the uncertainty in $S_N$ is totally dominated by the uncertainty in $N_T$.

Our result is not consistent with that found by PH, namely $S_{N,local} \leq 4$ (note that PH also used $B_V=24.7$ and $\sigma=1.4$ for the Virgo GCLF). There are two possible reasons for this discrepancy. First, PH did not have a separate background field, and their background may have been contaminated by the outer part of the GCS. Second, PH found evidence for a population of extended objects, perhaps dwarf galaxies, in their B data. Although we have not found any evidence for such a population in our R data, the effect would be to lower our $S_N$ value, since in that case our background would be underestimated; at the same time, PH would have overestimated their background and hence underestimated their $S_N$. Some significant fraction of our residual objects might be unresolved dEs, since we cannot resolve objects smaller than $\sim 0.6$ kpc in size at the distance of NGC 6166 with our $1''$ seeing. For instance, in the Coma cluster, Bernstein et al (1995) find that the faintest dEs in their sample for which they can reliably determine sizes (between 22.5 < R < 23.0, which would translate $\sim 0.5$ mag fainter in A2199) have half-light radii between 0.4–0.75 kpc; $r_{1/2}$ decreases with magnitude and objects 0.5 mag fainter than this are roughly a factor of two smaller.

However, this local value of $S_N$ may well differ from the global value. The main uncertainty, as discussed in PH, is the unknown behavior of the globular cluster spatial distribution outside the CCD field. If the clusters are more spatially extended than the halo light (which is certainly true inside the CCD field) at all radii, then $S$ will increase with radius. PH estimate that $S_{global}/S_{local} = 1.6$ if NGC 6166 is similar to M87 in this respect. In this context, it is interesting to compare our local value of $S_N$ for NGC 6166 with a similar one for M87. We have used the globular cluster counts of McLaughlin, Harris, & Hanes (1994) and the photometry of Carter & Dixon (1978) and Boroson, Thompson, & Schectman (1983) to compute $S_N$ for M87 out to 7 arcmin radius; this corresponds to $\sim 35$ kpc for a Virgo distance of 17 Mpc, roughly the same physical radius as our data for NGC 6166. With the same GCLF parameters and Virgo distance as assumed above, we find that $S_{N,M87}=11.7 \pm 1.7$ between 1.2 to 7 arcmin radius (McLaughlin et al did not carry out cluster counts within 1.2 arcmin of the galaxy centre). This value is not so different from what we have found for NGC 6166 above. Thus, the present data do not allow us to rule out the possibility of NGC 6166 being a high–specific frequency system. We plan to obtain deeper, wider-field data so that a better global $S_N$ value can be determined.

### 3.4 B–R Colours of NGC 6166 Globular Clusters

B–R colours were determined by matching objects from the earlier B data of PH with the present R data; only objects classified as stellar in both lists were used. The transformation between the two coordinate systems (including a small rotation of $\sim 4$ deg) was obtained from several bright stars in common.

In Figure 4, we show the R, B–R CMD for those (70) objects with 24.0 $\leq R \leq 25.0$ and 0.0 $\leq B–R \leq 2.0$; in the lower right hand corner is a representative error bar. To isolate a cleaner sample of NGC 6166 globular clusters, we applied magnitude and colour limits. The magnitude limits used were 24.0 $\leq R \leq 24.5$, where the bright end is set at the expected onset of the GCS, and the faint end is set at a completeness of 60%. The colour limits are 0.8 $\leq$ B–R $\leq 1.6$, which generously includes all known Galactic globular clusters (Harris 1995). The dashed and solid lines in Figure 4 show our cuts in B–R and R respectively. With these limits (ie. within the central box), there are 37 objects. In Figure 5, we plot B–R against galactocentric radius for these 37 objects (open circles); the solid horizontal line shows the mean colour of these objects (see below), and the filled squares represent the colour profile of the galactic halo light from Peletier (priv. comm.). While there is a colour gradient in the halo light, none is apparent in the globular clusters. However, a small gradient could easily be masked by the small number of clusters and our large uncertainties.

The B–R histogram of the NGC 6166 ‘clusters’ is shown in Figure 6. In this Figure, we show those (44) objects with 24.0 $\leq R \leq 24.5$, and 0.0 $\leq B–R \leq 2.0$. Again, these data are consistent with a globular cluster population, with a roughly Gaussian distribution and a mean B–R $\sim 1.25$. Within the small numbers there is no evidence for multimodality, as has been found for clusters in other ellipticals (e.g. Zepf, Ashman, & Geisler 1995a; Secker et al 1995). However, Ashman, Bird, & Zepf (1994) showed that it is essentially impossible to detect bimodality in datasets with N < 50.

In order to quantify the mean B–R colour, we have calculated the mean and median B–R for those (37) objects with 24.0 $\leq 24.5$ and 0.8 $\leq B–R \leq 1.6$, finding both the mean and median B–R to be $1.26 \pm 0.11 \pm 0.10$ of this comes from the possible systematic error in our R zero-point [Section 2], while the uncertainty in the B zeropoint is $\pm 0.05$ [PH]). The foreground extinction towards NGC
Figure 4. The R–B CMD of the NGC 6166 GCS. The region enclosed by the dashed and solid lines is where the globular clusters are expected to lie; there are 37 objects in this region. At the lower right hand corner is a representative error bar.

Figure 5. B–R vs. Galactocentric Radius. B–R (open circles) is plotted against Galactocentric Radius (arcsec); the solid line shows the mean colour of these objects. The filled squares are the colour profile of the halo light from Peletier.

Figure 6. B–R Histogram of NGC 6166 Globular Clusters. There are 44 objects with 24.0 ≤ R ≤ 24.5 and 0.0 ≤ B–R ≤ 2.0.

6166 is negligible, and we adopt E(B–V)=0.00 ± 0.015 mag (Burstein & Heiles 1984). Using the conversion between (B–R)0 and [Fe/H] established for Galactic globular clusters by Reed, Harris, & Harris (1994), this corresponds to [Fe/H]mean=−1.05 ± 0.40. The uncertainty in [Fe/H] includes both the photometric error in our mean (B–R)0 (± 0.11 mag), and the scatter in Reed et al.’s relation between (B–R)0 and [Fe/H] (± 0.21 dex in [Fe/H]; their equation 3c). Our incompleteness does not have a steep colour dependence, so the mean and median B–R colours are unchanged by the application of techniques like that of Zepf, Ashman, & Geisler (1995a) to account for colour-dependent incompleteness.

We have also experimented with relaxing the colour and magnitude limits given above between 24 ≤ R ≤ 25 and 0.0 ≤ B–R ≤ 2.0. While the number of matched objects increases to 70 in the most ‘relaxed’ case, the corrected median B–R only changes by ± 0.05. We summarize by stating that [Fe/H]=−1 ± 0.4. This mean cluster [Fe/H] is inconsistent with the metallicity of the A2199 ICM, which was recently determined by White et al (1994) to lie between [Fe/H]=−0.2 and −0.5, based on Ginga and Einstein X-ray data; see further discussion of this point in Section 4.

It is also interesting to compare the NGC 6166 mean cluster metallicity with that of clusters in other galaxies. In Figure 7, we show mean cluster [Fe/H] plotted against parent galaxy luminosity for 17 galaxies of all types (this Figure is adapted from Secker et al 1995); our value for NGC 6166 is shown as a triangle. Recent data (e.g. NGC 3923: Zepf, Ashman, & Geisler 1995a; NGC 3311: Secker et al 1995; NGC 6166: present work) have tended to increase the scat-
Figure 7. Mean [Fe/H] metallicity of globular cluster systems as a function of parent galaxy luminosity. This Figure has been adapted from Figure 7 of Secker et al (1995). The data for the S, Irr, E, and dE galaxies are taken from Harris (1991). Globular cluster data for NGC 1399 from Ostrov et al (1993), for M87 from Lee & Geisler (1993), and for NGC 3923 from Zepf et al (1995a). Globular cluster [Fe/H] for NGC 6166 from the present work, and galaxy photometry from RC3 with H_0=75 assumed.

4 DISCUSSION: THE ROLE OF COOLING FLOWS

What constraints can these and similar data place on the formation of globular clusters in cooling flows? Here we discuss several arguments that have been raised against forming clusters in cooling flows.

1: There is no correlation between cluster specific frequency S_N or total number of clusters, and properties of the X-ray gas (X-ray luminosity, gas temperature, total gas mass, or cooling flow rate).

Some cDs (e.g. M87, NGC 3311, NGC 4874) have huge cluster populations and low cooling flow rates, while others such as NGC 4073 (MKW 4) have ‘normal’ cluster systems and similarly low cooling flow rates. If cooling flows are putting the majority of their mass into low-mass objects (LMOs), and a small fraction into globular clusters, then S_N should *increase* with mass-flow rate since the LMOs basically have no effect on the galaxy luminosity, whereas more massive cooling flows would form a larger number of (luminous and hence observable) clusters. The lack of a correlation between N_{tot} and ICM properties is even harder to reconcile with a cooling flow scenario. While it should not be forgotten that N_{tot} and S_N (and the X-ray and cooling flow parameters) could be uncertain by factors of two or more, these numbers already cover such a huge intrinsic range that it is very hard to believe that any well-defined correlation could have been obscured just by observational scatter. Deeper imaging, and hence a better-constrained S_N value for NGC 6166, will be very useful, given its large cooling flow rate of ~150 M_☉ per yr. See Harris, Pritchet & McClure (1995) for a very thorough discussion of these points.

2: If cooling flows have been forming globular clusters continuously to the present day, we would expect to see some bright, blue young clusters formed recently.

While young clusters appear to have been found in several isolated mergers (NGC 3597: Lutz 1991; NGC 7252: Whitmore et al 1993; NGC 4038/4039 (The Antennae): Whitmore & Schweizer 1995), such objects have not been found in cooling flow cD/gE galaxies, with the possible exception of NGC 1275. The situation for NGC 1275 is quite controversial, since there is both a strong cooling flow and evidence for a recent merger in the form of shell-like features in the optical and IR. Holtzman et al (1992) argued against the blue clusters having formed from the cooling flow because there is no apparent correlation between colour and magnitude. Richer et al (1993) found a large scatter in the colours of the blue clusters based on ground-based photometry, which they used to argue for a cooling flow origin. Faber (1993) has questioned the Richer et al photometry, pointing out that some objects are simultaneously blue in B−V and red in V−I, and vice versa. Better photometry is needed to resolve this issue. The spectrum of the brightest blue object in NGC 1275 (Zepf et al 1995b) is equally consistent with a merger or a cooling flow origin, given its age (∼1 Gyr) and apparent solar metallicity.

Deep multicolour photometry of globular clusters in more cooling flow cD/gE galaxies will help a good deal. Clusters formed from cooling flow gas should have a unimodal colour/metallicity distribution (although one could imagine contrived ‘punctuated’ models, where cooling flows and associated star/cluster formation are interrupted from time to time by subcluster mergers or other processes), whereas clusters formed in one or more merger events should have multimodal distributions (e.g. Ashman & Zepf 1992).

3: The metallicity of the X-ray gas is 3–5 times higher than the [Fe/H] ≃ −1 typical of globular clusters in gE/cD galaxies.

At first glance, it seems that we are actually comparing two different things: X-ray gas metallicity at the current epoch, and globular cluster metallicities 10–15 Gyr ago. However, a consensus seems to be developing that the ICM iron originated in cluster ellipticals, ejected through SN-driven winds (e.g. Renzini et al 1993). With such models, several authors have concluded that the bulk of the ICM enrichment oc-
occurs at early times (≈ 10 Gyr) over a very short time (a few 10^8 years; e.g. David, Forman & Jones 1991; Renzini et al. 1993; Elbaz, Arnaud, & Vangioni-Flam 1995). Thus, if cooling flows have produced significant numbers of globular clusters, the majority of clusters are expected to have metallicities comparable to (or higher than, if cluster self-enrichment is important) the present ICM metallicity, since the gas enrichment occurs so rapidly. Instead, the ICM gas typically has [Fe/H] = −0.5 to −0.3 (e.g. White et al 1994), while the mean metallicity of clusters in gE/cD galaxies is typically [Fe/H] = −1 to −0.5. Note that ICM enrichment models are very uncertain, with the relative role of type I and type II SN being quite controversial, and the past SN rate being essentially unknown. A key issue to investigate is the expected spread in metallicity of ICM gas in SN models, and to compare with larger datasets of globular cluster metallicities. An interesting finding is that the gas iron abundance decreases slightly with ICM temperature, and it will be interesting to see if similar behavior is found for the globular clusters as well.

Secker et al (1995) have recently found that [Fe/H] ≈ −0.3 for globular clusters in NGC 3311, quite comparable to the typical ICM metallicity. At the same time, ASCA data have shown that [Fe/H] ≈ −0.8 for gas in NGC 1404 and NGC 4374 (Loewenstein et al. 1994). In NGC 4636, [Fe/H]_gas ≈ −0.5 near the galaxy centre, but declines to [Fe/H] ≈ −0.9 at R ∼ 9'. If such metallicity gradients are common, then previous X-ray data (which lacked the ASCA spatial resolution) have resulted in over-estimates of the ICM metallicity.

4: It is difficult to form objects with globular cluster masses from cooling flows.

It is well established that most of the gas condensing out of cooling flows cannot be forming stars with a ‘normal’ (i.e. Galactic) mass function, else the colours and spectra of cooling flow cDs and their halos would show this clearly (e.g. Fabian 1994). Instead, if star formation is occurring, it is presumably biased towards M ≤ 1 M⊙. This can be explained qualitatively by the high pressures expected in cooling flows, which would produce a low Jeans mass at T ≲ 10^4 K (M_J ∝ P^{−1/2}). However, if magnetic fields are present, clouds can cool below 10^4 K with lower densities and pressures than they would have in the absence of the field, and with a correspondingly higher Jeans mass. Unfortunately, it requires magnetic field strengths of ≈ 500–1000 μG to produce M_J ≈ 10^6 M⊙ (Fabian, private comm), and typical cluster magnetic fields as measured from Faraday rotation are only 1–100 μG (e.g. M87: Owen, Eilek, & Keel 1990; A1795: Ge & Owen 1993; A2029 and A4059: Taylor, Barton, & Ge 1994); however, the field strengths could be much higher on small scales.

In any case, the Jeans-mass thermal instability approach to globular cluster formation is difficult to reconcile with current observations. Most notably, (a) the distribution of clusters by mass shows no peak mass which could readily be identified with a ‘universal’ Jeans mass; instead, it shows a simple power-law form N(M)dM ∼ M^{−7} (e.g. Harris & Pudritz 1994; note that the GCLF in its conventional form as number of clusters per unit magnitude shows a distinct peak at MV ∼ −7.5, but this is an artifact of binning in log-luminosity); and (b) the cluster mass distribution is similar in all galaxies over a huge range in metallicity, i.e. the heavy-element composition of the protocluster gas. Cooling flows (dilute, hot inflowing gas) represent a much different gaseous environment than would a typical early protogalaxy (with lots of material in massive, cool clumps which are colliding and merging, perhaps embedded in an ambient hotter medium). Thus if cluster masses were determined by thermal instability we would expect cluster mass distributions in cooling-flow galaxies to be much different than those in spirals or normal ellipticals, which is contrary to the observations. A model more in accord with cluster formation either at early or present-day epochs is that put forward by Harris & Pudritz (1994), whereby globular clusters form within supergiant molecular clouds (10^8 – 10^9 M⊙) that are supported by turbulence and weak (10 – 100μG) magnetic fields rather than thermal pressure.

Summary

On balance, the above discussion argues that the bulk of the globular clusters in gE/cD were not formed from cooling flows, although some small fraction of globular clusters may have formed in this way. In particular, it seems most unlikely that cooling flows are responsible for the high S_N phenomenon. While cooling flows are not forming significant numbers of globular clusters at the present epoch, they may have played an indirect role at earlier times. Perhaps, as discussed by Merritt (1984,1985) and others, cD galaxies were formed in small groups/subclusters, and there was time for cooling flows to develop. Somewhat later, the rich clusters we see today were formed from the mergers of these subclusters. This merging process may have also triggered star and globular cluster formation from the collected cooling flow gas.

5 CONCLUSIONS

We have obtained photometry to a limiting magnitude of R ≥ 25 for globular clusters in NGC 6166. Our main conclusions are:

- The local globular cluster specific frequency is S_N = 9, with a possible range between 5 and 18, which is inconsistent with the earlier result of S_N ≤ 4 found by Pritchett & Harris (1990) from their B-band images, yet is consistent with a local S_N in a similar region of M87.
- The mean B–R colour for 37 globular clusters is 1.26 ± 0.11, which corresponds to a mean [Fe/H] = −1 ± 0.4 using a calibration based on Galactic globular clusters. This mean cluster metallicity is inconsistent with the [Fe/H] ∼ −0.4 found for the X-ray gas by White et al. (1994). Our result confirms and extends recent findings of significant scatter in any possible relation between mean cluster metallicity and parent galaxy luminosity at the high-luminosity end.
- There is no apparent trend between R mag and B–R, and no apparent globular cluster colour gradient.
The available data and theoretical/numerical models allow us to rule out cooling flows as a mechanism for forming significant numbers of globular clusters in gE/cD galaxies, and cooling flows appear not to be responsible for the high \( S_N \) phenomenon. However, some small fraction of globular clusters may form in cooling flows, and more and better data are needed of globular cluster systems in cooling flow and other environments. There also remain several interesting theoretical issues to explore (the metallicity evolution of ICM X-ray gas and the expected spread in metallicity, and the role of SN; numerical modelling of star/cluster formation in cooling flows, particularly the role of magnetic fields; a better understanding of cluster formation in merging galaxies).

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